Western Research Institute

Asphalt Research Consortium

Annual Work Plan for Year 2 – Revised
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RESEARCH PLAN FOR YEAR 2 OF FEDERAL HIGHWAY ADMINISTRATION CONTRACT DTFH61-07-H-00009 "ASPHALT RESEARCH CONSORTIUM"

INTRODUCTION

This document is the revised Research Plan for Year 2 of the Federal Highway Administration (FHWA) Contract DTFH61-07-H-00009, the Asphalt Research Consortium (ARC). The Consortium is coordinated by Western Research Institute with partners Texas A&M University, the University of Wisconsin-Madison, the University of Nevada Reno, and Advanced Asphalt Technologies. The revised Year 2 Work Plan contains Gantt charts for research activities, additional background materials and coordination material, and a master list of references compiled from work plans and quarterly reports. The master list of references is also available as a sortable Excel file on the ARC website, www.arc.unr.edu .

The Year 2 research plans are an extension of the Year 1 research plans and are grouped into seven areas, Moisture Damage, Fatigue, Engineered Paving Materials, Vehicle-Pavement Interaction, Validation, Technology Development, and Technology Transfer. In July 2007, the Consortium members received a set of written reviewer comments on the Year 1 Work Plan from FHWA Co-AOTR's Dr. Jack Youtcheff and Mr. Eric Weaver. The list of reviewer comments, as received from FHWA, and the responses can be found on the ARC website, www.arc.unr.edu.

The Year 1 Work Plan, with some amendment, was approved by the Co-AOTR's on July 19, 2007 and work commenced. In mid-December 2007, after discussions between the Consortium and the FHWA Co-AOTR's, it was decided to amend the performance year of the contract from January 1 – December 31 to April 1 – March 31. The change was agreed upon because it provides time for the Annual Work Plans to be reviewed by the three Expert Task Groups (ETG) which generally meet in the month of February. Therefore, the Year 2 Work Plans cover the time period of April 1, 2008 to March 31, 2009.

The format of the work plans follows the format that was presented in the Year 1 Work Plan with sections added for the progress during Year 1 and the plans for Year 2. Additionally, a Materials Selection Plan was prepared and is shown at the beginning of the Work Plan. The Moisture Damage and Fatigue areas contain work elements that are interrelated and thus will work together to advance the knowledge of mechanisms and models in these areas. In addition, there are some work elements that compliment one another by investigating a common principle using different methods. Using two different methods provides a check on one another so that the true significance and importance of each can be evaluated and related to performance properties. There are also examples of Modeling activities that compliment each other in a similar fashion. The Consortium members firmly believe that this approach makes the research more robust.

The research areas of Engineered Paving Materials, Vehicle-Pavement Interaction, and Validation generally contain work elements that are more "stand-alone" in nature but this doesn't mean that these work elements will operate independently because in most cases, at least two Consortium partners are teaming to conduct the work. These work elements will also provide useful information to the other research activities in the Consortium and are designed to provide solutions to specific problems.

Finally, the areas of Technology Development and Technology Transfer are the areas where the research deliverables will get transmitted to the user community. The Technology Development area will take promising research developments and refine them into useful tools for engineers and technologists involved in the design, construction, and maintenance of flexible pavement systems. In the first year, six promising methods were identified and have been forwarded to the three ETG's for review. The Technology Transfer area will also transfer Consortium research findings to the asphalt community using the Consortium website, presentations, publications, and workshops.

The Asphalt Research Consortium members strongly believe that the proposed research is responsive to the needs of asphalt engineers and technologists, state DOT's, and supports the FHWA Strategic Goals and the Asphalt Pavement Road Map.

MATERIALS SELECTION PLAN

The Materials Selection Plan is incorporated with the Research Database Plan in section TT1d.

PROGRAM AREA: MOISTURE DAMAGE

This work plan for year 2 of the Asphalt Research Consortium (ARC) was prepared by revising the five year work plan submitted in May of 2007. In that work plan the first year work effort was identified and emphasized within the five year plan. The same general approach was taken here with the second year work being emphasized. According to this approach, the overall work plan was modified in order to accommodate the feedback received from FHWA on the year 1 work plan, reflect accomplishments made in year 1 including revisions based on year 1 accomplishments and findings, and reflect the area of emphasis and milestones for year 2.

INTRODUCTION

The Moisture Damage Process

It is generally agreed among highway engineers that moisture damage in asphalt pavement is one of the most wide-spread and most severe forms of pavement distress that leads to early pavement failure. Moisture damage occurs in all types of climates including hot, dry, and desert climates. Moisture damage may result in stripping, raveling, fatigue damage and/or permanent deformation, i.e., moisture invasion into pavement reduces its structural strength thereby promoting one or more of the above described (visible) forms of distress.

There are, no doubt, multiple mechanisms by which moisture changes (reduces) the structural strength of the pavement. It has been shown that water can etch certain types of aggregate surfaces to disrupt the asphalt-aggregate bond, and it has been shown that asphalt can and will transport water thereby making it available at an aggregate surface. It has been shown that asphalts generally oxidize more rapidly when they are wet than when dry, and further, that oxidation produces small amounts of highly surface-active materials which are capable of emulsifying and/or softening asphalt. There is strong evidence that microorganisms cause damage to the pavement, especially in hot, wet climates, but the severity of this mechanism of damage is not yet clear.

Research Needed to Better Understand and Evaluate Moisture Damage

Numerous test methods have been developed over the past 50 or so years that were designed in order to predict the moisture sensitivity of any asphalt-aggregate mixture. These are empirical tests which, for the most part, do not correlate well with observed moisture sensitivity of the pavement in the field. One test (the Hamburg wheel-tracking test) is so severe that some moisture-insensitive pavement mixtures could fail the test. Another, the Lottman test, is considered by many to be a relatively reliable predictor of moisture sensitivity, but it requires so much time (several weeks) to perform that it normally cannot be used in the pavement design process. Other tests give mixed results. A major problem with all empirical tests, except the Lottman test, is that they do not provide information on mechanisms or causes of moisture damage. Therefore, engineers cannot use the test results to optimize the mixture resistance to moisture damage.

The mission of this program is to elucidate all of the major mechanisms of failure that result from the presence of moisture in the pavement. A most promising concept for investigating the propensity of the pavement to suffer moisture damage is to identify the adhesive bond between the asphalt binder and the aggregate as well as the cohesive strength of the asphalt mastic within the mixture. The basis of the calculation of both adhesive and cohesive bond strengths is the measurement of the surface energies of asphalt and aggregate. The calculations of adhesive bond strength between the asphalt and aggregate can be made dry and in the presence of moisture. Fundamental thermodynamic measurements of surface energy and the subsequent bond strength calculations show that the wetting of the aggregate surface with water is preferred over the wetting of the aggregate surface with asphalt. However, a pressing need is to understand and model the kinetics (rate) of displacement of asphalt by water.

Previous research has shown that aggregate surface energy is the major variable that influences the binder-aggregate adhesive bond. However, this finding is primarily based on measurements of newly prepared mixes, i.e., using new (unaged) asphalts. Clearly, asphalts age in the pavement and consequently the properties of asphalt change and probably vary substantially with age. So, in the future the concept of using fundamental thermodynamic measurements to predict moisture sensitivity must consider aged asphalts. Furthermore, the correlation of thermodynamic stability with the kinetics of displacement must be established. This type of relationship has been established for other chemical systems, so, in principle, it can be done for asphalt-aggregate systems as well.

Moisture damage that leads to early pavement failure consumes a disproportionate amount of highway maintenance funds. Therefore, development of a rapid, reliable method to predict moisture sensitivity of pavement mixtures is imperative. In summary, one of the primary goals of this program will be to develop a system to match asphalts (new and aged), aggregates, and additives to form a mixture that is highly resistant to moisture damage. The process of formulating such a mixture must be expedient enough so that it can become part of the pavement design process. Since surface energy is defined by composition, some portion of a comprehensive system to match asphalts, aggregates, and additives very likely will involve chemical analyses which are very rapid compared to physical tests.

In addition to the selection of materials, this program will target the development of tests and models that will be used to evaluate and quantify the resistance of asphalt mixtures to moisture damage. It is envisioned that the test methods will be similar to those discussed in the fatigue work plan. These tests will focus on the dynamic mechanical analysis of asphalt mastics and fine portion of the mixtures and the repeated dynamic loading of full mixtures. The models will be similar to the micromechanical and unified continuum models discussed in the fatigue work plan. The main difference is that the influence of moisture will be included in the models' parameters.

HYPOTHESES

The development of tests and models that reliably predict the moisture susceptibility of mixtures depends on the identification of the mechanisms that contribute to moisture susceptibility.

Multiple mechanisms are responsible for moisture damage, and the synergistic effects of all of these mechanisms must be considered in an effective model of the process of moisture damage and in developing tests for material and mixture properties as input to the model. The working hypotheses for the development of a methodology to rapidly and reliably predict moisture susceptibility of mixtures is:

> The moisture susceptibility of a mixture is determined based on the combined effect of material properties and mixture properties. The material properties must include the composition of the asphalt as well as the changes in composition upon aging of asphalt, the impact of the nature of the water at the aggregate-asphalt interface as reflected by pH levels of the water, aggregate structure and composition and the effect of aging and compositional changes in the aggregate surface over time of exposure to the local environment, surface energies of the asphalt and the aggregate that can be used to assess adhesive and cohesive bond strengths (dry and in the presence of moisture), and the hydraulic conductivity of the asphalt mastic. The mixture properties that must be considered include mixture volumetrics with a focus on air void distribution within the mixture.

OBJECTIVES

1. Identify the mechanisms that contribute to moisture susceptibility of mixture.
2. Understand the contribution of material properties such as aging of the asphalt, pH of the water, aggregate structure, diffusion properties of the binder or mastic, and surface energies of the asphalt and aggregate to the moisture susceptibility of mixes.
3. Understand the contribution of mixture properties such as internal void structure and diffusivity of the mixture.
4. Develop a model of the moisture damage process that is linked to and compatible with the model of fatigue damage being developed by the ARC (work element F3).
5. Develop and validate the utility of tests and models to evaluate the moisture susceptibility of mixtures and quantify the effect of moisture on pavement distress.

EXPERIMENTAL DESIGN

Although it is premature at this point to propose an exact experimental design, the development of an experimental design will be among the initial subtasks of each work element. The experiment design will be communicated to the AOTR before the work is begun for each individual work element, and each experimental design or plan will be approved and/or developed by the project statistician, who is in our case Dr. E. S. Park of the Department of Statistics at Texas A&M. Dr. Park has a research appointment with TTI and is very familiar with the design of experiments in asphalt related research. She has served as team statistician on several asphalt related research projects including NCHRP Project 9-37, "Using Surface Energy Measurements to Select Materials for Asphalt Mixtures".

The TTI team will use the Buckingham PI theorem of experiment design to identify dimensional ratios of material properties to minimize the size of the experiment and maximize the information to be obtained from them. This approach was used successfully in many fields of mechanics such as fluid flow and aerodynamics.

WORK ELEMENTS

Category M1: Adhesion

Work Element M1a: Affinity of Asphalt to Aggregate

Task Lead: Dante Fratta

Introduction

It is well recognized that adhesion and cohesion both between the coarse aggregate and the binder and within the mastic itself are important parameters that contribute to the mechanical properties of bonded materials. The performance of asphalt pavement is deeply related to the presence of moisture and the loss of chemical and physical affinity between asphalt binders and aggregates. In order to evaluate the susceptibility of asphalt pavement to moisture damage, the chemical and physical affinity is measured using loose asphalt mixtures or compacted asphalt mixtures in field-simulated environments. Although some of the tests show results comparable with real field responses, these tests fail to address the structural complexities of asphalt mixtures. Furthermore, these tests provide little insight for the development of analytical analysis.

Exploratory studies at the University of Wisconsin-Madison have shown a good correlation between binder adhesion and cohesion testing results and moisture effects on asphalt mixtures as measured by various tests such as the Hamburg wheel test and the tensile strength ratio (TSR). Recent work at Texas A&M University has also indicated that surface energy measurements and the estimated adhesion and cohesion derived from these measurements can explain some of the moisture damage behavior observed in the laboratory.

This work plan will study the possible relationship between adhesion and cohesion measured directly using a Dynamic Shear Rheometer (DSR) device modified to include the mineral surface and the surface energy measurements collected with the Universal Sorption Device. The intent is to compare the effectiveness of each system and propose a simple and practical surrogate binder-specific test to evaluate affinity of binder (or mastic) to the mineral aggregate surface. This study will be based on the use of simplified specimen geometries based on the DSR device and processed rock disks. Preliminary results using this newly developed moisture damage test have shown the applicability of the methodology to evaluate various testing conditions. Furthermore, the results will be correlated to data form the pull-off (PATTI) test, which is the focus of another work plan of the Consortium. This work plan will also allow building on the progress achieved so far and extend the work to mastics and effects of fillers in general on moisture damage.

Relationship to FHWA Focus Areas

The moisture damage work elements support the FHWA Focus Area of Optimizing Pavement Performance by providing a relationship between material property and pavement performance.

Hypothesis

The hypothesis is that the adhesive bond between asphalt binders and aggregates, along with the cohesive characteristics of the binders, are the main factors controlling moisture damage in asphalt-aggregate mixtures. Although it is difficult to predetermine which aggregates will be used with a binder, using model aggregate mineralogies that are typical of aggregates used in practice could allow for better binder selections.

Objectives

The main purpose of this work element is to find and evaluate physical/engineering correlations between mixture moisture damage test results with binder test results collected with the modified DSR procedure for different asphalt mixtures and mastics. In addition, new testing protocols for the evaluation of the potential of moisture damage using the DSR will be proposed based on the results from the planned experimental tasks. This objective will be achieved by carrying out the subtasks discussed here.

Experimental Design

The objective of this subtask will be addressed as follows:

Subtask M1a-1: Select Representative Asphalt Binders and Mastics, and Aggregate Materials (Year 1 start).

The data collected in this task will be shared with other Consortium members to decide on a set of binders, fillers, and aggregates that will be used in this and other Consortium work elements focused on moisture damage. It is expected that the materials will include at a minimum the following material parameters:

1. Asphalt binders:
    a. Several PG grades: 58, 64, 70, and 76
    b. Base binders should be from two different sources
    c. Modification methods: styrene-butadiene-styrene (SBS), terpolymer (Elvaloy), ethylene vinyl acetate (EVA), PPA, and chemical modification
2. Three different fillers:
    a. acidic (quartzite)
    b. basic (calcite)
    c. neutral (such as Ottawa sand)

3. Aggregates:
    a. Mineralogy: limestone (with two different moisture-susceptibility histories) and granite (with two different moisture-susceptibility histories)
    b. Angularity and gradation: one coarse aggregate and one fine aggregate with significant differences in their surface areas
4. Conditioning water:
    a. distilled water
    b. sodium chloride solution
    c. calcium chloride solution

<u>Subtask M1a-2. Use the Modified DSR Tests to Evaluate Various Moisture Testing Conditions, Including Control of Rate and Temperature and to Measure Affinity of Asphalts to Aggregates and also Cohesion of Binders (Year 1 start)</u>

In this subtask, the modified DSR device will be used. The testing system consists of composite sample of two cored rock disks (25 mm diameter and 5 mm thickness) sandwiched with asphalt binder (1 mm film thickness). The two disks are glued on the DSR metal spindle and the base metal plate respectively. In the DSR setup, the parallelism is obtained by aligning the disk using the metal DSR metal shafts while the epoxy binder dries. A water cup circumscribing the composite sample is used to allow the sample to be submerged. Shear stress sweeps are then used to measure the change of rheological properties according to increased stress before and after conditioning with water. Results for selected combinations will be also compared to PATTI test results. It is expected that texture may influence the results. For this reason the attempt is made to test all different mineral specimens with the same texture as obtained from the sawing and lapping during specimen preparation. Maintaining a constant texture and changing the aggregate type isolates testing parameters and allows evaluation of the effect of mineralogy in the moisture damage of aggregate-binder systems.

This test setup will be used to collect data for shear stress sweep at different times of conditioning, temperatures, and rates of loading. A wide range of combinations of materials based on the results of Subtask M1a-1 will be included. The results will be analyzed in coordination with Texas A&M University research activities to verify that what is being measured is, in fact, explainable by fundamental surface energy measurements and that the conditions selected for measurements are effective in determining adhesive bond strength as well as cohesive strength.

<u>Subtask M1a-3: Evaluate the Moisture Damage of Asphalt Mixtures with Selected Material Combinations by the TSR Test or an Alternative Test System</u>

Based on the results of Subtask M1a-2, a reduced number of aggregates, binders, water conditioning parameters (time, temperature, media), and testing temperatures will be selected. A detailed work plan will be developed to test moisture damage resistance of mixtures using the most recent protocol for TSR, or any newly developed moisture susceptibility test. A detailed literature review and phone interviews with researchers involved in developing mixture moisture damage tests will be conducted and tests will be selected accordingly.

Subtask M1a-4: Correlate Moisture Damage as Measured by the Modified DSR Test with the Mixture Test Results – Analyze Results on Each Combination and Material

In this subtask, the relationships between the modified DSR test results and the mixture test results will be analyzed using statistical analysis as well as using the surface energy measurements. If meaningful correlations are found, modeling of the relationships will be pursued to give physical/engineering explanations to the correlations and to sort the important variables that should be considered in using asphalt–aggregate tests. In addition, the probability of success of a binder-specific test will be determined and compared to the probability of success of the selected mixture moisture damage test.

Subtask M1a-5: Propose a Novel Testing Protocol

Based on the results of Subtask M1a-4, a final testing protocol will be developed. The cost of modification of DSR devices and the practicality of the test will be analyzed. Manufacturers of DSR devices in the US will be contacted to discuss possible commercialization of the test protocol. Also, selected state DOTs will be contacted to get feedback on the use of these tests. Based on collected feedback, a protocol will be developed in the AASHTO format.

Major Findings from Year 1

During Year 1, the materials and testing conditions for the plan were selected, as shown in table M1a.1. Materials prepared under ARC Work Element F2a are also included in this study. This will help in the investigation of the influence of different modifiers over the moisture damage properties of binders. On the aggregate side of the materials list, three types of filler (acidic, basic, and neutral) have been identified and acquired (sandstone, limestone, and Ottawa sand respectively).

Table M1a.1. Matrix of materials and conditions.

Neat Binders	PG 58-28	Mineral Fillers	Limestone
	PG 64-22		Sandstone
Modifiers	D1101 Kraton SBS		Ottawa Sand
	D1184 Kraton SBS	Conditioning Media	Distilled water
	Elvaloy AM		NaCl (aq)
	Elvaloy 4170		$CaCl_2$ (aq)
	PPA 115 (or 105)	Conditioning Time	24 hours
Testing Temperature	19 °C		No Time
	25 °C	Conditioning Temperature	60 °C
Aggregate	Limestone, Granite	Granite	Sandstone

A testing procedure has been developed for this project based on the stress sweep test and tack test developed at UW-Madison. The preliminary conclusions of the year one testing can be summarized as follows:

- The developed modified DSR moisture damage test can evaluate moisture effects of asphalt-aggregate interaction and can differentiate between different materials. The key benefit of this test is that it allows isolation of the physical and chemical effects of the interactions from mixture variables, which commonly confound the evaluation of moisture damage.
- The parameter defined as W/D YSS Ratio (that is, wet-conditioned yield shear strength / dry-conditioned yield shear strength) is sensitive enough to evaluate moisture effects of asphalt-aggregate combinations.
- The use of linear viscoelastic (LVE) G* as a performance-related parameter is shown to be insensitive to effects of moisture effects between the limestone and sandstone, as shown in figure M1a.1. This raises some concerns regarding the practice of using LVE rheology to evaluate moisture effects.

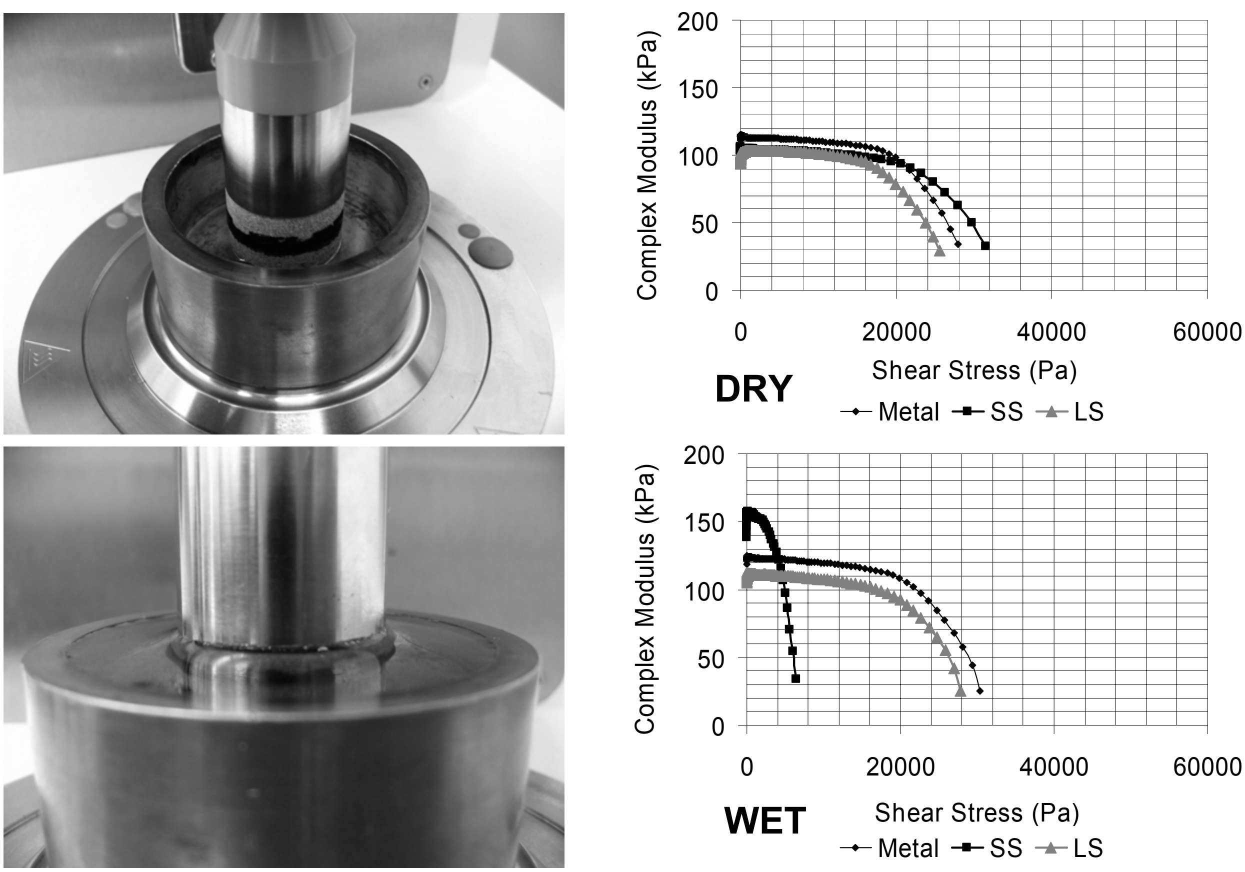


Figure M1a.1. Charts with photos. Representative data for the modified DSR test with wet and dry testing.

Year 2 Work Plan

The test setup will be used to collect data for shear stress sweep at different conditioning conditions, temperatures, and rates of loading. A wide range of combinations of materials will be included. The results will be analyzed in coordination with Texas A&M University research activities to verify that what is being measured is, in fact, explainable by fundamental surface energy measurements and that the conditions selected for measurements are effective in determining adhesive bond strength as well as cohesive strength. Figure M1a.2 depicts the research approach defined for this work element.

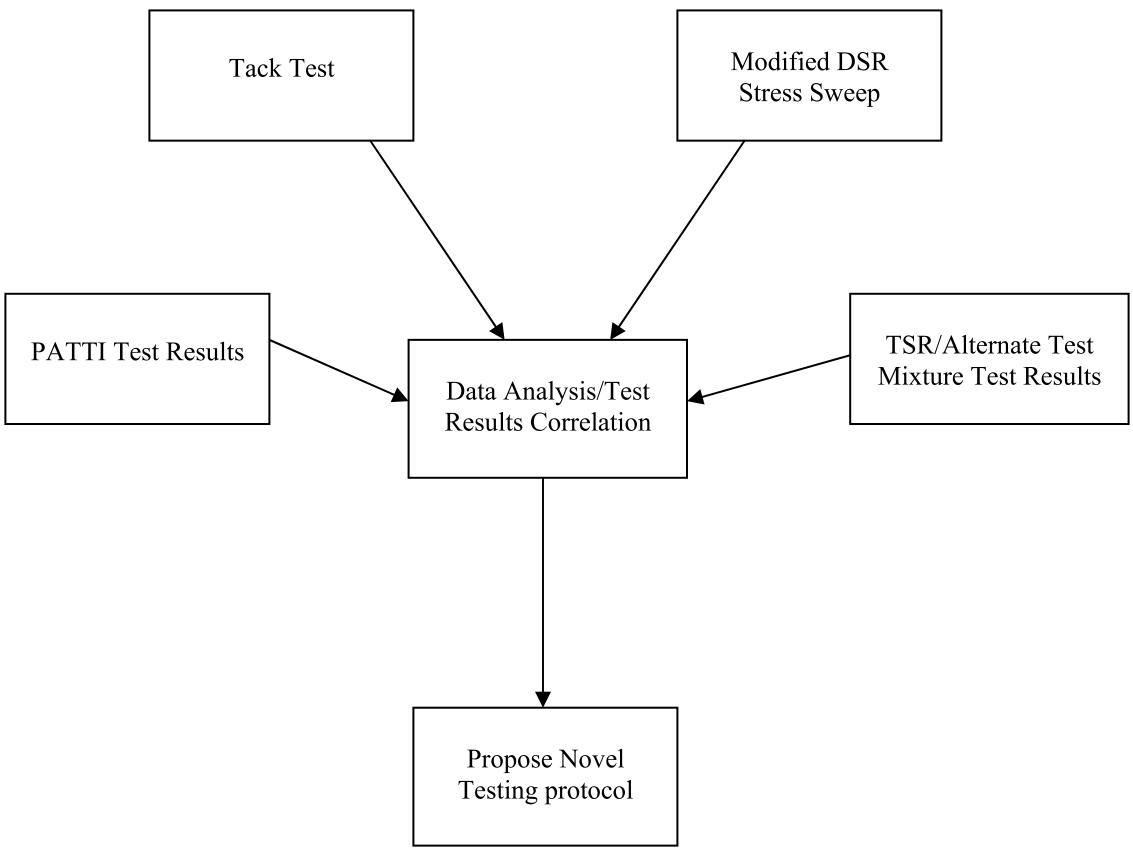


Figure M1a.2. Chart. Flow chart for research approach.

Year 2 Milestones

- Finalize the materials selection for tests in Year 2
- Start conducting modified DSR tests
- Start conducting moisture damage tests on asphaltic mixtures

Budget

The estimated budget for this subtask is $300,000 over the four years. The work will be conducted by the University of Wisconsin-Madison.

Work Element M1b: Work of Adhesion Based on Surface Energy

Subtask M1b-1: Surface Free Energy and Micro-Calorimeter Based Measurements for Work of Adhesion (Continued in Year 2).

The work of adhesion between asphalt binder and aggregate computed using surface energy components is due to the physio-chemical interactions between these two materials. The presence of active functional groups or chemically active fillers in asphalt binders may also contribute to adhesion by the formation of chemical covalent bonds (Bhasin and Little 2006). The contribution of these reactions to the work of adhesion will be assessed in this subtask using a micro-calorimeter. The objective of this subtask will be achieved as follows:

i. Determine surface energy components of modified and unmodified asphalt binders and model compounds that represent functional groups within the asphalt binder using the Wilhelmy plate device and/or sessile drop method (materials may overlap with subtask F1a-3).
ii. Determine surface energy components of aggregates and representative pure minerals using the Universal Sorption Device (materials may overlap with subtask F1a-3).
iii. Determine the total energy of adhesion between asphalt binders and aggregates using the micro-calorimeter.
iv. Evaluate methods to determine work of adhesion from total energy of adhesion measured using the micro-calorimeter to eliminate the contribution of entropy.
v. Compare total energy of adhesion versus work of adhesion due to surface free energy and quantify contribution of chemical bond formation to interfacial adhesion.

Significant developments were made in the development of a methodology to achieve objective (iii) in year 1 of this project. Preliminary results indicate that the micro calorimeter has very good sensitivity and precision to differentiate between the energy of adhesion of different types of aggregates. The procedure to address objective (iii) and testing of select materials to achieve objectives (i) through (iii) will be undertaken in year 2 of this project.

Subtask M1b-2: Work of Adhesion at Nano-Scale using AFM (Year 2 start)

Subtask Leader: Will Grimes

Introduction

Presently there is still a lot that is unknown regarding the thermodynamic processes of wetting and adhesion that occur at asphalt-aggregate interfaces in terms of molecular orientation and phase ordering phenomena of asphaltic compositional species. From the standpoint of interfacial thermodynamics, these phenomena fall within the realm of surface entropic properties. That is to say, with any thermodynamic process, the free energy, G, will be a sum of two types of energy contributions; the enthalpy (heat flow) contribution, H, and the entropy (molecular orientation) contribution, $-TS$, where free energy is then expressed as $G = H - TS$. Furthermore, the total energy of any system will also be characterized by both potential and kinetic energy contributions.

In this subtask, the entropic and kinetic properties of capillarity, wetting, and work of adhesion applicable to thin film coatings of asphalt will be investigated to determine how these properties are influenced by variations in asphalt crude source, temperature, presence of water and time. Furthermore roughness and frictional properties of aggregate surfaces will also be investigated to determine their influence upon adhesion hysteresis. Therefore, nano-technological methodologies, which include the wide range of scanning probe microscopy techniques, presently make it possible to investigate, at near molecular scale, entropic properties that may be crucial to adhesion thermodynamics in asphalt pavements.

Theoretical and Experimental Background

Lubrication Theory. Dynamic wetting of asphalt thin-films, which differ for asphalts derived from different crude source, have recently been investigated based on models derived from lubrication theory. This theory was recently adopted to model the wetting properties of asphalt thin-films prepared by spin coating techniques for the final purpose of imaging and surface energy analyses conduct by atomic force microscopy techniques. Asphalt thin films are conveniently prepared in this fashion by spin casting very small volumes of asphalt-solvent (usually toluene) solutions onto spinning glass microscope slides. Lubrication theory (Emslie et al. 1958; Boatto et al. 1993; Oron et al. 1997; Khomenko and Yushchenko 2003; Diez et al. 2000; Schwartz and Roy 2004; Brenner 1993) may be used to describe the physics of dynamic wetting of a "flat" solid substrate (e.g., a glass microscope in the present case) by a Newtonian fluid (e.g., a dilute asphalt-toluene solution) when modeled in terms of a balance of forces. The system, in the present case, is described by a small volume (usually a couple of microliters) of asphalt-solvent solution that is deposited onto a spinning glass microscope slide, where the angular velocity of rotation of the glass slide is varied between 300 and 1000 rpm.

Emslie et al. (1958) originally proposed that a simple balance of forces between the viscous force of a fluid, $\eta\nabla_z^{\;2}\upsilon$, as it resists a centrifugal force, $\rho\omega^2 r$, describes the process of dynamic contact line wetting of a spinning substrate by a viscous fluid, thus, an energy balance equation may be expressed as

$$0 = \rho\omega^2 r + \eta\frac{\partial^2\upsilon}{\partial z^2} \qquad \text{(M1b-2.1)}$$

Equation M1b-2.1 is essentially derived from the Navier-Stokes equation for the general case of modeling flow phenomena. Equation M1b-2.1 may be used to evaluate the change in thickness, or height h of a wetting film, derived as a function of the viscosity, η, density, ρ, angular velocity, ω, with vector component, $\hat{\omega}$, and fluid front velocity, υ, in terms of cylindrical polar coordinates, $(\hat{r}, \hat{\theta}, \hat{z})$, which define the frame of reference of the liquid once deposited on the spinning substrate, figure M1b-2.1.

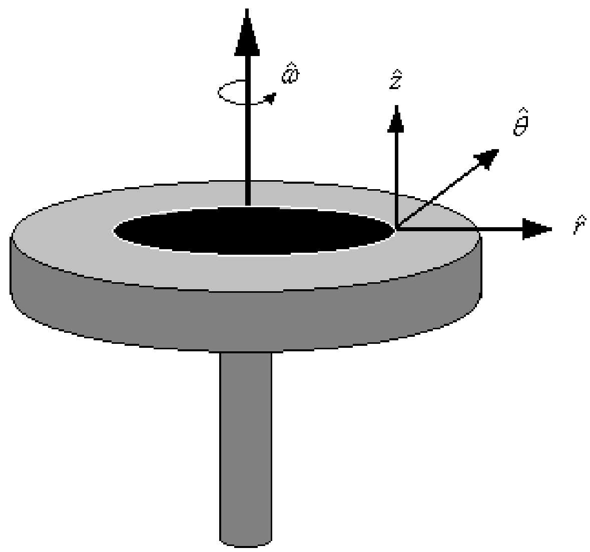
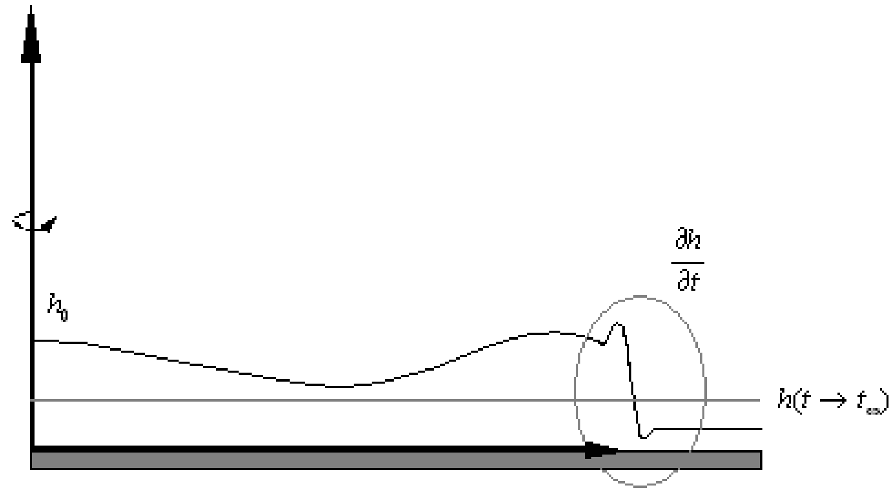


Figure M1b-2.1. Diagram of a wetting film of asphalt, spin cast onto a spinning substrate, defining the cylindrical polar coordinates $(\hat{r}, \hat{\theta}, \hat{z})$ in vector-component notation, which define the frame of reference of the liquid once deposited on the spinning substrate, spinning at an angular velocity, ω, with vector component, $\hat{\omega}$.

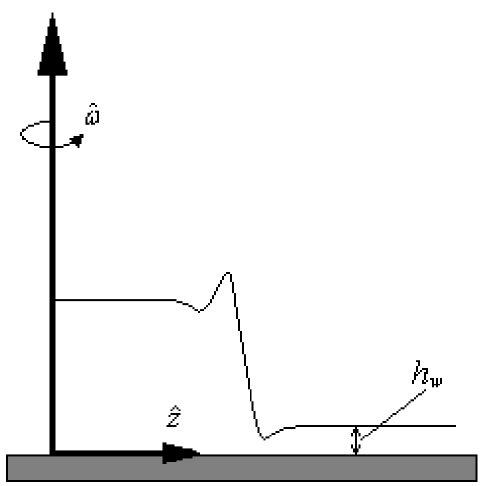
The film thickness at any time, *t*, may be described by the following expression

$$h(t \rightarrow t_{\infty}) = \frac{h_0}{\sqrt{1 + \frac{4\rho\omega^2 h_0^{\ 2} t}{3\eta}}} \qquad \text{(M1b-2.2)}$$

as the film approaches its final thickness. This solution has been referred to as the outer product solution, and constitutes an expression for relating changes in angular velocity, viscosity and initial film thickness (*h*-height) to the final thickness of the film, *h* (@ t = ∞). Figure M1b-2.2a depicts a schematic drawing of a thin-film liquid "wave-front' flowing out from the center of a substrate, starting with an initial film thickness of h_0. This transverse wave of "wetting fluid" is described by a wetting layer spreading out in front of the wave, defined by the wetting height, h_w, (figure M1b-2.2b).



a.



b.

Figure M1b-2.2. Schematic drawing of a thin-film liquid "wave-front' flowing out from the center of a substrate, starting with an initial film thickness of h_0. b. Schematic drawing of the transverse wave of "wetting fluid" described by a wetting layer spreading out in front of the wave, defined by the wetting height, h_w (Moriarty et al. 1991).

Since the time of the seminal paper reported by Emslie et al. (1958), dozens of publications have become available expounding on the topic of lubrication theory. To date, most authors agree that additional forces must be accounted for in order to better define the phenomena of the wetting layer associated with the two-phase contact line. Usually these forces include gravitational forces (Fraysse and Homsy 1994; Schwartz and Roy 2004; Schwartz 1989; Moriarty et al. 1991; Oron et al. 1997; Dandapat et al. 2003), in the case of spreading drops on inclined planes for example, frictional forces and shear (Yanagisawa 1987; Eres et al. 2000), Laplace pressure (Moriarty et al. 1991; Oron et al. 1997; Wilson et al. 2000; Neto et al. 2003; Dandapat et al. 2003; Schwartz and Roy 2004; Hwang and Ma 1989; Kim et al. 1990, 1992; Eres et al. 2000; Zhang and Lister 1999; Hocking 1992; Spaid and Homsy 1996, 1997), which entails surface tension and disjoining pressure terms, in addition to evaporation (Meyerhofer 1978; Stillwagon and Larson 1990; Oron et al. 1997; Middleman 1987; Danov et al. 1998) and temperature effects (Oron et al. 1997; David et al. 1999; Kitamura 2001), all of which influence the physical phenomenon of both Newtonian and non-Newtonian fluids wetting either smooth or rough surfaces. For example, if the Laplace pressure, *P*, is taken into account, equation M1b-2.1 may be re-written as

$$0 = \rho\omega^2 r + \eta \frac{\partial^2 \upsilon}{\partial z^2} - \frac{\partial P}{\partial r} \qquad \text{(M1b-2.3)}$$

where the Laplace pressure is defined as the product of the surface tension, γ, of the liquid that is deposited, times the curvature, κ, plus the disjoining pressure, Π, expressed as

$$P = \kappa\gamma + \Pi \qquad \text{(M1b-2.4)}$$

The curvature may derived in terms of cylindrical polar coordinates as

$$\kappa = -\left\{\frac{\partial^2 h}{\partial r^2} + \frac{1}{r}\frac{\partial h}{\partial r}\left[1 + \left(\frac{\partial h}{\partial r}\right)^2\right]\right\}\left[1 + \left(\frac{\partial h}{\partial r}\right)^2\right]^{-3/2} \qquad \text{(M1b-2.5)}$$

where *r* defines the radius of curvature at the contact line interface. For the sake of simplifying the derivation in equation M1b-2.3, and in order to obtain a second equation in the change in thickness, or height, *h*, of the film as a function of time, the disjoining pressure term in equation M1b-2.4 may be ignored, and the surface tension is considered to be a constant material property (i.e., the dependence of temperature upon surface tension is taken to be constant if all samples are spun at the same temperature). Equation M1b-2.3 may then be re-written as

$$-\eta \frac{\partial^2 \upsilon}{\partial \mathrm{z}^2} = \rho\omega^2 \mathrm{r} - \left(\kappa \frac{\partial}{\partial \mathrm{r}}\gamma + \gamma \frac{\partial}{\partial \mathrm{r}}\kappa\right) \qquad \text{(M1b-2.6)}$$

Hwang and Ma (1989) have shown that equation M1b-2.6 may be derived as

$$\frac{\partial h}{\partial t} = \frac{-1}{3\eta r}\frac{\partial}{\partial r}\left(\rho\omega^2 r^2 h^3 + \gamma r h^3 \frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial h}{\partial r}\right)\right)\right) \qquad \text{(M1b-2.7)}$$

Exhaustive solutions have been proposed, employing the use of dimensionless quantities to arrive at a general solution to equation M1b-2.3, but to date the problem remains essentially unsolved.

Dynamic Wetting and Observation of Fingering Instabilities. Figure M1b-2.3 depicts a photographic image of solvent spin cast films "developed" for SHRP core asphalt AAD-1, spin cast at six different speeds (i.e., angular frequency; ω = 300, 400, 500, 600, 700, and 800 rpm). Figure M1b-2.4 depicts a plot of film thickness (film thickness, h (nm) determined by a Filmetrics F20 analysis versus angular velocity.

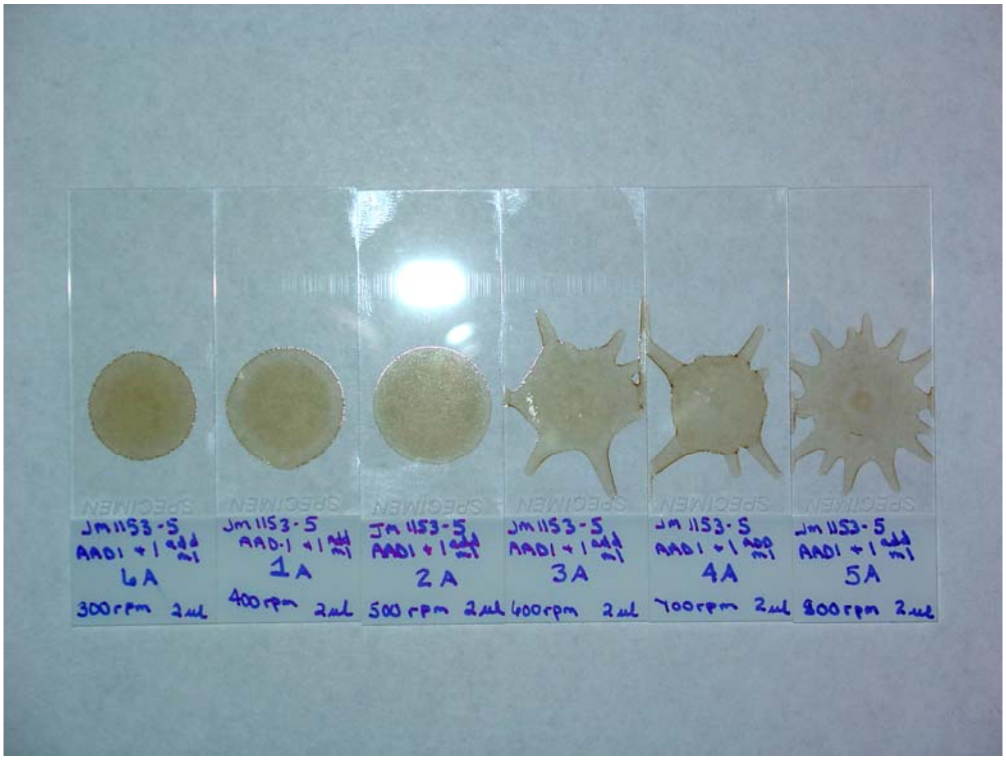


Figure M1b-2.3. Photographic image depicting spin cast films "developed" for SHRP core asphalt AAD-1 spin cast at six different speeds (angular frequency, ω = 300, 400, 500, 600, 700, and 800 rpm).

It is readily observed in figure M1b-2.3 that as a film is spin cast at increasingly faster speeds, the film becomes less and less uniform (non-circular), and little "fingers" begin to develop at the edges of the film. This phenomenon is referred to as a fingering instability, as will be discussed.

Inspection of equation M1b-2.2 suggests that as the final film thickness is approached, film thickness is found to be inversely proportional to the viscosity of the fluid that is initially deposited onto a substrate, but is directly proportional to the angular velocity at which the fluid is spun onto the substrate. In other words, if a set of asphalt solutions, given a set of test asphalts which differ significantly by viscosity, are prepared at the same concentration, the highest viscosity materials should be expected to develop into thicker films as compared to less viscous materials. Furthermore, thinner films should be expected to develop for a given material as the material, in solution, is spun at incrementally increasing speeds.

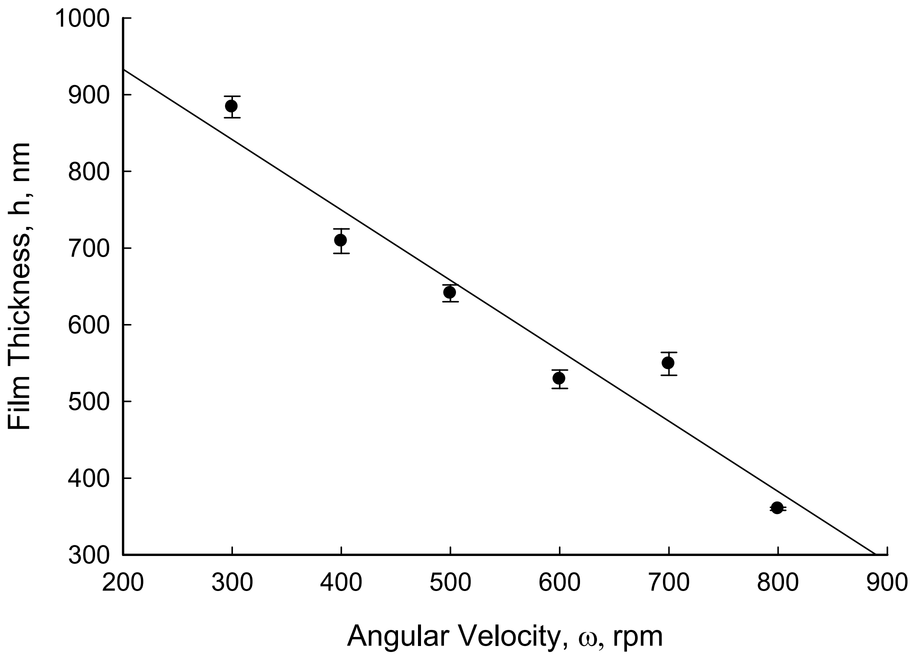


Figure M1b-2.4. Plot of film thickness (film thickness, *h* (nm) determined by Filmetrics F20 analysis, versus angular frequency for SHRP asphalt AAD-1, corresponding to photographic images depicting spin cast films "developed" for SHRP core asphalt AAD-1 in figure M1b-2.3.

One important consequence of the lubrication model is the observation of fingering instabilities (figure M1b-2.3). Fingering occurs when the centrifugal force "over powers" the line tension or disjoining pressure forces at the leading edge of the fluid wave-front. When this occurs, the flowing film is observed to "break over the levee", as it were, at the leading edge of the transverse wave-front of the moving film, effectively spilling out past the front of the film in the form of a "finger", thus, constituting a fingering instability in the spin-cast film. Fraysse and Homsy (1994) have suggested that a count of the number of fingers, N_{finger}, produced per film is inversely proportional to the surface tension, γ, of the liquid, according to the following expression

$$N_{finger} \cong \frac{\pi}{7} r_c^{\,2} \left(\frac{\pi \rho \omega^2}{\gamma V_{drop}} \right)^{1/3} \qquad \text{(M1b-2.8)}$$

In equation M1b-2.8, r_c is the critical radius of the fluid at the contact line where the fluid wave-front contacts the substrate, ρ is the fluid density, ω is the angular velocity of the spinning substrate, and V_{drop}, is the volume of the drop of liquid initially deposited onto the substrate.

Force-Distance AFM Microscopy. Contact mechanics models are commonly applied to predict the strength of adhesive bonding in polymers. Asphalts are not polymers, but asphalts do exhibit similar adhesive and viscoelastic behaviors to those of polymers. For this reason, data measured for asphalts can be interpreted based on contact mechanics models such as the Johnson-Kendall-Roberts (JKR) contact theory and the Derjaguin-Muller-Toporov (DMT) model (Johnson et al. 1971; Derjaguin et al. 1975; Kinloch 1987; Hui and Baney 1998; Israelachvili 1992; Pollock et al. 1978). These models have been applied to measure the surface energies of the eight SHRP asphalts in thin-film samples originally solvent spin cast onto glass slide substrates. In these studies, in order to determine the surface energy of asphalts, AFM is employed to measure force curves acquired as a function of contact load and sampling frequency using cantilevers with a glass micro-bead attached to the tip of the cantilever.

Fundamental contact mechanics models describe a frictionless interaction between a spherical surface brought into contact with a flat surface, followed by a pull-away of the two surfaces by a Hertzian load (P_{Hertz}) (Shull 2002). A Hertzian contact load, in turn, is defined in terms of the reduced bulk modulus, E*, the contact area, a^3, and the radius of curvature of the contacting surfaces, R, as

$$P_{Hertz} = \frac{4E^* a^3}{3R} \tag{M1b-2.9}$$

The contact displacement (figure M1b-2.5) is then defined in terms of the contact radius a, as

$$\delta_{hertz} = \frac{a^2}{R} \tag{M1b-2.10}$$

where the radius of curvature is defined in terms of the radii of both surfaces (1-spherical tip, 2-flat surface) as

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{(R_2 \to \infty)} \to \frac{1}{R_1} \tag{M1b-2.11}$$

where the reduced bulk modulus is defined for both surfaces as

$$\frac{1}{E^*} = \frac{\left(1-\nu_1^{\ 2}\right)}{E_1} + \frac{\left(1-\nu_2^{\ 2}\right)}{E_2} \tag{M1b-2.12}$$

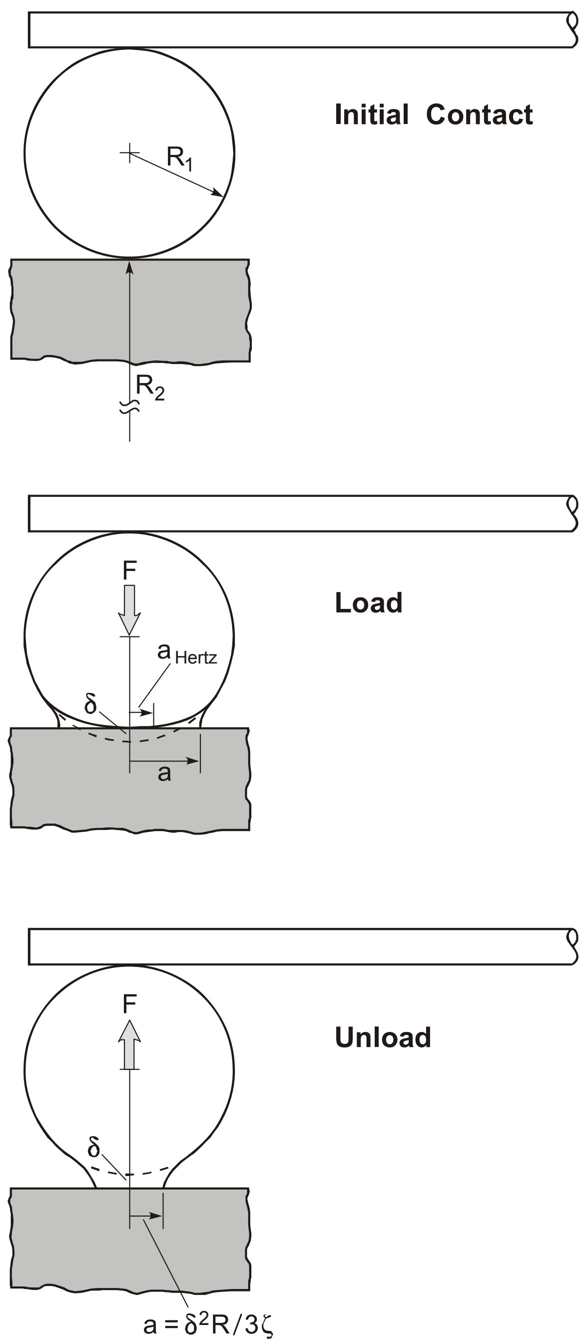


Figure M1b-2.5. Depiction of contact between a glass micro-bead cantilever tip and a glass slide surface during loading and unloading of the system.

Here, v_i's are values of Poisson's ratio, and E_i's are values of Young's modulus. The fracture energy release rate, G, may then be derived as

$$G = \frac{\left(\frac{4E^* a^3}{3R} - P\right)^2}{8\pi E^* a^3} = \frac{\left(P_{hertz} - P\right)^2}{8\pi E^* a^3} = W_{12} \qquad \text{(M1b-2.13)}$$

and is shown to approximate the work of adhesion of the system. P_{Hertz} and P are the frictionless load and the actual applied load, respectively. The fracture energy release rate is equivalent to the work of adhesion in this case since the surfaces are at the point of separation, or "cracking." The work of adhesion is then simply twice the surface energy.

With viscoelastic materials where the stiffness of one or the other or both of the surfaces are shear rate and temperature dependent, the contact area that is measured may result in a transition in the contact area corresponding to either the JKR or DMT model in order to interpret the actual work of adhesion. It is then assumed that the load, P, approaches zero at a contact corresponding to the equilibrium work of adhesion, where equation M1b-2.15 may then be solved for in terms of the bulk modulus to find that a limiting contact area (Carpick et al. 1999), $A = 1/\zeta$,, exists, where

$$E^* = \frac{9\pi\gamma_{12} a}{\delta^2} \qquad \text{(M1b-2.14)}$$

and where

$$\frac{1}{\zeta} = A \qquad \text{(M1b-2.15)}$$

Depending on the compliance of the two surfaces (i.e., rigid sphere contacting rigid flat surface, rigid sphere contacting deformable flat surface, deformable sphere contacting rigid flat surface, deformable sphere contacting deformable flat surface), different models will apply. The JKR-load limit corresponds to contact between compliant surfaces where weak adhesive forces, and a high radius of curvature exists,

$$P_{JKR} = \lim_{\zeta \to 3a/\delta^2 R} \frac{E^*}{\zeta} = 3\pi\gamma_{12} R \qquad \text{(M1b-2.16)}$$

and the DMT-load limit corresponds to contact between stiff surfaces where strong adhesive forces, and a lower radius of curvature exist,

$$P_{DMT} = \lim_{\zeta \to 9a/4\delta^2 R} \frac{E^*}{\zeta} = 4\pi\gamma_{12} R \qquad \text{(M1b-2.17)}$$

AFM "pull-off" force measurements are conducted when a cantilever tip is retracted, after initially contacting the surface of a sample thin-film, when enough stress is applied which exceeds the adhesive/cohesive strength of the contact and the joint (contact between the cantilever-tip and sample) fails, and constitutes a measure of the work of adhesion of the system. In addition to providing a measure of the work of adhesion, analysis of the shapes of the various sections of the force curves potentially reveal a great deal about the mechanical properties of the material at the microscopic, and nanoscopic level. Figure M1b-2.6 depicts a typical force curve with labeled force regions.

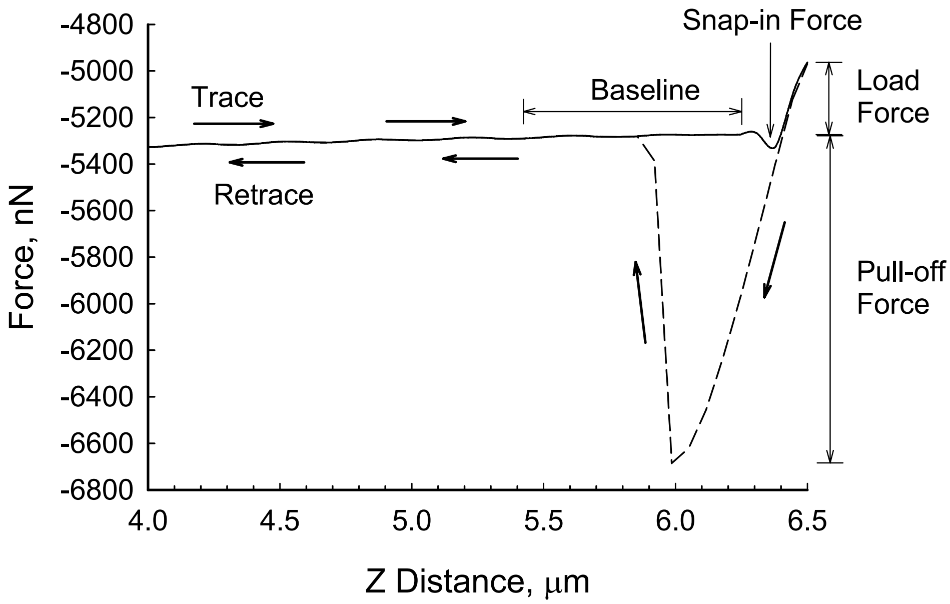


Figure M1b-2.6 Force curve plot depicting the applied load force, the snap-in force, the pull-off-force, and the baseline.

Topographic Morphology and Surface Friction Analysis of Course and Fine Aggregate Particles via AFM. In research conducted at WRI within the past few years, imaging of aggregate course and fine particles investigated by atomic force microscopy has shown that aggregates which differ by source also differ by surface roughness and surface friction. These findings may suggest that the roughness and frictional properties of these particle surfaces may contribute directly to their adhesion and wettability. Figure M1b-2.7 depicts AFM images of aggregate surfaces for four aggregates which differ by mineralogy where aggregates derived from granite and quartzite sources are generally found to have less rough smoother-rounded and lower friction surfaces as compared to limestone and sandstone aggregate materials. Theories of adhesion hysteresis commonly suggest that surface roughness and frictional properties of solids in contact with liquids contributes significantly to wetting and de-wetting propensities. Thus, it is presently thought that studies which focus on the contribution of aggregate surface roughness and frictional properties are warranted to better understand the fundamental mechanism of bonding between aggregate and asphalt.

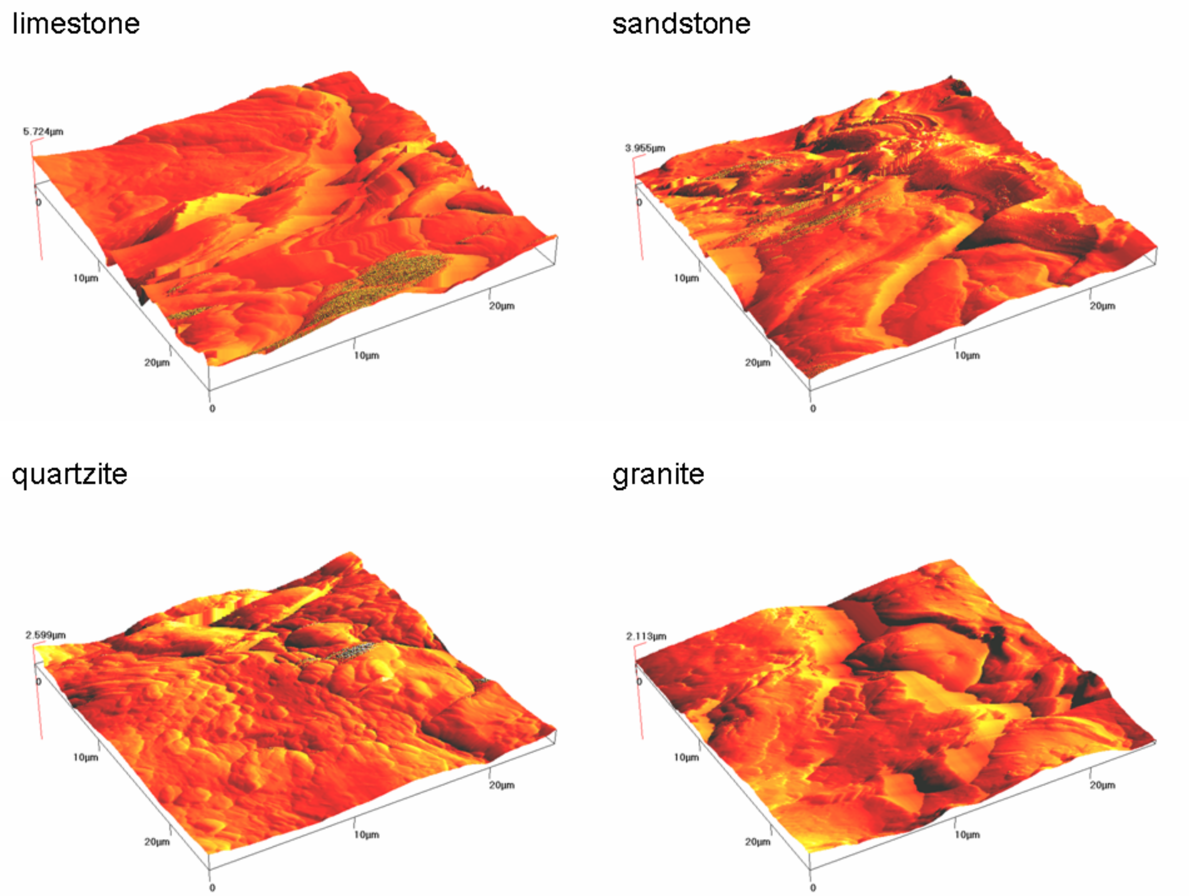


Figure M1b-2.7. AFM images of aggregate surfaces for four aggregates which differ by mineralogy.

Relationship to FHWA Focus Areas

This work element is related to the following focus areas:

- Optimum Pavement Performance- Introducing methods for better characterization of neat asphalts.
- Advanced quality systems: Further development of test methods that are more related to actual pavement performance.

Hypothesis

The thermodynamic and mechanical properties of asphalt binder adhesion compounded by the presence of water, specifically the adhesive processes of molecular orientation and phase ordering in the native binder which falls within the realm of surface entropy, are directly related to the physico-chemical nature of asphalt chemical composition and aggregate mineralogy.

Objectives

The primary objective of this subtask is to determine the entropic contribution to the surface free energy of adhesion in support of other subtasks within the work element relating to surface energy. By studying the kinetics of wetting and the frictional nature of adhesion hysteresis a more fundamental thermodynamic model of asphalt-aggregate bond strength will be developed.

Experimental Design

The research philosophy that will be adopted in this subtask will rely on "modeling the experiments" to obtain fundamental measurements of physico-chemical properties of the asphalt binder and aggregate surfaces which directly influence adhesive qualities of the materials considered. Modeling the experiments will entail adopting the models discussed in the Introduction to interpret the propensities of asphalt to wet aggregate surfaces, adhesive contact (pull-off-force), between aggregate and asphalt thin films.

A literature search will be conducted to aid in development of tests and models which determine compositional and physico-chemical properties that define the adhesive properties of asphalts and aggregate surfaces.

SHRP core asphalts, WRI asphalt binder type validation site asphalts, as well as other asphalt and aggregates will be selected for study.

Molecular orientation and phase ordering in the native binder will be controlled by varying the thickness of films which will be prepared using spin casting techniques. In this manner, film confinement effects are expected to result which will represent the first layers of asphalt in contact with an aggregate surface.

Work of adhesion measurements will then be conducted on the films of various thicknesses as a function of temperature to study the changes in pull-off-force. Phase domains of these films will be further identified by employing AFM imaging techniques. In several cases, films will be imaged prior to and after pull-off-force measurements are conducted to study the impact of the pull-off-force measurements on the film.

Aggregate roughness and friction will be measured for aggregate fine particles and filler particles (hydrated lime) commonly used in pavement applications. In some cases, aggregate fine materials and filler materials may be coated with thin films of asphalt then further imaged to study.

One of the key motivations for this research is to verify that the correct physico-chemicals are being identified and measured so that modeling efforts and test methodologies will be representative of the desired performance prediction data.

Overall Work Plan

Sub-Subtask M1b-2.1: Selection of neat asphalt samples which very based on compatibility and wax content (SHRP asphalt, validation site asphalts, Accelerated Loading Facility Site asphalts, etc.). Preparation of aged asphalt samples employing RTFO-PAV methodologies.

Sub-Subtask M1b-2.2: Preparation of neat and aged asphalt thin-films that vary as a function of film thickness which range in thickness between 100-nm to 1000-nm prepared as solvent spin coated samples.

Sub-Subtask M1b-2.3: Conduct contact mechanic measurements as a function of load, rate of contact and sample temperature on asphalt thin films.

Sub-Subtask M1b-2.4: Conduct surface roughness and frictional imaging analyses of selected course and fine aggregate materials

Year 2 Schedule

Sub-Subtask M1b-2.1, M1b-2.2, and M1b-2.3 will be conducted during the remainder of year 2 and part of year 3.

Year 2 Milestones

Four asphalts and four aggregate samples will be selected. Asphalt samples will be aged at three different times at 60°C, which will constitute 16 samples total. AFM analysis will be conducted on neat and aged asphalt samples to determine wetting and adhesive properties.

Overall Schedule

Sub-Subtask M1b-2.1, M1b-2.2, and M1b-2.3 will be conducted during the remainder of year 2 and part of year 3. Testing should be completed toward the mid-point of year 3 at which time a progress report will be submitted. Sub-Subtask M1b-2.4 will begin in year 3.

References

Boatto, S., L. P. Kadanoff, and P. Olla, 1993, Traveling-wave Solutions to Thin-film Equations. *Physical Review E*, 48(6): 4423-4431.

Brenner, M., 1993, Spreading of Droplets on a Solid Surface. *Physical Review Letters*, 71(4); 593-596.

Carpick, R. W., D. F. Ogletree, and M. Salmeron, 1999, A General Equation for Fitting Contact Area and Friction vs Load Measurements. *Journal of Colloid and Interface Science*, 211: 395-400.

Dandapat, B. S., P. Daripa, and P. C. Ray, 2003, Asymptotic Study of Film Thinning Process on a Spinning Annular Disk. *Journal of Applied Physics*, 94(6): 4144-4151.

Danov, K. D., N. Alleborn, H. Raszillier, and F. Durst, 1998, The Stability of Evaporating Thin Liquid Films in the Presence of Surfactant. I. Lubrication Approximation and Linear Analysis. *Physics of Fluids*, 10(1): 131-143.

David, M. B., Y. Zvirin, and Y. Zimmels, 1999, Determination of the Quench Velocity and Rewetting Temperature of Hot Surfaces: Formulation of a Nonisothermal Microscale Hydrodynamic Model. *Physical Review E*, 59(6): 6687-6698.

Derjaguin, B. V., V. M. Muller, and Y. P. Toporov, 1975, Effect of Contact Deformations on the Adhesion of Particles. *Journal of Colloid Interface Science*, 50: 314-326.

Diez, J. A., L. Kondic, and A. Bertozzi, 2000, Global Models for Moving Contact Lines. *Physical Review E*, 63(011208): 1-13.

Emslie, A. G., F. T. Bonner, and L. G. Peck, 1958, Flow of a Viscous Liquid on a Rotating Disk. *Journal of Applied Physics*, 29(5): 858-861.

Eres, M. H., L. W. Schwartz, and R. V. Roy, 2000, Fingering Phenomena for Driven Coating Films. *Physics of Fluids*, 12(6): 1278-1295.

Fraysse, N., and G. M. Homsy, 1994, An Experimental Study of Rivulet Instabilities in Centrifugal Spin Coating of Viscous Newtonian and Non-Newtonian Fluids. *Physics of Fluids*, 6(4), 1491-1504.

Hocking, L. M., 1992, The Influence of Intermolecular Forces on Thin Fluid Layers. *Physics of Fluids A*, 5(4): 793-799.

Hui, C. Y., and J. M. Baney, 1998, Contact Mechanics and Adhesion of Viscoelastic Spheres. *Langmuir*, 14: 6570-6578.

Hwang, J. H., and F. Ma, 1989, On the Flow of a Thin Liquid Film Over a Rough Rotating Disk. *Journal of Applied Physics*, 66(1): 388-394.

Israelachvili, J., 1992, *Intermolecular & Surface Forces*, 2nd Ed., Academic Press Limited, Academic Press Inc., San Diego, CA.

Johnson, K. L., K. Kendall, and A. D. Roberts, 1971, Surface Energy and the Contact of Elastic Solids. *Proceedings of the Royal Society of London A.*, 324: 301-313.

Khomenko, A. V., and O. V. Yushchenko, 2003, Solid-Liquid Transition of Ultrathin Lubricant Film. *Physical Review E*, 68(036110): 1-6.

Kim, S., J. S. Kim, and F. Ma, 1990, On the Flow of a Thin Liquid Film Over a Rotating Disk. *Journal of Applied Physics*, 69(4): 2593-2601.

Kim, S., J. S. Kim, and F. Ma, 1992, Topographic Effect of Surface Roughness on Thin-Film Flow. *Journal of Applied Physics*, 72(1): 422-428.

Kinloch, A. J., 1987, *Adhesion and Adhesives Science and Technology*, Chapman and Hall, New York, NY, p. 339-400.

Kitamura, A., 2001, Thermal Effects on Liquid Film Flow During Spin Coating. *Physics of Fluids*, 13(10): 2788-2794.

Meyerhofer, D., 1978, Characteristics of Resist Films Produced by Spinning. *Journal of Applied Physics*, 49(7): 3993-3997.

Middleman, S., 1987, The Effect of Induced Air-Flow on the Spin Coating of Viscous Liquids. *Journal of Applied Physics*, 62(6): 2530-2532.

Moriarty, J. A., L. W. Schwartz, and E. O. Tuck, 1991, Unsteady Spreading of Thin Liquid Films with Small Surface Tension. *Physics of Fluids* A 3(5): 733-742.

Neto, C., K. Jacobs, R. Seemann, R. Blossey, J. Becker, and G. Grün, 2003, Correlated Dewetting Patterns in Thin Polystyrene Films. *Journal of Physics: Condensed Matter*, 15: S421-S426.

Oron, A., S. H. Davis, and S. G. Bankoff, 1997, Long-Scale Evolution of Thin Liquid Films. *Reviews of Modern Physics*, 69(3): 931-980.

Pollock, H. M., D. Maugis, and M. Barquins, 1978, The Force of Adhesion Between Solid Surfaces in Contact. *Applied Physics Letters*, 33(9): 798-799.

Schwartz, L. W., 1989, Viscous Flows Down an Inclined Plane: Instability and Fingering Formation. *Physics of Fluids* A 1(3): 443-445.

Schwartz, L. W., and R. V. Roy, 2004, Theoretical and Numerical Results for Spin Coating of Viscous Liquids. *Physics of Fluids*, 16(3): 569-584.

Shull, K. R., 2002, Contact Mechanics and the Adhesion of Soft Solids. M*aterials Science and Engineering R.*, 36: 1.

Spaid, M. A., and G. M. Homsy, 1996, Stability of Newtonian and Viscoelastic Dynamic Contact Lines. *Physics of Fluids*, 8(2): 460-478.

Spaid, M. A., and G. M. Homsy, 1997, Stability of Viscoelastic Dynamic Contact Lines: An Experimental Study. *Physics of Fluids*, 9(4): 823-832.

Stillwagon, L. E., and R. G. Larson, 1990, Leveling of Thin Films Over Uneven Substrates During Spin Coating. *Physics of Fluids* A 2(11): 1937-1944.

Wilson, S. K., R. Hunt, and B. R. Duffy, 2000, The Rate of Spreading in Spin Coating. *Journal of Fluid Mechanics*, 413: 65-88.

Yanagisawa, M., 1987, Slip Effect for Thin Liquid Film on a Rotating Disk. *Journal of Applied Physics*, 61(3): 1034-1037.

Zhang, W. W., and J. R. Lister, 1999, Similarity Solutions for van der Waals Rupture of a Thin Film on a Solid Substrate. *Physics of Fluids*, 11(9): 2454-2462.

Subtask M1b-3: Identify Mechanisms of Competition Between Water and Organic Molecules for Aggregate Surface (Continued in Year 2).

Thermodynamic descriptions of the work of adhesion between asphalt binders and aggregates are based on macroscopic properties of these materials. Work at TTI-WRI under funding administered by the FHWA has demonstrated that electrostatic interactions are small but important interactions that affect the impact of moisture on the strength of the aggregate-bitumen interaction. Other molecular-scale interactions that are likely to be important include electron-donor acceptor reactions between aromatic organics and specific surface functional groups on the aggregate surface, hydrophobic interactions, organic hydrolysis reactions, and secondary precipitation reactions between inorganic salts and organic molecules.

Asphalt binders as well as aggregates are highly heterogeneous in terms of their chemical or mineralogical composition. Identification of the molecular mechanisms of interaction between specific organic functional groups and mineral surfaces will allow prediction of the degree of adhesion in heterogeneous materials through an additive mixing model. This subtask will investigate molecular mechanisms responsible for adhesion and debonding using pure representative minerals and model organic compounds (representing functional groups in asphalt binder). This research will couple spectroscopic characterization of water and organic bonding at the mineral and aggregate surface using sum frequency generation spectroscopy, infra-red and Raman spectroscopy, and other microscopic and macroscopic tests. This information is extremely important in order to: i) provide tools by which to make informed modifications to the asphalt binders and/or aggregates that will improve the mixture's resistance to moisture damage, and ii) refine the existing methods used to measure material properties such as surface free energy.

Major Findings from Year 1 for Work Element M1b

A methodology to determine the total energy of adhesion between the asphalt binder and aggregate at room temperature was developed. This methodology was found to be repeatable and sensitive to the type of aggregate used. A brief description of this methodology and some results were presented in the quarterly report (ending September 2007). Work is in progress to evaluate the sensitivity of this methodology (using a micro calorimeter) to different types of asphalt binders and fillers.

In addition to use of the micro calorimeter as discussed above, a dual mode flow adsorption calorimeter was also developed in year 1. The flow adsorption calorimeter measures the strength of the interfacial bond between different adsorbates and adsorbents in terms of the molar heats of reaction. The flow adsorption calorimeter will be used in Subtask M1b-3 to determine the mechanisms of competition between water and organic molecules for aggregate surfaces using model compounds to represent asphalt binder functional groups and pure mineral specimens to represent the most commonly found mineral phases on aggregate surfaces.

Year 2 Milestones for Work Element M1b

i. Finalize a test protocol in AASHTO format to determine the energy of adhesion between the asphalt binder and aggregate using a micro calorimeter.
ii. Use the micro calorimeter to determine the energy of adhesion for select combinations of asphalt binders and aggregates as well as certain model compounds that represent functional groups in the asphalt binder and aggregates.
iii. Continue the use of USD and WP test methods to determine the surface free energy and concomitant energy of adhesion for select materials and model compounds.
iv. Complete the development of a flow micro calorimeter and conduct initial tests using model organics and minerals.

***Work Element M1c: Quantifying Moisture Damage Us*ing DMA**

The Dynamic Mechanical Analyzer (DMA) provides a unique tool to quantify the impact of moisture damage in fine aggregate matrix (FAM) of asphalt mixtures. The fine aggregate matrix is comprised of binder, filler, and aggregate particles finer than the #16 sieve. Several field studies and observations have shown that the fine portion of the mixture is responsible for most of the resistance to moisture damage. This phase holds coarse aggregate particles together in an asphalt mixture. The DMA provides exclusive characterization of the FAM by eliminating the complex interaction effects due to the heterogonous air void structure with coarse aggregate particles present in an asphalt mixture. However, since the FAM utilizes fine aggregates that represent mineralogy of coarse aggregates used in the whole asphalt mixture, the test procedure does consider the influence of mineral aggregate–binder interaction, which is at least partially responsible for stripping. The DMA will be used to quantitatively assess the relative impact of:

i. work of adhesion,
ii. work of cohesion, and
iii. provide the rate of energy dissipation, which is an important parameter for the analytical model discussed in section F3c-1 of the fatigue work plan and section M2a of the moisture work plan.

Major Findings from Year 1 for Work Element M1c

All moisture damage analysis methods that have been developed in the past are deterministic. These methods compare mixtures at a fixed number of cycles and they do not take into account material and/or testing variability. A probabilistic method to determine the effect of moisture sensitivity on the fatigue cracking of the fine aggregate matrix (FAM) was developed and evaluated using different materials with known performance. This method takes into account the variability in the results of a laboratory based fatigue test. It can be applied to fracture mechanics based models that were previously developed at Texas A&M to quantify crack growth in the FAM under DMA loading. A brief description with results to demonstrate the application of this method was presented in the quarterly report ending September 2007. The developed probabilistic approach provides comparative analysis of different mixtures based on the probability that these mixtures can survive a certain number of cycles. The results obtained in Phase 1 have shown that some mixtures can be similar in their performance for a certain number of cycles, but they significantly differ at a higher number of cycles. As such, the analysis provides useful information about the suitability of certain mixtures for a given number of cycles.

Year 2 Milestones for Work Element M1c

The experimental and analytical procedure to evaluate the performance of moisture conditioned FAM specimens is very similar to the procedure used for unconditioned or dry specimens (developed in work element F2b). However, in the case of the former, the FAM specimens are moisture conditioned prior to testing. In year 2 of this project, the final protocol for moisture conditioning FAM specimens will be developed and used with select materials for evaluation using the DMA.

Category M2: Cohesion

Work Element M2a: Work of Cohesion Based on Surface Energy

Work of cohesion within the asphalt binder or mastic is a fundamental material property that dictates the magnitude of work required for crack growth within these materials. Previous research at the Texas A&M University has led to the development of test methods to determine the surface energy components of asphalt binders.

Moisture damage can occur due to disintegration of the adhesive bond between the asphalt binder and the aggregate as well as due to inherent deterioration in the mechanical properties of the asphalt binder or mastic. Deterioration or degradation within either the binder or mastic can be due to fatigue damage, moisture damage or a combination of the two processes. It is important to determine the work of cohesion of asphalt binders or mastics, after the mastic or binder has been saturated with water. This work element will be addressed in the form of the following two subtasks:

Subtask M2a-1: Methods to Determine Work of Cohesion of Saturated Asphalt Binders (Continued in Year 2).

Work of cohesion of asphalt binders is an important material property input for various analytical and micromechanics models. It is important to determine how the magnitude of this material property changes for an asphalt binder that is saturated with moisture and how its can be measured. The objective of this subtask will be to address this question. This will be achieved as follows:

i. Explore the possibility of using existing static (sessile drop) and dynamic test methods (Wilhelmy plate) to determine the surface free energy and work of cohesion for saturated asphalt binders or mastics. Investigate the limitations or considerations in using such techniques to derive the parameters of interest. The sessile drop method will serve only as an investigative tool to evaluate the effect of saturation on surface properties of the asphalt binder or mastic. For these specific cases, the sessile drop method offers real time contact angle measurement that may have certain advantages over the Wilhelmy plate method.

ii. Review methods to determine practical work of cohesion (and work of adhesion) using a combination of mechanical tests with analytical techniques that are based on computation of fracture energy. The efforts in this task will be conducted in close coordination with the efforts in task M2c to avoid duplication of effort. A significant difference between this approach and the objectives of task M2c is that in this case, the objective is to use a combination of mechanical tests and advanced analytical approaches to determine the change in fundamental material properties of the asphalt binder before and after moisture conditioning. For example, Craton and Lakrout (2000) and Shull (2002) have presented extensive analysis on mechanisms of failure of thin compliant films between rigid substrates. This analytical approach can be potentially combined with conventional mechanical tests such as the mandrel, fixed arm and T peel methods (Kawashita et al. 2006) in order to determine the work of cohesion and adhesion for dry as well as saturated asphalt binders. Adhesive failure between the rigid substrates and the asphalt binder can be avoided with the use of special treatments / compatibilizers at the substrate-binder interface that will promote cohesive failure even under saturated conditions. In the absence of such treatments, adhesive or apparent adhesive failures may occur. For such cases, researchers will conduct a detailed analysis of the fracture surface to determine the nature and amount of residual binder on the rigid substrates. This will be accomplished using an Atomic Force Microscope.

This task will be accomplished in coordination with research activities at the University of Nottingham and the Adhesive group of Imperial College. The TTI researchers have a collaborative program with these institutions on research areas that directly focus on experimental measurements of work of adhesion and work of cohesion. This collaborative program includes exchange of researchers between the three institutions. More information about this collaborative program is available on the website http://acim.civil.tamu.edu/intproject.html

Subtask M2a-2: Work of Cohesion Measured at Nano-Scale using AFM (Year 2 start)

Subtask Lead: Will Grimes

Introduction

Thermodynamic properties of asphalt cohesion, further compounded by the presence of water are directly related to the physico-chemical properties of the asphalt binder. Just as with adhesion, (i.e., refer to Subtask M1b-2), processes of molecular orientation and phase ordering in the native binder, which fall within the realm of entropic events directly influence the free energy properties of the binder. As shown in Subtask M1b-2, with any thermodynamic process, the free energy, G, will be a sum of two types of energy contributions; the enthalpy (heat flow) contribution, H, and the entropy (molecular orientation) contribution, $-TS$, where free energy is then expressed as $G = H - TS$. Furthermore, the total energy of any system will also be characterized by both potential and kinetic energy contributions. Nucleation theory may then be considered as a means for modeling the kinetic and entropic properties of asphalt when modeled as a solidifying material. Based on this modeling approach, the work of cohesion becomes a function of the cohesive energy density, which in turn is a measure of the solvent strength of the material. This property of "solvency" is thus important to the material's susceptibility to "mixing" with water, either by processes of emulsification or de-wetting, both of which will likely lead to material degradation in real-world pavement structures.

Theoretical and Experimental Background

Surfaces and Interfacial Thermodynamics. In the present subtask, the kinetic processes of nucleation will be employed to describe the adhesive and cohesive properties of asphalt. From classical interfacial thermodynamics (Adamson and Gast 1997) a liquid-vapor interface, for example, may be described in terms of the surface free energy, G^S, expressed as

$$G^S \equiv \gamma = \left(\frac{dG}{dA}\right)_{T,P} \qquad \text{(M2a-2.1)}$$

Such an interface is then modeled by initially considering a hypothetical solid plane of area, A, sliding across the surface of a volume of liquid at the liquid surface interface. The total surface energy, E^S, may then be derived in terms of a surface tension/temperature derivative expressed as

$$E^S = \gamma - T\frac{d\gamma}{dT} \qquad \text{(M2a-2.2)}$$

Substitution of the surface tension, γ, from equation M2a-2.1 for the surface free energy, G^S, into equation M2a-2.2 gives

$$G^S \equiv \gamma = E^S + T\frac{d\gamma}{dT} \qquad \text{(M2a-2.3)}$$

where the total surface entropy is defined as

$$-S^S = \frac{d\gamma}{dT}, \qquad \text{(M2a-2.4)}$$

and the total surface enthalpy is approximated as

$$H^S \approx E^S \qquad \text{(M2a-2.5)}$$

Based on this type of approach, Guggenheim (Adamson and Gast 1997) showed that the critical temperature at which a phase transformation occurs in both liquid metals and organic liquids could be fitted by the following expression,

$$\gamma = \gamma^o \left(1 - \frac{T}{T_c}\right)^n \qquad \text{(M2a-2.6)}$$

where "n" is a function of the type of liquid, whether it be a molten metal, where $n = 1$ corresponds to atomic particles, or an organic liquid, i.e., molecular particles, in which case $n = 11/9$. The variable, γ^o is then found to be proportional to the total surface energy, E^S, for $n = 1$ type materials, expressed as

$$\gamma = E^S \left(1 - \frac{T}{T_c}\right) \qquad \text{(M2a-2.7)}$$

It may be inferred from equation M2a-2.7, that at absolute zero, 0° K, surface tension and surface energy become synonymous, i.e., $\gamma = E^S$.

Thermodynamics of Nucleation. A liquid-vapor interface, for example, may be modeled in terms of the formation of a drop of liquid, as in a sessile drop experiment, as the basis for quantifying the surface free energy associated with the formation of the drop (Adamson and Gast 1997). It turns out that if n is the number of molecules of type "A" which form A_n clusters, the free energy of this process is expressed as

$$\Delta G = -nk_B T \ln\left(\frac{P}{P_0}\right) \qquad \text{(M2a-2.8)}$$

where ΔG is a measure of the free energy to transfer n molecules of A-type from the vapor phase to the liquid phase in the absence of surface energy. Then, if the surface free energy consumed or released in the formation of the drop is taken into account, equation M2a-2.8 may be re-written as

$$\Delta G = -nk_B T \ln\left(\frac{P}{P_0}\right) + 4\pi r^2 \gamma \qquad \text{(M2a-2.9)}$$

Assuming further, based on symmetry considerations that spherically shaped drops will preferentially form; Gibb's free energy of formation of such a liquid drop will necessarily be re-defined as

$$\Delta G = -\frac{4}{3}\pi r^3 \frac{\rho}{M} RT \ln\left(\frac{P}{P_0}\right) + 4\pi r^2 \gamma \qquad \text{(M2a-2.9)}$$

The derivative in ΔG, taken relative to the drop radius (i.e., a radius of curvature term) is then shown to go through a maximum "critical" radius, r_c, defined within the pressure regime of $P \rightarrow P_0$, if measured both inside and outside of the drop, respectively. The critical radius is then expressed in terms of the following derivative:

$$0 = \left[\frac{\partial (\Delta G)}{\partial r} \right]_{r \to r_c} = -4\pi r_c^{\,2} \frac{\rho}{M} RT \ln\left(\frac{P}{P_0} \right) + 8\pi r_c \gamma \qquad \text{(M2a-2.9)}$$

as the liquid drop radius approaches its critical value. This expression may be simplified, when derived by solving equation M2a-2.9, which is expressed as

$$RT \ln\left(\frac{P}{P_0} \right) = \frac{2\gamma M}{r_c \rho} = \frac{2\gamma \overline{V}}{r_c} \qquad \text{(M2a-2.10)}$$

Assuming further that not only pressure, but also temperature changes could influence this "nucleation" process leading to the formation of drops of liquids, the Clausius-Clapeyron equation may be conveniently employed to express the thermodynamic relationship between T and P, which is written as

$$\ln\left(\frac{P}{P_0} \right) = \frac{\Delta H_{vap}}{R} \left(\frac{1}{T} - \frac{1}{T_b} \right) \qquad \text{(M2a-2.11)}$$

A liquid-vapor interface is then modeled in terms of the pressure changes measured relative to temperature changes across the drop interface by combining equations M2a-2.10 and M2a-2.11, where the critical radius of the drop is conveniently defined in terms of a temperature change, as

$$\Delta T = T_b - T = \frac{2\gamma M T_b}{r_c \Delta H_{vap} \rho} = \frac{2\gamma \overline{V} T_b}{\Delta H_{vap} r_c} \qquad \text{(M2a-2.12)}$$

Further rearrangement of equation M2a-2.12 then leads to an expression for the enthalpy of vaporization, described by the interfacial energy measured relative to the temperature differential at the drop interface as the drop radius approaching the critical radius, expressed as

$$\Delta H_{vap} = \frac{2\gamma M T_b}{\Delta T r_c \rho} = \frac{2\gamma \overline{V} T_b}{\Delta T r_c} \qquad \text{(M2a-2.13)}$$

Finally, recognizing that the enthalpy of vaporization is related to the solubility parameter of a fluid which comprises the liquid drop, written as

$$\Delta H_{vap} = \delta^2 \overline{V} + RT\,, \qquad \text{(M2a-2.14)}$$

upon substitution of equation M2a-2.14 into equation M2a-2.13, an expression may be derived directly relating the solubility parameter to the surface tension, which is written as

$$\gamma_i(T) = \frac{r_{c,i}}{2T_b} \left[\left(\delta_i(T) \right)^2 + P_{atm} \right] \Delta T \qquad \text{(M2a-2.15)}$$

In equation M2a-2.15 substitution of $P_{atm} = RT / \overline{V}$ is employed to define the pressure of the vapor phase at the interface, in this case where it is approximated as atmospheric pressure. Equation M2a-2.15 now constitutes an interesting relation between *T*, *P*, the surface tension, and the cohesive energy density (i.e., the solubility parameter, δ, squared), that adequately describes a general energy balance condition at any liquid-vapor interface.

The energy balance relationship expressed by equation M2a-2.15, in principle, describes an equilibrium state of an interface in terms of the force balance, $(Area)\bullet\left\{2\gamma_i(T)T_b/r_{c,i}\,\Delta T = (\delta_i(T))^2 + P_{atm}\right\} \equiv \{F_\sigma = F_l + F_v\}$ defined relative to a Laplace pressure at the liquid-vapor interface. The Laplace pressure is further defined by the sum of pressure contributions at the material phases of the interface (i.e., the cohesive energy density plus the atmospheric or vapor pressure, $\Delta P = (\delta_i(T))^2 + P_{atm}$), which is multiplied by the critical radius, r_c. Furthermore, a temperature difference, $\Delta T = T_b - T$, is defined at some critical temperature applicable to the type of material phase transition that corresponds to the system, in the present case the boiling point temperature, T_b. Thus, at $T = T_b$, under normal atmospheric pressure, the liquid turns to vapor, and the interface disappears, and hence, the surface tension, in principle, becomes diffuse then goes to zero as the material completely vaporizes. Thus, the thermodynamic state of a multi-phase system (asphalts and modified asphalt systems in a liquid-solid phase transition state, for example) should be particularly importance to its stability when liquid-solid phase transformation phenomenon are considered.

The Gibbs-Thomson Equation-Application of Nucleation Driven Asphalt Solidification to Aggregate Surfaces. Gibbs-Thomson capillary undercooling, which applies to solidification processes, may be derived in terms of an equilibrium state defining the interfacial tension between two phases, (i.e., $l \rightarrow s$) (Tiller 1991). In solidification processes involving the casting of metals, by controlling the cooling rate of the system (melt in a crucible), a liquid metal is often cooled, at least locally around growing crystal interfacial sites below the equilibrium crystallization point. Thus, by controlling the rate of cooling/heating, microscopic, as well as macroscopic physical properties of the material may be controlled and predicted.

The Gibbs-Thomson capillary undercooling effect is often stated as follows: With the creation of a new interface, there is associated with it an excess interfacial energy, described by heat convection and spatial re-arrangement of the particles (atoms, molecules), that is sensitive to the area-to-volume ratio of the heat sink surface (casting pot) on which nucleation growth may occur. The Gibbs-Thomson undercooling (temperature difference, $\Delta T = T - T_{melt}$, i.e., curvature, is expressed as

$$\Delta T = \kappa\Gamma \quad , \qquad \text{(M2a-2.16)}$$

where the Gibbs-Thomson coefficient, Γ, is defined for a liquid-vapor interface in terms of the entropy of fusion, ΔS_f, and interfacial free energy, γ, as

$$\Gamma = \frac{\gamma}{\Delta S_f} \quad , \qquad \text{(M2a-2.17)}$$

The curvature, κ, is then defined as

$$\kappa = \frac{dA}{dV} = \frac{1}{r_1} + \frac{1}{r_2} \propto \frac{2\overline{V}}{r_c} \qquad \text{(M2a-2.18)}$$

where r_1 and r_2 are the major and minor radii of interfacial curvature of an "ellipsoid growth" microstructure, for example, referred to as dendrites, defined at the "growing" liquid-solid phase transition interface where A is the area, $\overline{V}$ is the molar value, and r_c is the critical radius at the nucleating crystal site. Combining equations M2a-2.16, M2a-2.17 and M2a-2.18 leads to an expression of the form

$$\Gamma = \frac{r_c \Delta T}{2\overline{V}} \qquad \text{(M2a-2.19)}$$

If a liquid-vapor interfacial "system" is considered for example, where the system is assumed to be in an isothermal state at equilibrium, then

$$T_b \Delta S_{vap} = \Delta H_{vap} \sim at \sim \Delta \mu_{vap} = 0 \qquad \text{(M2a-2.20)}$$

for $T \rightarrow T_b$ where T_b is the boiling point temperature of the liquid. Then, by combining equations M2a-2.17, M2a-2.18, and M2a-2.19, the change in the entropy of formation of the liquid interface "condensation" may be derived in terms of the critical radius, which occurs at the interface, close to the defined critical temperature, where

$$\Delta S_f = \frac{2\gamma\overline{V}}{r_c \Delta T} \qquad \text{(M2a-2.21)}$$

From equations M2a-2.17 and M2a-2.21, and the condition stated by equation M2a-2.20, (i.e., $T_c \Delta S_f = \Delta H_f \sim at \sim \Delta \mu_f = 0$) it may be shown that the chemical potential of a molecule, or ensemble of molecules that are transferred between two phases (in this case the liquid-vapor interface), is expressed in terms of the heat of formation (vaporization in the present case), ΔH_f, as

$$\Delta \mu_f = \frac{\Delta H_f \Delta T}{T_c} \qquad \text{(M2a-2.22)}$$

Thus, if equation M2a-2.14 is substituted into equation M2a-2.21 given the condition of equation M2a-2.20, the same self-consistent expression as M2a-2.15 is obtained

$$\gamma = \frac{r_c}{2\overline{V}}\left(\delta^2\overline{V} + RT\right)\frac{\Delta T}{T_b}$$
$$= \frac{r_{c,i}}{2T_b}\left[\left(\delta_i(T)\right)^2 + P_{atm}\right]\Delta T \qquad \text{(M2a-2.23)}$$

If the molar volume of the liquid is then defined in terms of the molar radius as

$$N_0\overline{r}^3 = \overline{V} \qquad \text{(M2a-2.24)}$$

where the molar radius, $\overline{r}$, is defined by

$$\overline{r} = \left(\frac{M}{\rho N_0}\right)^{1/3} \qquad \text{(M2a-2.25)}$$

the entropy of formation at either a liquid-vapor or liquid-solid interface may then be generally expressed as

$$\Delta S_f = \frac{2\gamma N_0\overline{r}^3}{r_c\Delta T} \qquad \text{(M2a-2.26)}$$

where an energy dissipation "extinction efficiency" factor, Q, may be defined, after re-arrangement of equation M2a-2.26 multiplying through by unity $1 = 2\pi/2\pi$ to give

$$Q \equiv \frac{2\pi r_c}{\overline{r}} = \frac{4\pi\gamma N_0\overline{r}^2}{\Delta S_f\Delta T} = \frac{E_{stored}}{E_{dissipated}} \qquad \text{(M2a-2.27)}$$

Thus, energy expenditure "dissipation" to create an interface is directly related to the change in the critical radius of the cluster (i.e., formation or erosion of clustering, r_c , where $\overline{r} \rightarrow r_c$), at the interface, i.e., a molecular re-orientation effect.

Surface Entropy and its Relationship to Temperature Susceptibility of Viscous Flow. Asphalt surface tensions were previous measured as a function of temperature employing a DuNouy ring surface tensiometer (Robertson et al. 2001, 2005). Figure M2a-2.1 depicts a plot of surface tension in dyne/cm versus temperature °C measured for SHRP core asphalt AAB-1. Surface tension values specifically depicted at 25°C were derived from AFM force-distance measurements. Clearly, unlike ideal liquids which generally exhibit a linear variation in surface tension with changing temperature, asphalts, measured throughout the temperature range from ambient, 25°C to ~ 120°C, exhibit non-linear variation in surface tension with changing temperature. Curve fit analysis of surface tension versus temperature suggests that a third-order polynomial function approximates the trend in the data. Table M2a-2.1 lists regression parameters and phase transition temperatures calculated for the eight SHRP core asphalts, based on a fit of non-linear γ vs. T data points to a third order polynomial equation

$$\gamma(T°C) \approx g_0 + g_1 T + g_2 T^2 + g_3 T^3 \tag{M2a-2.28}$$

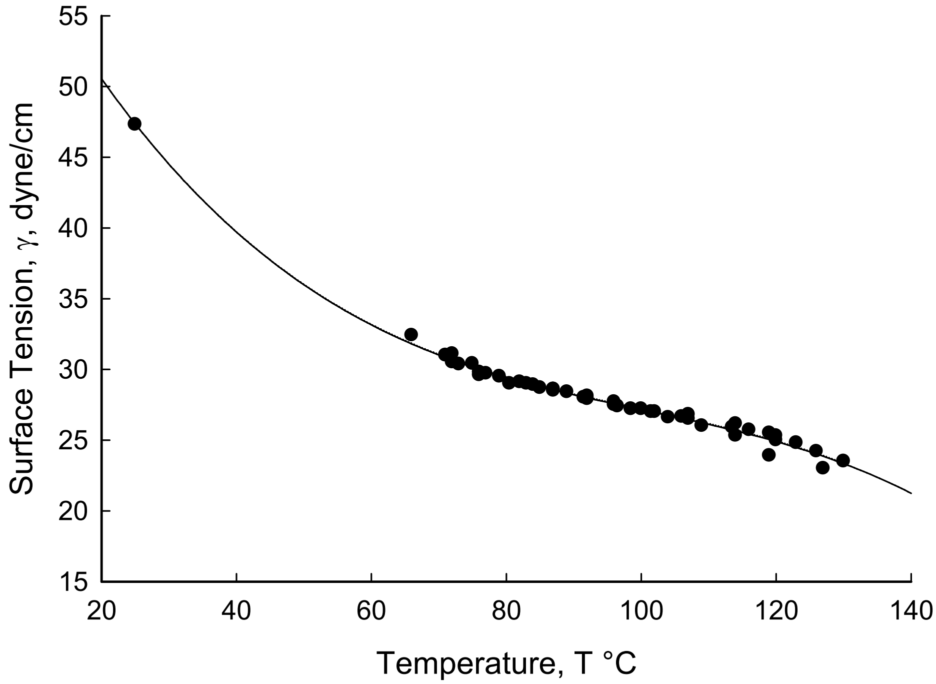


Figure M2a-2.1. SHRP asphalt AAB-1; temperature, T °C, plotted versus surface tension, γ (dyne/cm).

Table M2a-2.1. Regression parameters and phase transition temperatures, T*, calculated and/or estimated for seven of the eight SHRP core asphalts.

Asphalt	g_0	g_1	g_2	g_3	T* °C(@$d^2\gamma/dT^2$=0) = $-g_2/3g_1$
Est. AAA-1	175.40	-2.0000E-04	5.2300E-02	-4.7421	87.17
AAB-1	67.07	-2.9536E-05	8.9000E-03	-0.9920	100.44
AAC-1	59.09	-2.0673E-05	6.3000E-03	-0.7488	101.58
AAD-1	50.36	-1.4300E-05	4.0000E-03	-0.5001	93.24
AAF-1	63.72	-1.4729E-05	5.1000E-03	-0.7345	115.42
Est. AAG-1	81.87	-3.9095E-05	1.2300E-02	-1.3827	104.87
Est AAK-1	-0-	-0-	-0-	-0-	95
AAM-1	67.39	-2.2339E-05	7.3000E-03	-0.9045	108.93

Phase-transition temperatures, *T** °C, listed in table M2a-2.1 were derived for the eight SHRP asphalts by taking the second derivative of the third order polynomial function in order to determine the inflection point, estimated as

$$\frac{d^2}{dT^2}\gamma(T°C) = \frac{d^2}{dT^2}\left(g_0 + g_1T + g_2T^2 + g_3T^3\right)$$
$$= -\frac{dS^S}{dT} \tag{M2a-2.29}$$

$$T*°C(@\, dS^S / dT = 0) \approx \frac{-g_2}{3g_3} \tag{M2a-2.30}$$

This phase transition may best be defined as a Newtonian liquid to viscoelastic liquid phase change at the "softening" temperature $T^* \rightarrow T_m$ where figure M2a-2.2 further shows that the transition temperature correlates directly with the activation energies of viscous flow, $E_a(\eta)$, of the asphalt. Thus, it is one of the objectives of this subtask to further investigate this relationship between surface properties and flow properties.

The results presented here demonstrate that variations in the thermal-rheological properties of asphalt, $E_a(\eta)$, from different crude sources correlate directly to surface entropy, $-S^S = d\gamma/dT$. Surface entropy should then be related to the surface free energy of mixing with water.

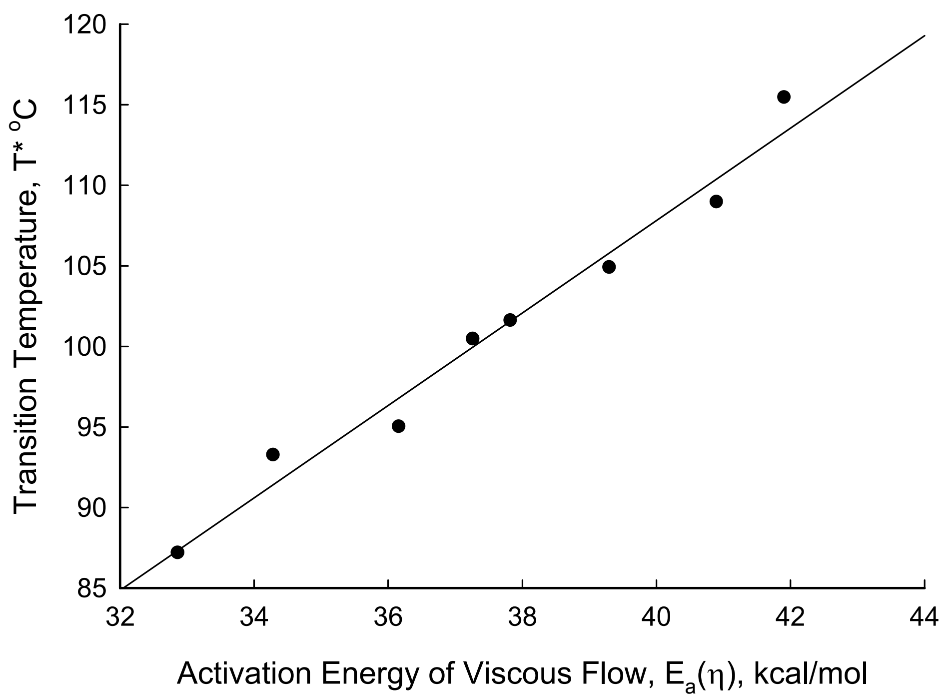


Figure M2a-2.2. Phase transition temperature of the Newtonian-liquid to viscoelastic liquid phase transition, T^* °C, measured by temperature dependent surface tensiometry, plotted versus the asphalt activation energy of viscous flow, $E_a(\eta)$, reported for the eight SHRP core asphalts, (i.e., $E_a(\eta)$, $\propto \Delta T(\Delta\gamma)$ relationship).

Relationship to FHWA Focus Areas

This work element is related to the following focus areas:

- Optimum Pavement Performance- Introducing methods for better characterization of neat asphalts.
- Advanced quality systems: Further development of test methods that are more related to actual pavement performance.

Hypothesis

The cohesive properties of asphalt, when considered as a function of temperature, directly impact the viscoelastic properties in terms of molecular orientation at free interfaces as well as with in the bulk material. Thus, thermodynamically speaking, "self" cohesion may be modeled as a process of nucleation which leads to the solidification of the binder from a soft to hardened state. Cohesive breakdown of the binder then becomes dependent upon the tendency of asphalts to soften then mix with water by processes of emulsification that begins with the softening of the material at an exposed interface.

Objectives

The primary objective of this subtask is to determine the nature surface entropy of asphalts and relate this property to moisture susceptibility through interfacial thermodynamic theories. Some of the approaches that will be considered will include the tendency of asphalts to form surfactant materials as a function of oxidation which lead to emulsification in the presence of water, the rates of softening of asphalt, and the determination of interaction potentials between asphalt molecular components and water.

Experimental Design

The research philosophy that will be adopted in this subtask will rely on "modeling the experiments" to obtain fundamental measurements of physico-chemical properties of the asphalt binder cohesive qualities of the materials considered. Modeling the experiments will entail adopting the models discussed in the Theoretical and Experimental Background section to interpret the propensities of asphalt cohesive integrity in the presence of moisture as a function of temperature.

A literature search will be conducted to aid in development of tests and models which determine compositional and physico-chemical properties that define the adhesive properties of asphalts and aggregate surfaces.

SHRP core asphalts, WRI asphalt binder type validation site asphalts, as well as other asphalt and aggregates will be selected for study.

Experiments will then be conducted to determine the phase transition temperatures of neat and oxidized asphalts to determine how well these values correlate with the viscoelastic properties of these same materials. Models will then be developed from these correlations and compared with known thermodynamic models.

One of the key motivations for this research is to verify that the correct physico-chemical properties of asphalt are being identified and measured so that thermodynamic modeling efforts and test methodologies will be representative of the desired performance prediction data.

Overall Work Plan

Sub-Subtask M2a-2.1: Selection of eight asphalts and four aggregate materials to prepare samples. Measure surface tension as a function of temperature of asphalts and asphalt fractions over temperature ranges experienced in the pavement. Determine phase transition temperatures from surface tension vs. temperature data and correlate data with physical and performance data, including dynamic viscosity and fracture temperature.

Sub-Subtask M2a-2.2: Prepare and conduct temperature varied water soaking experiments for four sets of mastics comprised of four asphalts prepared with four different asphalts. Determine asphalt stripping temperatures of asphalt mastic materials in temperature varied water soaking experiments.

Sub-Subtask M2a-2.3: Conduct AFM pull-off force "nano-contact mechanics" measurements on asphalt thin-film and aggregate surfaces employing chemically functionalized cantilever tips. Determine polarity components of surface energy of both asphalt thin-films and aggregate fine particles and relate these properties to the tendency of these materials to promote emulsification.

Year 2 Schedule

Conduct testing described in sub-subtask M2a-2.1.

Year 2 Milestones

Prepare report of findings in Sub-Subtask M2a-2.1 at end of year 2.

Overall Schedule

Sub-Subtask M2a-2.1- Conducted in year 2
Sub-Subtask M2a-2.2- Conducted in year 3
Sub-Subtask M2a-2.3- Conducted in year 4

References

Adamson, A. W., and A. P. Gast, 1997, *Physical Chemistry of Surfaces*, 6th Ed., A Wiley-Interscience Publication, John Wiley & Sons, Inc., New York, 534-535.

Robertson, R. E., J. F. Branthaver, P. M. Harnsberger, J. C. Petersen, S. M. Dorrence, J. F. McKay, T. F. Turner, A. T. Pauli, S.-C. Huang, J.-D. Huh, J. E. Tauer, K. P. Thomas, D. A. Netzel, F. P. Miknis, T. Williams, J. J. Duvall, F. A. Barbour, C. Wright, 2001, *Fundamental Properties of Asphalts and Modified Asphalts, Volume I: Interpretive Report*, FHWA-RD-99-212. U. S. Department of Transportation, Federal Highway Administration, McLean, VA.

Robertson, R. E., K. P. Thomas, P. M. Harnsberger, F. P. Miknis, T. F. Turner, J. F. Branthaver, S-C. Huang, A. T. Pauli, D. A. Netzel, T. M. Bomstad, M. J. Farrar, J. F. McKay, and M. McCann. "Fundamental Properties of Asphalts and Modified Asphalts II, Final Report, Volume I: Interpretive Report," Federal Highway Administration, Contract No. DTFH61-99C-00022, Chapters 1-4 submitted for publication, November 2005.

Tiller, W. A., 1991, *The Science of Crystallization: Macroscopic Phenomena and Defect Generation*, Cambridge University Press, Great Britain, New York, NY.

Year 2 Milestones for Work Element M2a

The effort in year 2 for this subtask will be to develop an experimental plan to measure the practical work of cohesion for dry and saturated asphalt binders. The experiment plan will include details of the test setup, the test procedure, and methods of analysis. The ongoing collaboration between researchers from the Texas A&M University and the materials faculty from University of Nottingham, UK, and Imperial College of London will facilitate the development of this work plan. This detailed plan will also address objectives related to work element F1a.

In addition, experiments will be conducted to determine the feasibility of using the Wilhelmy plate device or the sessile drop method in order to determine the thermodynamic or theoretical work of cohesion based on surface free energy measurements. The primary outcome of this task is to determine material properties (viscosity, plasticity) that influence the relationship between the theoretical work of cohesion and the practical work of cohesion.

Work Element M2b: Impact of Moisture Diffusion in Asphalt Mixtures

The equilibrium state and the potential difference between the current and equilibrium state that drives moisture damage in asphalt mixtures can be determined based on principles of thermodynamics. However, in order to combine environmental conditions and external loads into a model used to predict realistic pavement responses, it is imperative to consider kinetics of moisture damage in addition to these thermodynamic properties. The following three components dictate the time required for moisture to cause debonding under given environmental (boundary) conditions: (i) flow and retention of moisture in the pavement structure, which is governed by the void structure of the mixture; (ii) diffusion of moisture from voids to aggregate-binder interfaces, which is governed by the diffusivity rates of the binder or mastic films; and (iii) debonding of aggregate-binder interface, which is governed by the thermodynamic potential and kinetic rate constants at the interface. The various subtasks within this work element will be designed to formulate the three components listed above into a form that can be implemented in a numerical scheme to simulate moisture damage in asphalt mixtures under any given environmental boundary conditions and loads.

Subtask M2b-1: Measurements of Diffusion in Asphalt Mixtures (Continued in Year 2)

Diffusion of moisture through air voids, asphalt binder or mastics is an important rate controlling phenomenon in the moisture damage process. There is a lack of repeatable and reliable methods for measuring this important property. This subtask will develop experimental methods to measure moisture diffusion in asphalt mixtures and their constituents. The following steps will be carried out in this subtask:

i. Identify and develop test methods to measure diffusion of moisture through asphalt binder / mastic films and asphalt mixtures. Based on previous experience, the use of psychrometers to measure relative humidity (or suction) appears to be a very good candidate. The experimental results will be modeled using a composite model that considers that diffusion in the binder, air voids and aggregates in calculating the diffusion in the asphalt mix composite. This model considers the percentage and tortuosity of each of the mixture phases.

ii. Determine diffusivity of different types of asphalt binders and mastics. Analytical techniques such as Fourier Transform Infra-Red (FTIR) have been used in the past to determine the rate at which water displaces the asphalt binder from its interface with standardized surfaces (Nguyen et al. 1996). The attenuated total reflectance (ATR) technique is used with FTIR and allows the interface to be subjected to a variety of boundary conditions. Using different controlled thicknesses of asphalt binder films or mastics, one can determine the rate of diffusion of moisture through the binder or mastic films. The use of FTIR offers the advantage that both the time dependency related to moisture diffusion through the binder as well as the kinetics of debonding at the binder-solid interface (addressed in Subtask M2b-2) can be captured in real time with very little modification to the test set up. However, in addition to the use of an FTIR, the researchers will also coordinate with other research entities using alternate techniques such as electronic impedance spectroscopy to obtain similar measurements.

iii. Determine the absorption-desorption-absorption rates for different asphalt binders. In other words, determine the diffusivity of the asphalt binder after subjecting it to one or more cycles of absorption and desorption. The hypotheses here is that diffusivity rates of dry asphalt film are significantly smaller than diffusivity rates of an asphalt film that has been subjected to one full cycle of moisture absorption and desorption. The ATR-FTIR technique, as described in (ii) above will be used to make these measurements.

iv. Determine the effect of pore pressure on the diffusivity rates for asphalt binders / mastics. The action of external loads can induce pore pressure in entrapped water, especially if the mixture is in the pessimum void structure range. This pore pressure due to external loads can accelerate diffusion of the moisture through the binder or mastic film. The ATR-FTIR technique as described in (ii) above will be used to make these measurements on the binder and mastic films. Due to equipment limitations, the magnitude of water pressure that can be allowed on the binder or mastic film might not be equivalent to that of the pressure exerted due to wheel loads on the pavement. However, within certain limits, the impact of pore pressure on the diffusivity constants of the binder or mastic can be easily estimated using this test technique.

Subtask M2b-2: Kinetics of Debonding at the Binder-Aggregate Interface

This subtask will evaluate factors that influence kinetics or rate of debonding after moisture reaches the aggregate-binder interface. The purpose of this subtask is to verify the hypothesis that once water is at the binder-aggregate interface, the rate of debonding is mostly influenced by the thermodynamic potential for water to cause debonding (determined using surface energy components) and micro texture of the aggregate surface. This will be accomplished as follows:

i. Determine and compare rate of debonding for different binder-aggregate interfaces as a function of the thermodynamic potential for moisture damage determined using surface energy components. The aggregate surfaces will be prepared to have uniform roughness.
ii. Determine influence of aggregate surface texture or specific surface area (sub micron scale) on the rate of debonding for different binder-aggregate interfaces.

Major Findings from Year 1 for Work Element M2b

Significant advances were made in the development of a method to measure the rate of diffusion of moisture through the asphalt binder. The FTIR-ATR cell was used to make these measurements. A simple gravimetric method was also used to determine the rate of diffusion of moisture through FAM specimens. A more detailed description of the test methods is presented in the quarterly report ending September 2007.

A method was developed for measuring moisture diffusion in FAM and full mixtures using psychrometers. The method was applied for mixtures with different binder sources, aggregate sources and volumetrics. The current work focuses on modeling the mixture diffusion using a composite model.

Year 2 Milestones for Work Element M2b

i. Determine the diffusivity of water through select asphalt binders using the FTIR and gravimetric methods and compare results from other techniques where available.
ii. Determine the rate of debonding by water at the binder – solid interface for select systems and compare it to the thermodynamic potential based on surface energy measurements.
iii. Predict mixture diffusion using a composite model based on the diffusion of the individual constituents and distribution (percentage and tortuosity) of these constituents.

Work Element M2c: Measuring Thin Film Cohesion and Adhesion Using the PATTI Test and the DSR

Task Lead: Codrin Daranga

Introduction

In order to evaluate the susceptibility of moisture damage within asphalt pavements, the chemical and/or physical affinity is commonly measured with loose asphalt mixtures or compacted asphalt mixtures in a field-simulated environment. Although some of these tests show results comparable with real field data, the actual mechanism of moisture damage and the role of components in the failure response cannot be sorted from these tests. Therefore, there is significant room for improvement, mainly because of the structural complexity of asphalt mixtures and the confounding effects that result from it. The difficulty of accurately measuring the role of the various variables (e.g., binder cohesion, adhesive bond, airvoids, aggregate surface characteristics and shape, etc.) makes an analytical approach for selecting materials that will resist moisture damage very complex. The use of simplified testing systems that can separate the contribution of different components under the effect of water could provide a more effective method for moisture damage analysis and prediction of damage risk. Among the many ideas proposed in the last 10 years, two systems show the greatest potential for satisfying the simple analytical approach criteria. One of these is the Pneumatic Adhesion Tensile Testing Instrument (PATTI) and the other is the testing procedure developed using a Dynamic Shear Rheometer (DSR) to measure cohesive strength (Cho and Bahia 2007).

The PATTI device was initially developed by the National Institute of Standards and Technology (NIST) and was utilized by Youtcheff and Aurilio (1997) at FHWA to evaluate the adhesive loss of asphalt-aggregate systems exposed to water. The PATTI device is advantageous for several reasons: it allows the use of aggregate surface, the sample specimen is conditioned in water after applying asphalt between the pull stub and aggregate surface, and the test allows one to observe the failure surface to define adhesive versus cohesive failure. In addition, the device is low-cost, simple, and well described by an ASTM standard. The PATTI device and methodology are therefore considered as a good testing procedure for measuring moisture damage properties of binders.

The DSR thin film cohesion test was developed more recently based on concepts widely used in paint and adhesive fields (Kanitpong and Bahia 2003). The main advantage of using the DSR test is the very precise control of factors such as temperature, film thickness, and rate of loading. The DSR test allows precise measurements of time-based responses such as load, deflection, and rheological properties. The DSR test also permits the application of different loading paths (e.g., shearing and uniaxial loading). The initial testing data show the potential of the methodology for measuring factors affecting moisture damage for a wide variety of testing conditions. For example, combining different aggregate-made discs and varying the binder film thickness will yield more insight on the binder’s cohesive properties and aggregate-binder adhesive responses.

Moisture damage is also affected by polymer modification. Using these new measurement systems, modified asphalt cements have shown to have better cohesion and adhesion properties than their non-modified counterparts. Better understanding of the influence of different types of polymer modifiers on the binder's cohesion properties, as well as the interaction with mineral surfaces of the different chemical modifiers, is desired. This better understanding will help develop enhanced testing methods and the selection of procedures for improving the resistance to moisture damage of pavements.

Moisture damage is also known to be affected by mineral fillers. The effect of fillers on moisture damage has not been explored carefully. Mineral filler constitute a major portion of the surface area of the binder- mineral aggregate interface. These two systems are suitable for testing cohesion and adhesion of mastics and thus could give some specific insight of effects of fillers.

Relationship to FHWA Focus Areas

The moisture damage work elements support the FHWA Focus Area of Optimizing Pavement Performance by providing a relationship between material property and pavement performance.

Hypothesis

The moisture damage in asphaltic mixtures is a very complex mechanism and is affected by many variables. The use of simplified testing systems that can separate the contribution of different components under the effect of water could provide a more effective method for moisture damage analysis and prediction of damage risk.

Objectives

This work element includes objectives focused on the PATTI and DSR thin film rheology test. It is expected that both of these systems will be evaluated to define factors that have significant effect on responses:

- Modification of the pull-off test (PATTI) to allow measurement of load, deflection and control film thickness. The cost and practicality of the modification as well as the precisions will be evaluated.
- Further development of the DSR thin film test by evaluating the following factors:
    - The effect of different pulling rates on the PATTI and DSR responses.
    - The testing temperature plays an important role in adhesion and cohesion. The effects of testing temperature on the results will be quantified and used to define role of climate on moisture damage. The testing temperature will also help in establishing relationships between different mixture testing temperatures.
    - Changing loading frequencies in the shear mode will have an important effect on the cohesion and adhesion test results and it will better simulate different traffic speed.
    - The temperature during the water conditioning plays an important role in effect of water on cohesion and adhesion of binder or mastic.

Experimental Design

The objective of this subtask will be addressed as follows:

i. Evaluate Load and Deflection Measurements using the Modified PATTI Test (Year 1 start). The pull-off test is a simple and efficient way to investigate the combined effect of cohesion and adhesion properties of binders and changes due to moisture effects. However the test in its current format is not able to produce stress-strain curves. It measures maximum pressure which can only be used as an index. This task will focus on evaluating the possibility of modifying the pull-off test so that it would produce load vs. deflection responses. This modification will enable the calculation of the total energy to failure and the study of how the failure process by identifying trends in the behavior of the binder during loading. The differentiation between cohesive and adhesive failure will also be studied. A consideration of a metal or glass surface that allows full adhesion could be used to measure cohesion. The dry and wet testing on aggregate surfaces could be used to study effects of aggregate interactions with or without water conditioning. Imaging will be used to quantify the failure as cohesive or adhesive based on the percentage of the surface failure that has been "stripped" of binder. This should provide better information on the type of failure.

ii. Evaluate Effectiveness of the Modified PATTI Test for Detecting Modification Effects (Year 1 start). Modified binders will be prepared using different "base" virgin and modifiers. Each "base" binder will be modified using the selected chemical additives. Preliminary testing at the selected conditions will be conducted in this task. The results will validate the applicability of the test methods to modified asphalts and their effectiveness in measuring the contribution of modifiers in the cohesive behavior of binders. The results will lead to the selection of a reduced number of combinations to be tested in the following task.

iii. Validation of the Modified PATTI Test using Results from DSR Testing. Selected samples of the modified and unmodified binders tested in the previous task will be tested using the DSR instrument. This testing will be used to validate the results form the modified PATTI test and to indicate which modification is necessary and which is not to measure important in the evaluation of binder cohesion and aggregate-binder adhesion behavior. The tests will be structured to investigate the influence of the temperature of testing, the conditioning temperature, and the pulling rate. In addition, the comparison between the axial pull-off testing and shear stress sweep will be included in the testing.

iv. Testing of Mastics Using Modified PATTI and DSR Tests. The same testing protocol used for testing binders will also be used for the testing of selected mastics. The results will identify suitability of the test systems to binder-filler mastics.

v. Commercialization and Practicality Evaluation of the Modified PATTI Test. The increase in cost of the PATTI device and the information gained by the modification will be analyzed to make a recommendation regarding the use of the test for studying thin film cohesion and affinity of binders and mastics to aggregates. In this task, manufacturers of the PATTI device will be contacted to explore the cost and commercialization possibilities the modified PATTI test. State DOTs and consulting labs will be contacted to collect feedback about the practicality of the test system and the merits of standardizing the modified PATTI test for the evaluation of binder cohesion and aggregate-binder adhesion. Presentations at the binder and mixture ETGs will be prepared and delivered to collect feedback form experts. The feedback will be summarized and used to make modifications in the developed system.

vi. Analysis and Recommendations for the Modified PATTI Test. The objective of this task is to analyze experimental data and evaluate the responses collected during the various tasks to make recommendations regarding the modified PATTI test and its applicability to moisture damage of asphalt mixtures. The results of binder and mastic will be shared with other work elements to evaluate the relationship to surface energy and the results of the Sorption Device.

<u>Major Findings from Year 1</u>

During year one, the materials and testing conditions for the plan were selected and are shown in table M2c.1. A testing plan was also developed and the proposed tests are shown in table M2c.2.

Table M2c.1. Matrix of materials and conditions.

Mineral surfaces	Granite	Conditioning environment	Air
	Limestone		0.5 M NaCl (aq)
	Glass Plate		0.5 M CaCl (aq)
Binders	neat PG58-22 binder		
	PG64-22 SBS-modified binder		
	PG64-22 Elvaloy-modified binder		

Table M2c.2. Proposed tests on asphalt binders and mixes.

Testing technique	Modified PATTI	Binding temperatures	Two (65 and 135 °C)
	DSR	Condit. temperature	One (65 °C)
Mineral surfaces	Three	Testing temperatures	Two (10 and 25 °C)
Binders	Three	Pullout rates	Two (slow and fast)
Conditioning environments	Three		

Since the start of Year 1 work plan, the team has extensively evaluated the modification of the traditional pullout test methodology and the proposed modification on the measured parameters Major findings include:

a. Design and build the testing component. The different component of the modified PATTI test methodology were selected and put together. These components include an 8-channel data acquisition card, pressure transducer, displacement transducer and support for the pullout stub, and displacement transducer frame. The system was put together and testing and evaluation began.

b. Design of the test methodology. The proposed testing methodology was developed considering all testing parameters and condition. The step-by-step methodology is detailed here.

Binder preparation. Put the binder in the oven at 135°C until it becomes fluid. Stir the hot binder in one direction to homogenize the temperature in the binder. Pour the molten binder in a clean silicone mold. Dress the binder as shown in figure M2c.1 and let the binder cool down to room temperature.

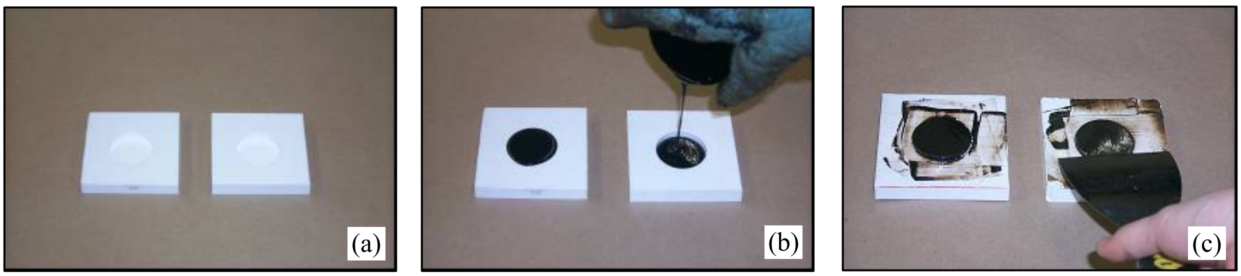


Figure M2c.1. Photo. (a) Prepare clean silicone molds. (b) Pour the molten binder. Let the binder to cool down to room temperature (approx. one hour). (c) Dress the binder with a heated putty knife (Picture by Kitae 2005).

Aggregate surface preparation. Place the flat surface of the aggregate to be tested on a hot plate or oven set at the required preparation temperature (typically 135°C). Leave the aggregate surface on the plate until the surface temperature of the aggregate equilibrates with the temperature of the hot plate. The aggregate surface temperature is measured with an infrared thermometer. At the same time, place the bottom of the pullout stub on the surface of the hot plate or in an oven set at 135°C. The stub needs to be heated to allow binding to the asphalt binder.

Place the binder onto the heated aggregate surface. Remove the aggregate from the hot plate or oven (however, keep the pullout stub on the hot plate). Measure the aggregate surface temperature with the infrared thermometer (this is the preparation temperature). Place the silicone mold face down on the heated aggregate surface so that the binder makes contact with the heated aggregate.

Remove the silicone mold. Let the binder-mineral system cool to room temperature and carefully remove the silicone mold (to facilitate the binder demolding, place the silicone mold and binder in a refrigerator for about 5 minutes). The silicone mold should be easily removed and the binder must remain on the aggregate surface. If the binder peels off from the aggregate, repeat procedure from step 1 using a fresh mineral surface.

Attach the pullout stub to the binder. Place the split pull-off stab support around the binder. Remove the pullout stab from the hot plate and rapidly place it on the center of the pullout stab support (see figure M2c.2). This support leaves a binder thickness equal to 0.5 mm. Let the system pullout stub cool down until it reaches the ambient temperature.

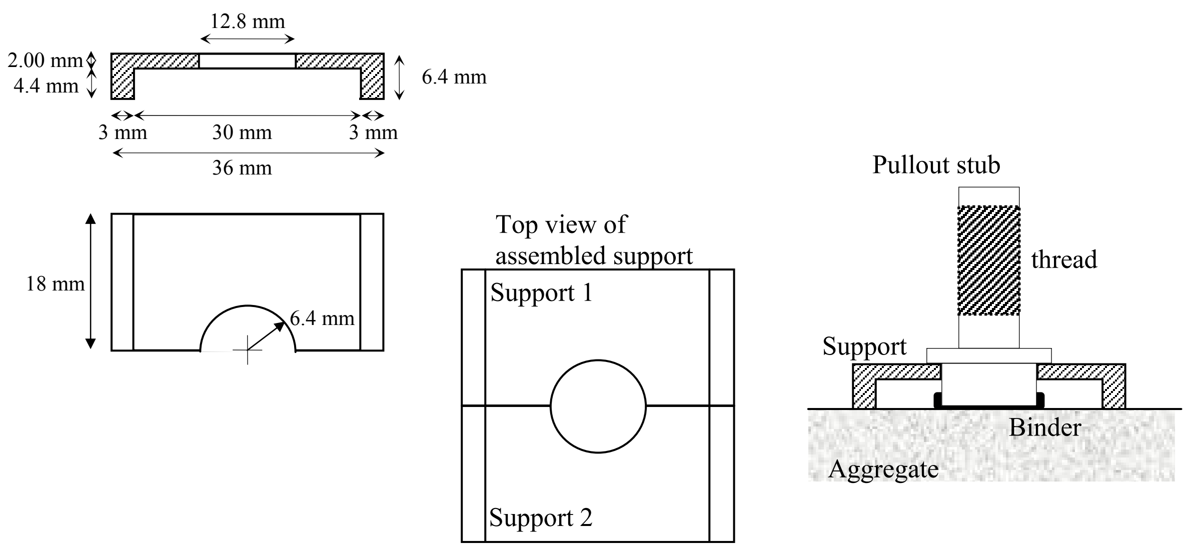


Figure M2c.2. Diagram. Details of the split pullout stub support and assembled aggregate, binder, support and pullout stub.

Binder mineral conditioning. Submerge the assembled aggregate-binder-pullout stub system in a temperature-controlled water or salt aqueous-solution bath for a predetermined period of time. Once this process is complete, the aggregate-binder system is ready for the pullout testing. If the system will be tested without conditioning, let the system equilibrate with the testing temperature for at least one hour.

Setting the pullout test. Place the aggregate, binder and pullout system on a bench top for ambient temperature testing or in an environmental chamber for temperature control testing. Separate the split support and use them as spacer (figures M2c.3 and M2c.4). Assemble the PATTI test pressure ring (on top of the spacers), silicone gasket, and the pressure line to the PATTI pressure controller. The added spacers allow a pullout deformation of about 6 mm (at total strain of 1200%). The operation includes the following procedures.

- Screw the self-aligning bearing plate following the procedure described in ASTM standard D4541.
- Set the three-leg LDVT frame on top of the mineral rock and align the high resolution LVDT on the top of the pullout stab. The modified PATTI test also

includes a pressure transducer to monitor the pressure history during the test (see figures M2c.4 and M2c.5).

- Connect the pressure transducer and LVDT to the data acquisition card. The recorded data allow for the reconstruction of the deformation-force history and the evaluation of the energy dissipated during the pullout test.
- Set the pullout rate in the PATTI pressure controller; the test is ready to begin.

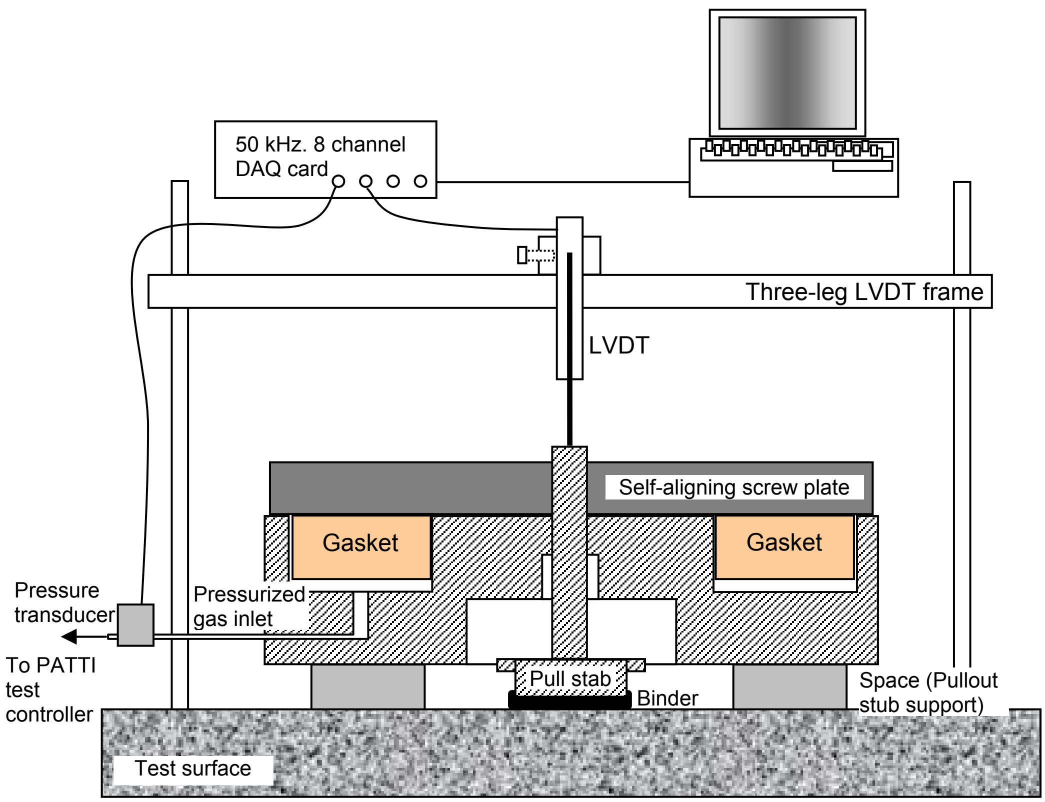


Figure M2c.3. Diagram. Schematic of the complete ensemble modified PATTI test.

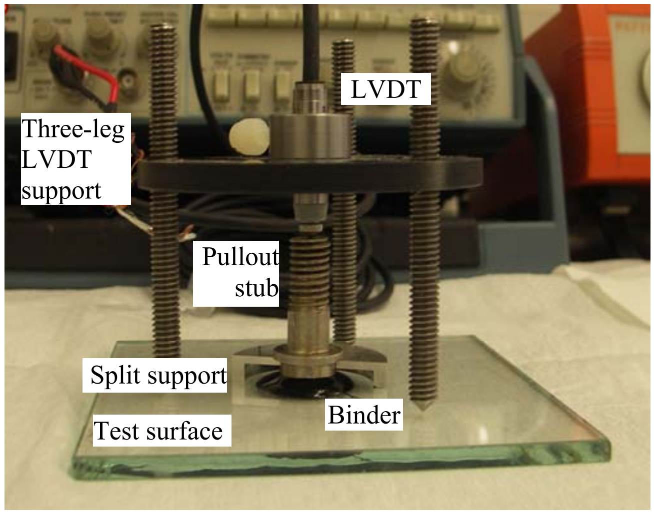


Figure M2c.4. Photo. Picture of the ensemble modified PATTI test setup
(the PATTI pressure ring is not shown).

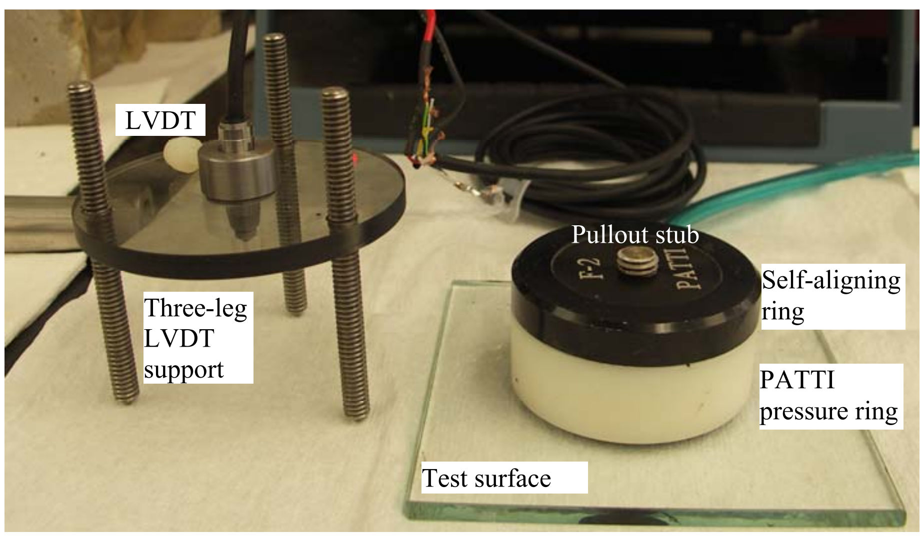


Figure M2c.5. Photo. Picture of the ensemble modified PATTI test setup
(the PATTI pressure ring is not shown).

Run the pullout test. Set the pressure rate in the PATTI pressure control panel. Run the test by applying pressure to the line. The data acquisition system will collect the data post-failure. Once the test is completed, remove the pullout stab and take a picture of the failure surface to document if the failure was cohesive or adhesive. Use the deformation-load history data to evaluate the energy dissipated during testing and the type of failure (ductile or brittle).

c. Evaluation of the modified testing methodology. Several controlled tests were run to calibrate and validate the proposed methodology. These tests include:

1. The calibration of the pressure transducer and linear variable displacement transducer and linear potentiometer
2. The calibration of the pressure rate applied by the PATTI pressure panel
3. The evaluation of the relative location of the pressure transducer to reduce the air pressure losses
4. The initial evaluation of the binder-aggregate response

Initial set of results are presented in figures M2c.6 and M2c.7.

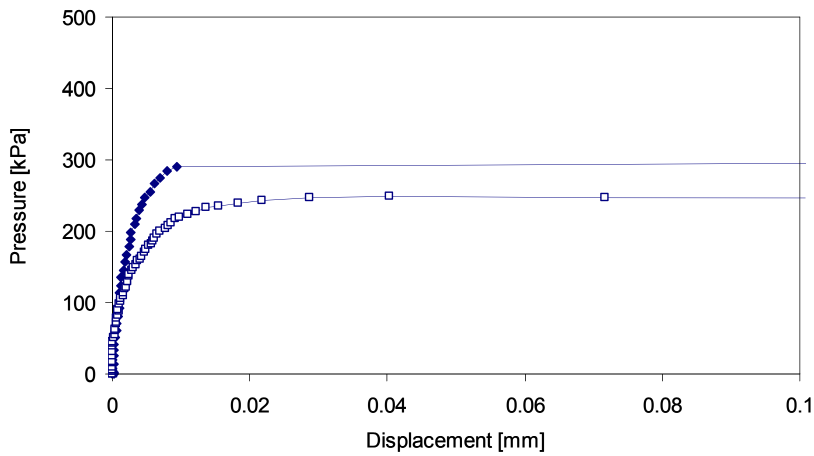


Figure M2c.6. Chart. Typical modified PATTI test results: PG 58-22 neat binder, glass plate test surface and slow and fast pressure rates.

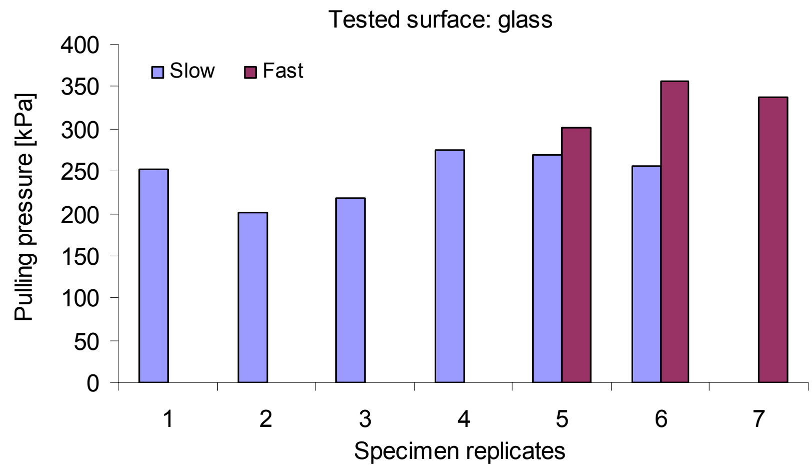


Figure M2c.7. Chart. Summary modified PATTI pulling pressure test results: PG 58-22 neat binder, glass plate test surface and slow and fast pressure rates.

Year 2 Work Plan

During Year 2, the research team at the University of Wisconsin-Madison will complete the validation of the modified PATTI test methodology and will further evaluate the results by comparing binder-aggregate system behavior with results using the DSR testing methodology. Additional tests will be performed using different mastics. If the methodology is validated, efforts will be placed on evaluating moisture damage with the modified PATTI test.

The analysis methodology proposed is a statistical evaluation of the tested parameters. PATTI tests have problems with repeatability: the evaluation of the maximum pullout pressure, the energy dissipated, and failure type (adhesion vs. cohesion) variability during testing allow identification of spurious events and affect the quality of the data. Once the validity of the testing results is confirmed, material behavior will be evaluated. Moisture damage studies will be performed to evaluate material behavior with the proposed new methodology. Emphasis will be placed on the evaluation of the conditioning environment and surface mineralogy on the strength and failure mechanism of the aggregate-binder system.

Figure M2c.8 depicts the research approach defined for this work element.

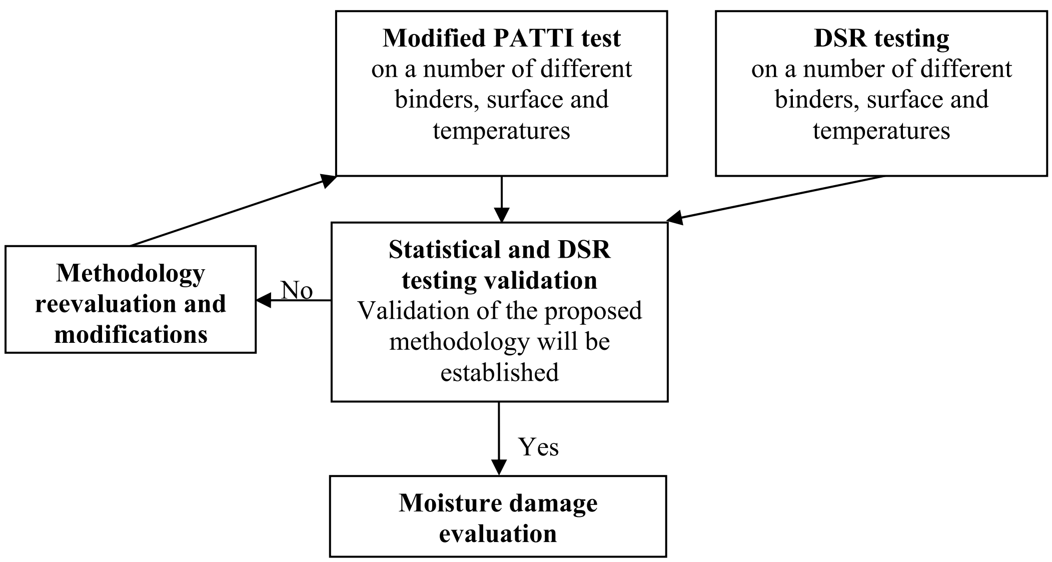


Figure M2c.8. Chart. Flow chart for research approach.

Year 2 Milestones

- Complete report on review of literature for rutting of asphalt binders and asphaltic mixtures
- Finalize material selection and experimental plan

- Conduct the proposed tests on asphalt binders and prepare for mix tests
- Develop framework for emulsion selection and design of surface treatments

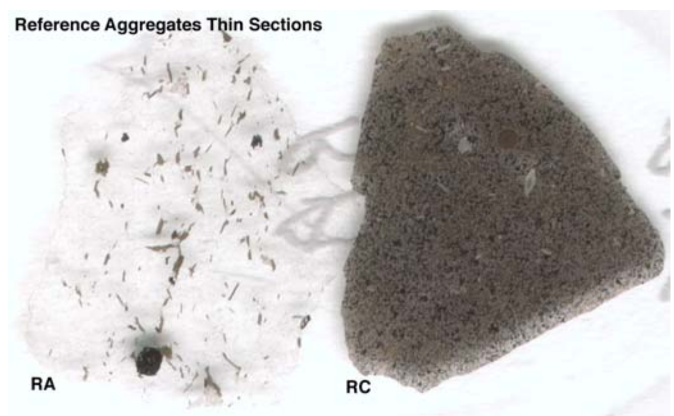
<u>Budget</u>

The estimated budget for this subtask is $350,000 over the four years. The work will be conducted by the University of Wisconsin-Madison.

Category M3: Aggregate Surface

Work Element M3a: Aggregate Surface

Physical and chemical properties of aggregates at the macro and micro scale influence the performance of asphalt mixtures. These properties control the nature and durability of the bond between the aggregates and the bitumen in wet and dry conditions and its resistance to moisture induced damage and fatigue cracking.



Recent research by Little and colleagues (Little and Bhasin 2006) has shown that surface energy of the aggregate-bitumen interface is a reliable predictor of engineering properties of the asphalt mixture. Current understanding of the aggregate and bitumen properties that control and shape surface energy is limited, limiting our ability to *a priori* predict surface energy of any given aggregate-bitumen combination. We propose to develop a predictive model of aggregate surface energy based upon a linear additive model of the surface energies of individual minerals that compose the aggregates. While aggregate properties are very heterogeneous, most aggregates are composed of a relatively few minerals (table M3a.1). The image to the right shows thin sections of two common aggregates. The images clearly show the mineralogical heterogeneity of the aggregates.

Our task will be to characterize the chemical properties of representative minerals given in table M3a.1 using elemental mapping by electron microprobe, backscatter electron spectroscopy and X-ray dispersive spectroscopy.

Table M3a.1. Chemical and mineralogical properties of common aggregates.

Mineral	Group	Chemical Formula	Occurrence
Microcline	Feldspar	$KAlSi_3O_8$	
Na-Plagioclase	Plagioclase Feldspar[1]	$NaAlSi_3O_8$	Dominant feldspar in andesite, an igneous rocks. Minor component in granite and metamorphic rocks.
Labradorite	Plagioclase Feldspar[1]	$Ca_{(0.5-0.7)}Na_{(0.3-0.5)}(Al,Si)AlSi_2O_8$	
Andesine	Plagioclase Feldspar[1]	$Na_{(0.5-0.7)}Ca_{(0.3-0.5)}(Al,Si)AlSi_2O_8$	Dominant feldspar in andesite, an igneous rocks. Minor component in granite and metamorphic rocks.
Olivine[2]	Nesosilicates	$(Mg,Fe)_2SiO_4$	Olivine is found in ultramafic igneous rocks and marbles that formed from metamorphosed impure limestones.
Augite	Pyroxene	$(Ca,Na)(Mg,Fe,Al)(Al,Si)_2O_6$	An important rock-forming mineral in many igneous rocks, especially in gabbros and basalts. Augite is also found in some hydrothermal metamorphic rocks.
Hornblende[3]	Amphibole	$Ca_2(Mg,Fe,Al)_5(Al, Si)_8O_{22}(OH)_2$	An important rock-forming mineral in many igneous rocks, especially in gabbros and basalts.
Ilmenite	Oxyhydroxides	$FeTiO_3$	Ilmenite forms as a primary mineral in mafic igneous rocks
Magnetite	Oxyhydroxides	Fe_3O_4	
Dolomite	Carbonates	$CaMg(CO_3)_2$	A common sedimentary rock-forming mineral, dolomitic limestone.

[1] The plagioclase series comprises minerals that range in chemical composition from pure NaAlSi3 O8, Albite to pure CaAl2 Si2 O8, anorthite. Andesine by definition must contain 70-50% sodium to 30-50% calcium in the sodium/calcium position of the crystal structure.

[2] Olivine is actually a name for a series between two end members, fayalite and forsterite. Fayalite is the iron rich member with a pure formula of Fe2SiO4. Forsterite is the magnesium rich member with a pure formula of Mg2SiO4.

[3] Hornblende is actually the name given to a series of minerals that are rather difficult to distinguish by ordinary means. The iron, magnesium and aluminum ions can freely substitute for each other and form what have been distinguished as separate minerals. The minerals are given the names Magnesio-hornblende, Ferrohornblende, Alumino-ferro-hornblende and Alumino-magnesio-hornblende.

Steps involved in the detailed characterization of the aggregates:

i. Examine a comprehensive range of representative aggregate materials to determine mineralogical content, grain size and texture. This will initially be done by optical petrography techniques (polished thin sections), followed by elemental distribution maps acquired on an electron microprobe using wavelength-dispersive (WDS) X-ray as well as backscattered electron (BSE) signals. The compositions of the individual aggregate minerals will then be determined by quantitative individual-point X-ray WDS analyses on the electron microprobe.
ii. Based on the mineralogy of the aggregates, acquire suitable individual mineral reference materials for further testing. These minerals will include both compositional end-members and intermediate members of the common rock forming minerals found in the aggregate materials. For example, in the plagioclase feldspar series, nearly pure Na plagioclase (albite), Ca plagioclase (anorthite) and intermediate Na-Ca plagioclase compositions (andesine, and/or labradorite, etc.) will be acquired and analyzed so that these individual well-characterized mineral components can be used in some of the aggregate-asphalt experiments.

Examples of properties of aggregates that will be characterized include:

- specific surface area for different size fractions,
- major mineralogical composition,
- chemical composition (major oxide) of minerals, and
- concentration of water and acid solubles.

Results from this task will also be extremely useful to explain mechanisms from other tasks such as effect of binder aging on the properties of the binder-aggregate interface.

<u>Year 2 Milestones</u>

Specimens for representative mineral phases identified in this task will be collected from different sources. Purity of the specimens will be established by testing them for their mineralogical composition using electron microprobing and other techniques. The specific surface area and surface free energy of the minerals will be determined.

Category M4: Modeling

The modeling efforts and approaches will be similar to those discussed in the fatigue work plan. These approaches are summarized here for completeness.

Work Element M4a: Micromechanics Model

Similar to the fatigue work plan, it is envisioned that the lattice and cohesive zone models will be the primarily methods to develop the micromechanical analysis framework. The asphalt mix microstructure will be captured using X-ray CT imaging at multiple resolutions. The measured material properties with the influence of moisture (adhesive and cohesive bonds, viscoelastic properties) will be assigned to the various constituents of the microstructure. Furthermore, multi-scale methods can be applied in order to link the experimental measurements conducted at constituent-level scales to the global scale where damage-associated performance behavior of asphaltic composites induced by moisture effects will be modeled.

Major Findings from Year 1 for Work Element M4a

An extensive review of the micromechanics-based computational models to characterize damage-dependent behavior of asphalt materials and mixtures was conducted by ARC researchers at the University of Nebraska. Some of the findings from this review are:

i. The model developed needs to be the one that can successfully represent material properties (viscoelastic properties) and fracture behavior (both adhesive and cohesive fracture) influenced by moisture effects.
ii. The model parameters should be obtainable from well-designed testing protocols which are based on theoretical rigor and also practically applicable. Other tasks associated with the development of testing methods in this project need to be closely incorporated with this modeling effort.
iii. For a more accurate characterization and modeling of damage in asphaltic materials, inelastic (e.g. viscoelastic) fracture should be included in the process. Asphalt demonstrates a significant complexity of rate-dependent and inelastic damage behavior.
iv. In order to better simulate heterogeneity and corresponding interactions among mixture components in the asphalt mixture, the concept of micromechanics with the aid of computational techniques (such as the finite element method) and advanced image analysis techniques (e.g. X-ray CT imaging) should be pursued.
v. The model being developed at the University of Nebraska is based on the cohesive zone concept to simulate initiation and propagation of viscoelastic damage. This approach looks reasonable, since the cohesive zone modeling can be applied to both cohesive and adhesive fracture within the same theoretical-numerical framework. An appropriate modification and/or improvement to the current model would provide a tool to predict the inelastic damage incorporated with the moisture effects.

Year 2 Milestones for Work Element M4a

i. Continue the literature review related to the micromechanics-based computational modeling techniques.
ii. Modify and/or elaborate the current cohesive zone model to incorporate fracture and damage characteristics including moisture effects so that the model can be better fit with material and damage properties that will be measured and provided by the TAMU and UWM.

Work Element M4b: Analytical Fatigue Model for Mixture Design

The same fracture model developed for fatigue will be used here. The main difference is that the model will include parameters that are obtained from testing specimens subjected to moisture conditioning. The model accounts for the energy dissipated in fracture, energy dissipated in permanent deformation, physio-chemical properties of mixture (adhesive and cohesive bonds), and viscoelastic properties (Masad et al. 2006). This model can also be used to analyze experimental measurements conducted on the mastic and fine portions of the mixture using the dynamic mechanical analysis and on full mixtures using repeated loading. As discussed in the fatigue work plan, the testing protocols will be developed under work element F2b and F2c. In the Moisture work plan, we will develop the methods for moisture conditioning of mastic, FAM and mixture specimens.

Major Findings from Year 1 for Work Element M4b

During the first year, the researchers developed a fracture model that accounts for mixture viscoelastic properties and bond energy. These model parameters vary based on the material state (dry versus wet). The model was demonstrated to capture the influence of changes in materials and volumetrics (mixture design) on moisture susceptibility. This model was extended to account for the probability of failure as a function of loading cycles. The fracture model was also extended to account for the nonlinear viscoelastic response of asphalt mixtures in dry and wet states.

Year 2 Milestones from Year 1 for Work Element M4b

The research in Year 2 will focus on the development of a damage nonlinear-viscoelastic model for the analysis of fatigue response of asphalt mixtures under dry and wet states. This model is an extension of the fracture model that was developed during Year 1. However, it has the advantage that it is a constitutive model that can be formulated in the general three dimensional form that can be implemented in a numerical scheme for the analysis of performance under various loading and boundary conditions.

Work Element M4c: Unified Continuum Model

The unified continuum model described in the fatigue plan will be further developed in order to account for the effects of moisture. This will be achieved by solving the coupling between the fluid flow equations and the constitutive equations that govern the mixture mechanical behavior. The fluid flow equations will be solved to determine the moisture distribution within the mixture. The constitutive equations will be solved to determine the mechanical behavior given the moisture presence in the mixture.

Moisture will be treated as an external variable that influence the evolutions of the model's parameters and functions. The model yield surface will evolve as a function that combines stresses (hydrostatic and deviatoric) and moisture content. All the model parameters will be determined by testing specimens after moisture conditioning. This approach is similar to developments in geo-environmental studies that account for the coupling between the concentration of chemicals and the constitutive behavior of geomaterials. The presence of moisture in asphalt mixtures will be modeled analogous to the presence of chemicals in geomaterials.

The basics for developing the continuum model with the effect of moisture are documented in the literature. In the past few years, considerable developments have been achieved in coupling the chemical reactions with the performance of geomaterials (Hueckel 2002). In the asphalt pavement area, researchers have developed numerical models for the simulation of fluid flow in the asphalt mixture microstructure (Al-Omari and Masad 2004 and Kutay et al. 2007). The researchers at Delft have made significant advances in developing a model that couples the fluid flow equations with the constitutive equations governing the mechanical behavior (Kringos and Scarpas 2005, 2006). The processes that are considered in the Delft model are summarized in table M4c.1. This work element will build on recent advances by focusing on making the improvements listed in table M4c.2.

Major Findings from Year 1 for Work Element M4c

Most of the components of the continuum model have been implemented in finite element. The model includes a nonlinear viscoelastic component and a viscoplastic component. However, the influence of moisture on the model parameters and response has not been accounted for yet.

Year 2 Milestones for Work Element M4c

The model will be fully implemented in finite element during the second year. It will be evaluated using based on its ability to predict experimental measurements conducted at TAMU and NC-State on various mixtures during the past three years. It addition, the researchers will utilize the comprehensive testing database available at the University of Nottingham to validate and calibrate the model. The model verification during the second year will focus on the tests conducted on dry mixtures.

Table M4c.1. Processes simulated in the model of moisture damage of Kringos and Scarpas (2005, 2006).

Damage process	Description	Comments
Desorption of the mastic (process 1)	Loss of mastic that is washed away by a non-stationary flow (advective flow). The process occurs in a short timescale and affects the outer layers of the binder that surround the aggregates.	Macroscopic phenomenon. Advective transport will not occur without flow.
Dispersion of the mastic (advective dispersion) (process 2)	Deterioration in the material's cohesive bond (loss of concentration or dispersion) caused by moisture diffusion into mastic. The process occurs on a long timescale.	Microscopic phenomenon. Requires the presence of a water flow field although the process is dominated by the diffusion coefficients of the material.
Deterioration of the aggregate-binder interface (process 3)	Long term process due to a combined effect of moisture diffusion and mechanical loading.	Microscopic phenomenon. An energy-based model was developed to include moisture content as a control parameter.

Table M4c.2. Accomplishments of the current model and future work.

Accomplishments	Future work
Mathematical formulation of fluid flow in asphalt mixtures using two different methodologies	Calibrate current models.
Mathematical formulation of three important processes related to moisture damage	Include more complex and realistic geometry.
Successful numerical implementation of aforementioned processes	Include pore pressure and any other relevant effects.
Simulation of damage with a mechanical and thermodynamic coupled model	Analyze moisture damage processes in different types of mixtures.
Better understanding of moisture damage mechanisms in open graded friction courses	Analyze the validity of the current damage evolution law and consider new formulations for coupling micro- or mesodamage with macrodamage.
	Determine the relevance of material properties in terms of the time required for the manifestation of damage.

Category M5: Moisture Damage Prediction System

This work element will be performed in close coordination with other agencies in the Technology Development work area of this Consortium. Accordingly, some part of the budget for this work element has been allocated in the Technology Development work area.

This task will develop a moisture damage prediction system that will consist of the following components:

i. A method for the selection of materials with good resistance to moisture damage. This method is based on the components of surface energy of asphalt binders and aggregates.
ii. An experimental method that accounts for the resistance of asphalt mastic and fine portion of the mixture to moisture damage. This will be done primarily using the dynamic mechanical analyzer.
iii. An experimental method for measuring the resistance of the full mixture to moisture damage.
iv. Models that account for the material, microstructure, and loading factors that affect moisture damage.

RELATIONSHIP TO FHWA FOCUS AREAS

The moisture damage work elements support the FHWA Focus Area of Optimizing Pavement Performance by providing a relationship between material property and pavement performance.

BUDGET

		Year 1	Year 2	Year 3	Year 4	Year 5
M1a	Affinity of Asphalt to Aggregate - Mechanical Tests (UWM)	75,000	75,000	75,000	75,000	
M1b	Work of Adhesion (TAMU)	75,000	75,000	50,000	50,000	25,000
	Work of Adhesion (WRI)		134,500	146,000	152,500	126,500
M1c	Quantifying Moisture Damage Using DMA (TAMU)		75,000	75,000	100,000	75,000
M2a	Work of Cohesion Based on Surface Energy (TAMU)	75,000	75,000	75,000		
	Work of Cohesion Based on Surface Energy (WRI)		134,500	146,000	152,500	126,500
M2b	Impact of Moisture Diffusion in Asphalt (TAMU)	75,000	150,000	150,000	175,000	
M2c	Thin Film Rheology and Cohesion (UWM)	75,000	100,000	75,000	75,000	
M3a	Impact of Surface Structure of Aggregate (TAMU)	75,000	100,000	125,000		
M4a	Development of Model (TAMU)		125,000	125,000	125,000	150,000
M5a	Moisture Damage Prediction System*				150,000	150,000
TOTAL		450,000	1,044,000	1,042,000	1,055,000	653,000
		4,244,500				

Note* Tentatively only budget from TAMU is reflected here but this element will involve coordination from all agencies.

CITED AND RELATED REFERENCES

Al-Omari, A., and E. Masad, 2004, Three Dimensional Simulation of Fluid Flow in X-ray CT Images of Porous Media. *International Journal for Numerical and Analytical Methods in* Geomechanics, 28: 1327-1360.

ASTM, 2002, "D 4541 – 02 Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers." *American Society of Testing and Materials*. 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959, United States.

Bhasin, A., and D. N. Little, 2006, Application of Micro-Calorimeter to Characterize Adhesion Between Asphalt Binders and Aggregates. *Journal of Materials in Civil Engineering*, in review.

Cho, D.-W., and H. Bahia, 2007, Effects of Aggregates' Surface and Water on Rheology of Asphalt Film. Accepted to the *Transportation Research Record*, 2007.

Creton, C., and H. Lakrout, 2000, Micromechanics of Flat Probe Adhesion Tests of Soft Visocelastic Polymer Films. *Journal of Polymer Science: Part B: Polymer Physics*, 38: 965-979.

Hueckel, T., 2002, Reactive Plasticity for Clays during Dehydration and Rehydration. Part I: Concepts and Options. *International Journal of Plasticity*, 18(3): 281-312.

Kanitpong, K., and H. Bahia, 2003, Role of Adhesion and Thin Film Tackiness of Asphalt Binders in Moisture Damage of HMA. *Journal of the Association of Asphalt Paving Technologists*, 72: 502-528.

Kawashita, L. F., D. R. Moore, and J. G. Williams, 2006, Protocols for the Measurement of Adhesive Fracture Toughness by Peel Tests. *Journal of Adhesion*, 82(10), 973-995.

Kringos, N., and A. Scarpas, 2005, Raveling of Asphaltic Mixes Due to Water Damage: Computational Identification of Controlling Parameters. *Transportation Research Record*, 1929, 79-87.

Kringos, N., and A. Scarpas, 2006, Numerical Simulation of the Physical Processes Inducing Moisture Damage in Asphaltic Mixtures. *Proc., 10th International Conference on Asphalt Pavements (ICAP)*, Quebec, Canada, 732-741.

Kutay, E. M., M. Aydilek, E. Masad, and T. Harman, 2007, Evaluation of Hydraulic Conductivity Anisotropy in Asphalt Specimens. *International Journal of Pavement Engineering*, 8(1), 29-43.

Little, D. N., and A. Bhasin, 2006, Using Surface Energy Measurements to Select Materials for Asphalt Pavement. *Final Report for NCHRP Project 9-37*, Transportation Research Board, Washington D.C.

Masad, E., C. Zollinger, R. Bulut, D. Little, and R. Lytton, 2006, Characterization of HMA Moisture Damage Using Surface Energy and Fracture Properties. *Journal of the Association of Asphalt Paving Technologists,* 75: 713-748.

Nguyen, T., E. Byrd, D. Bentz, and J. Seiler, 1996, Development of a Method for Measuring Water-Stripping Resistance of Asphalt/Siliceous Aggregate Mixtures. NISTIR 5865, National Institute of Standards and Technology, Gaithersburg, MD.

Shull, K. R., 2002, Contact Mechanics and the Adhesion of Soft Solids. *Material Science and Engineering, R.*, 36(1), 1-45.

Youtcheff, J., and V. Aurilio, 1997, Moisture Sensitivity of asphalt Binders: Evaluation and Modeling of the Pneumatic Adhesion test Results. *Proc., Canadian Technical Asphalt Association*.

Moisture Damage Year 2

		Year 2 (4/08-3/09)											
		4	5	6	7	8	9	10	11	12	1	2	3
Adhesion													
M1a	**Affinity of Asphalt to Aggregate - Mechanical Tests**												
M1a-1	Select Materials						DP						
M1a-2	Conduct modified DSR tests					P					P		
M1a-3	Evaluate the moisture damage of asphalt mixtures												DP
M1a-4	Correlate moisture damage between DSR and mix tests												
M1a-5	Propose a Novel Testing Protocol												
M1b	**Work of Adhesion**												
M1b-1	Adhesion using Micro calorimeter and SFE												
M1b-2	Evaluating adhesion at nano scale using AFM												
M1b-3	Mechanisms of water-organic molecule competition												JP,D
M1c	**Quantifying Moisture Damage Using DMA**												
Cohesion													
M2a	**Work of Cohesion Based on Surface Energy**												
M2a-1	Methods to determine SFE of saturated binders												
M2a-2	Evaluating cohesion at nano scale using AFM												
M2b	**Impact of Moisture Diffusion in Asphalt**												
M2b-1	Diffusion of moisture through asphalt/mastic films											JP,D	
M2b-2	Kinetics of debonding at binder-agreagte interface											JP,D	
M2c	**Thin Film Rheology and Cohesion**												
M2c-1	Evaluate load and deflection measurements using the modified PATTI test		DP		JP					D			F
M2c-2	Evaluate effectiveness of the modified PATTI test for Detecting Modification									D	DP		F
M2c-3	Conduct Testing												
M2c-4	Analysis & Interpretation												P
M2c-5	Standard Testing Procedure and Recommendation for Specifications												
Aggregate Surface													
M3a	**Impact of Surface Structure of Aggregate**												
M3a-1	Aggregate surface characterization												
Models													
M4a	**Development of Model**												
M4a-1	Micromechanics model development										JP		
M4a-2	Analytical fatigue model for use during mixture design												
M4a-3	Unified continuum model												

LEGEND

Deliverable codes	**Deliverable Description**
D: Draft Report	Report delivered to FHWA for 3 week review period.
F: Final Report	Final report delivered in compliance with FHWA publication standards
M&A: Model and algorithm	Mathematical model and sample code
SW: Software	Executable software, code and user manual
JP: Journal paper	Paper submitted to conference or journal
P: Presentation	Presentation for symposium, conference or other
DP: Decision Point	Time to make a decision on two parallel paths as to which is most promising to follow through
[x]	Indicates completion of deliverable x

Work planned
Work completed
Parallel topic

	Moisture Damage Year 2 - 5	Year 2 (4/08-3/09)				Year 3 (4/09-3/10)				Year 4 (04/10-03/11)				Year 5 (04/11-03/12)			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Adhesion																	
M1a	**Affinity of Asphalt to Aggregate - Mechanical Tests**																
M1a-1	Select Materials		DP														
M1a-2	Conduct modified DSR tests		P		P												
M1a-3	Evaluate the moisture damage of asphalt mixtures				DP		P			P							
M1a-4	Correlate moisture damage between DSR and mix tests						P		P								
M1a-5	Propose a Novel Testing Protocol				P				P				JP, F				
M1b	**Work of Adhesion**																
M1b-1	Adhesion using Micro calorimeter and SFE						JP				JP,F						
M1b-2	Evaluating adhesion at nano scale using AFM							JP					JP				JP, F
M1b-3	Mechanisms of water-organic molecule competition				JP,D	F					JP	D	F				
M1c	**Quantifying Moisture Damage Using DMA**										JP	D	F				
Cohesion																	
M2a	**Work of Cohesion Based on Surface Energy**																
M2a-1	Methods to determine SFE of saturated binders														JP		
M2a-2	Evaluating cohesion at nano scale using AFM							JP					JP				JP, F
M2b	**Impact of Moisture Diffusion in Asphalt**																
M2b-1	Diffusion of moisture through asphalt/mastic films				JP,D	F					JP	D	F				
M2b-2	Kinetics of debonding at binder-agreagte interface				JP,D	F											
M2c	**Thin Film Rheology and Cohesion**																
M2c-1	Evaluate load and deflection measurements using the modified PATTI test	DP	JP	D	F												
M2c-2	Evaluate effectiveness of the modified PATTI test for Detecting Modification			D	DP,F												
M2c-3	Conduct Testing						JP										
M2c-4	Analysis & Interpretation				P						D, JP		F				
M2c-5	Standard Testing Procedure and Recommendation for Specifications											D	P,F				
Aggregate Surface																	
M3a	**Impact of Surface Structure of Aggregate**																
M3a-1	Aggregate surface characterization																
Models																	
M4a	**Development of Model**																
M4a-1	Micromechanics model development				JP				JP				M&A	D	DP	F, SW	
M4a-2	Analytical fatigue model for use during mixture design															M&A,D	F
M4a-3	Unified continuum model								JP				M&A	D	DP	F, SW	

LEGEND

Deliverable codes	Deliverable Description
D: Draft Report	Report delivered to FHWA for 3 week review period.
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SW: Software	Executable software, code and user manual
JP: Journal paper	Paper submitted to conference or journal
P: Presentation	Presentation for symposium, conference or other
DP: Decision Point	Time to make a decision on two parallel paths as to which is most promising to follow througjh
[x]	Indicates completion of deliverable x

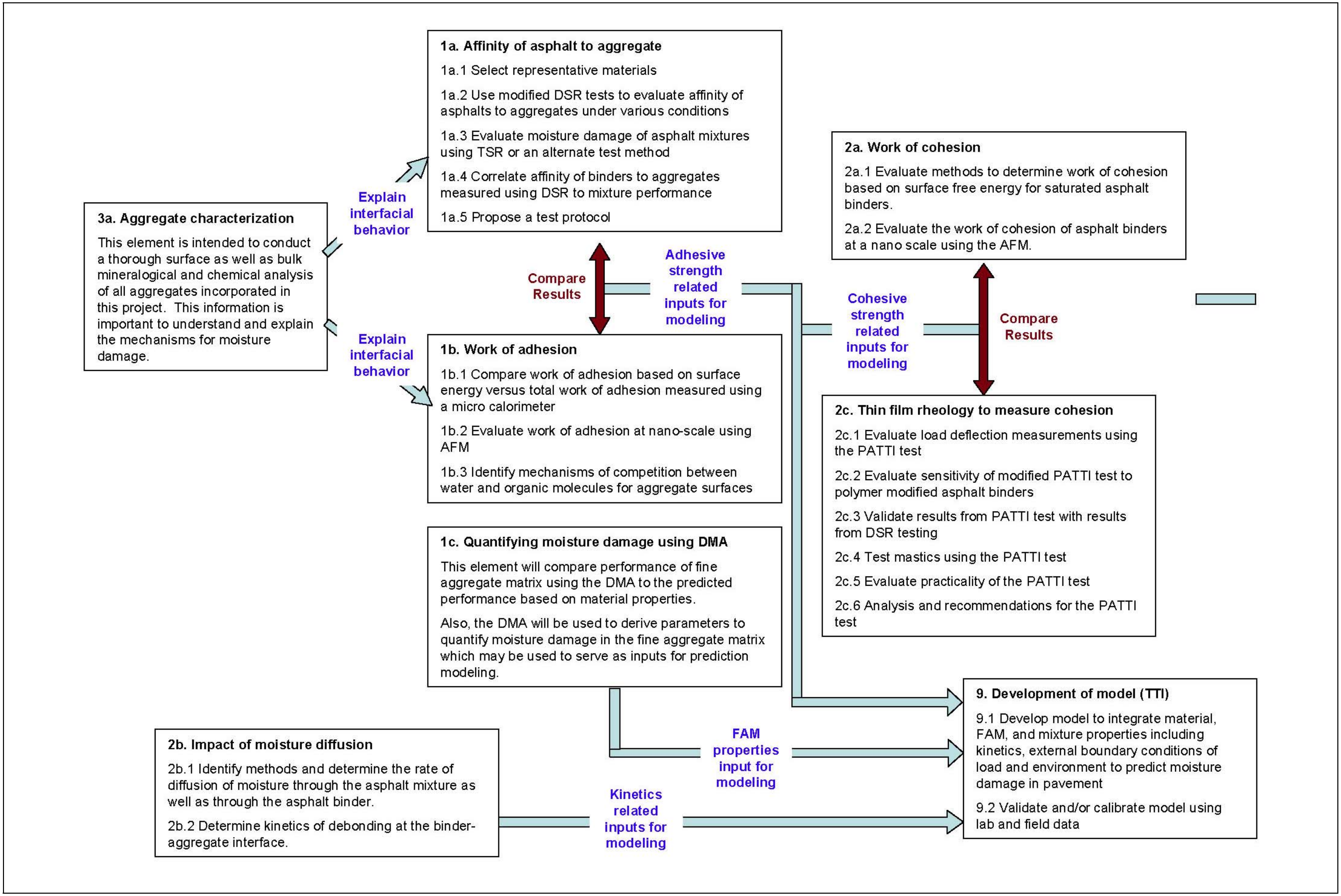
Work planned

Work completed

Parallel topic

Appendix M1

Flow Chart Illustrating Integration of Elements
for
Moisture Damage Work Area


1a. Affinity of asphalt to aggregate
1a.1 Select representative materials
1a.2 Use modified DSR tests to evaluate affinity of asphalts to aggregates under various conditions
1a.3 Evaluate moisture damage of asphalt mixtures using TSR or an alternate test method
1a.4 Correlate affinity of binders to aggregates measured using DSR to mixture performance
1a.5 Propose a test protocol
2a. Work of cohesion
2a.1 Evaluate methods to determine work of cohesion based on surface free energy for saturated asphalt binders.
2a.2 Evaluate the work of cohesion of asphalt binders at a nano scale using the AFM.
3a. Aggregate characterization
This element is intended to conduct a thorough surface as well as bulk mineralogical and chemical analysis of all aggregates incorporated in this project. This information is important to understand and explain the mechanisms for moisture damage.
Explain interfacial behavior
Explain interfacial behavior
Compare Results
Adhesive strength related inputs for modeling
Cohesive strength related inputs for modeling
Compare Results
1b. Work of adhesion
1b.1 Compare work of adhesion based on surface energy versus total work of adhesion measured using a micro calorimeter
1b.2 Evaluate work of adhesion at nano-scale using AFM
1b.3 Identify mechanisms of competition between water and organic molecules for aggregate surfaces
2c. Thin film rheology to measure cohesion
2c.1 Evaluate load deflection measurements using the PATTI test
2c.2 Evaluate sensitivity of modified PATTI test to polymer modified asphalt binders
2c.3 Validate results from PATTI test with results from DSR testing
2c.4 Test mastics using the PATTI test
2c.5 Evaluate practicality of the PATTI test
2c.6 Analysis and recommendations for the PATTI test
1c. Quantifying moisture damage using DMA
This element will compare performance of fine aggregate matrix using the DMA to the predicted performance based on material properties.
Also, the DMA will be used to derive parameters to quantify moisture damage in the fine aggregate matrix which may be used to serve as inputs for prediction modeling.
9. Development of model (TTI)
9.1 Develop model to integrate material, FAM, and mixture properties including kinetics, external boundary conditions of load and environment to predict moisture damage in pavement
9.2 Validate and/or calibrate model using lab and field data
FAM properties input for modeling
2b. Impact of moisture diffusion
2b.1 Identify methods and determine the rate of diffusion of moisture through the asphalt mixture as well as through the asphalt binder.
2b.2 Determine kinetics of debonding at the binder-aggregate interface.
Kinetics related inputs for modeling

PROGRAM AREA: FATIGUE

This work plan for year 2 of the Asphalt Research Consortium (ARC) was prepared by revising the five year work plan submitted in May of 2007. In that work plan the first year work effort was identified and emphasized within the five year plan. The same general approach was taken here with the second year work being emphasized. According to this approach, the overall work plan was modified in order to accommodate the feedback received from FHWA on the year 1 work plan, reflect accomplishments made in year 1 including revisions based on year 1 accomplishments and findings, and reflect the area of emphasis and milestones for year 2.

INTRODUCTION

The Fatigue Process

Fatigue damage is normally defined as incremental damage that occurs gradually in the pavement due to stresses induced by traffic loading. The fatigue cracking mechanism can be divided into two stages: initiation of cracks of sufficient length to grow under repeated loading and propagation of these cracks due to repeated loading. When a sufficient number of cracks develop within a wheel path, severe distress results and pavements quickly lose serviceability. However, fatigue may also manifest as permanent deformation or rutting in the wheel path. Such permanent deformation is traditionally considered to be due to plastic flow, but it can also be the result of weakening of the mixture due to a concentration of small cracks caused by a fatigue process. Researchers in the Asphalt Research Consortium (ARC) consider both of these mechanisms to be part of the fatigue process. We also consider recovery during rest periods to be part of the fatigue process or that the fatigue process is actually a balance between crack propagation on the one hand and healing on the other. Healing is quantified by the recovery of the mechanical ability of a material to store and release fracture energy and the result of healing is extended fatigue life. The reality and significance of the impact of healing during rest periods has been proven in previous WRI-directed research and is now well established in the literature by some of the most respected research entities in the world.

Complicating the fatigue process is the changing nature of the binder over time due to oxidative hardening in pavements. Evidence is mounting that binders oxidize in pavements, and well below the surface. This oxidation reduces healing, reduces stress relaxation of the binder, and increases binder stiffness. These combined material property changes result in a binder that is more susceptible to fatigue, a hypothesis that has been confirmed by laboratory mixture tests.

Research Needed to Better Understand and Evaluate Fatigue Damage

Historically fatigue damage has been quantified in the laboratory as the number of load cycles applied to a specimen that causes the specimen to fail due to crack growth. Such fatigue tests normally either apply the same level of stress at each load cycle (controlled-stress) or apply the same level of strain at each load cycle (controlled-strain). The consensus among materials and pavement engineers has been that thick, stiff pavements should be tested in a controlled-stress mode, while thin pavements should be tested in a controlled- strain mode. The results of these tests are hard to compare simply based on the number of cycles to failure. A pressing need has been to develop a unified method, based on sound mechanics, by which to evaluate both modes of fatigue testing. In addition to the mode of introducing load in a fatigue experiment, several other factors impact the fatigue damage characteristics of asphalt mixtures. These include adhesive and cohesive bond strengths within the mixture, anisotropy of the aggregate matrix, composition of the mastic portion (including interaction between mineral filler and asphalt), aging, and the ability of the mixture to recover during rest periods (healing). The WRI and Texas A&M research teams have demonstrated the importance of adhesive and cohesive bond strengths in the fatigue process. Further, they have developed protocols to measure surface energies of the mixture components (binder and aggregate) from which bond strengths can be reliably calculated.

Recent work at Texas A&M has demonstrated that a unified model based on dissipated pseudo strain energy and fracture mechanics and including bond strength can indeed unify the stress-controlled and strain-controlled modes of loading. A first generation version of this approach has been developed and reported as a deliverable of research at Texas A&M under the recently completed WRI-led contract with FHWA (DTFH61-99C-00022). This approach is based on separating the dissipated pseudo strain energy measured during cyclic, torsional fatigue testing into the components associated with permanent deformation, change in the phase angle, and changes in stiffness among load cycles. It is critically important to finalize this analysis methodology and to validate the efficacy of this approach.

Work at Texas A&M has demonstrated that well-dispersed fillers (aggregate smaller than about 75 µm) substantially affect the growth of microcracks and that the effect of the fillers is determined by their mineralogy and physical properties. Healing during rest periods has a profound impact on fatigue life and also impacts the potential for mixtures to exhibit an endurance limit. Research at Texas A&M has shown that the healing process is related to the filler properties of the mastic and the adhesive and cohesive bond strengths of the mixture. This work needs to be completed and expanded.

Of course, when studying the fatigue damage process, it is absolutely necessary to consider the impact of moisture. Moisture affects the cohesive strength of the mastic as well as the bond strength between the asphalt binder and/or mastic and the aggregate particles. The ability to measure surface energy and to calculate cohesive and adhesive bond strengths (dry and in the presence of moisture) has provided a tool by which to scientifically investigate the effects of moisture on fatigue. We will focus on the asphalt -aggregate interaction as it affects the fatigue process, dry and in the presence of moisture. We will also focus on the impact of moisture on the cohesive bond strength of the mastic. In fact two major concept areas within the ARC project (Moisture Damage and Fatigue Damage) will work "hand-in-hand" for the duration of the ARC to synergistically consider the mechanisms of damage due to moisture and load-induce fatigue.

This research must remain focused on the deliverables that the ARC is committed to provide. In the area of fatigue, the ARC is committed to provide tools capable of assessing the fatigue damage process and of identifying specific factors that influence fatigue damage, i.e., aggregate properties, binder properties, mixture volumetrics, presence of moisture, filler type, etc. We are committed to developing and delivering predictive models that rely on the fundamentals of integrated fracture mechanics, micromechanics, and elasto-visco-plastic continuum damage mechanics. We are also committed to developing the most promising characterization tools into ASTM and AASHTO type specifications. One such tool that continues to surface as an excellent method by which to assess fatigue damage potential, the impact of rest periods, the impact of moisture, and the impact of fillers is dynamic mechanical analysis (DMA). Our goal is to develop this into a guideline type specification test in the second year of the grant.

Other tests that have been proven to be useful in characterizing the bond strength in asphalt mixtures are the Wilhelmy plate, universal sorption device, sessile drop apparatus and the micro-calorimeter. We will continue to develop these test methods in order to deliver practical and easy-to-use test methods that can be integrated into the routine analysis of asphalts and aggregates. We will work closely with FHWA in order to determine the relationship between bond energy and compliance calculations and more direct measurements of bond strength such as the pull-off test being developed at FHWA.

In this research, we will utilize the most recent technologies in imaging and nondestructive evaluation to understand the mechanisms of crack initiation and propagation in asphalt mastics and mixtures. In recent years, the research at Texas A&M has made significant strides in nondestructively measuring crack distribution and evolution in asphalt mixes using X-ray Computed Tomography and image analysis techniques. These measurements will be used in our efforts to validate the models that will be developed by the Consortium.

HYPOTHESES

Fatigue damage is the result of the growth of small cracks and voids to form larger cracks that result in damage. The initiation of cracks to a critical size and the propagation of these larger cracks can be successfully explained and evaluated based on the principles of viscoelasticity and viscoplasticity, dissipated pseudo strain energy, micromechanics, and fracture mechanics. A unified model of fatigue damage must be based on sound principles of mechanics and pertinent materials characteristics and must also consider adhesive and cohesive bond strengths of the mixture, the ability of the mixture to heal or recover damage between load cycles, the impact of the mixture's internal structure on stress distribution within the mixture, and the impact of moisture on mixture properties and the rate of damage and healing in the composite mixture, including the changes in all of these properties with oxidative aging. The damage model should be able to predict fatigue damage from the material properties discussed above and from the dissipated pseudo strain energy measurements derived from fatigue experiments whether they are performed in the controlled-stress or controlled-strain mode of loading.

OBJECTIVES

1. Develop a fundamental understanding of the material properties and mechanics associated with fatigue.

2. Develop a unified fatigue damage model that incorporates and integrates the important mixture properties and responses that affect fatigue life. These properties and responses include cohesive and adhesive bond strengths, viscoelastic properties, fracture properties, energy dissipation, cohesive and adhesive bond strengths, healing and/or recovery during rest periods, effect of binder aging, and the internal structure of the mixture composite. The unified model will be capable of evaluating fatigue when loading is applied in either the controlled-stress or controlled-strain mode.
3. Assess the impact of modification and aging on the binder and mastic and the impact of filler type and quantity on the mastic and/or fine aggregate matrix using the unified model.
4. Develop testing protocols for mixture, mastic, and binder characterization that provide the information required in the unified model for binder, fillers, mastic, and the total composite mixture.
5. Implement the unified fatigue damage model by integrating it into a numerical scheme to assess the fatigue behavior of mixtures under different laboratory and field boundary conditions.
6. Develop micromechanical models that are based on fundamental material properties and can be used to study the interaction among the mixture constituents and their influence on mixture performance. These micromechanical models will be used to relate the parameters of the unified fatigue model to material properties.
7. Verify the unified model using microstructural measurements of fatigue damage by monitoring crack evolution through such non-destructive techniques as computer assisted x-ray tomography.
8. Validate the unified model and testing methods through comparisons of predictions made based on the model and full scale field testing and evaluation of pavement test sites.
9. Develop component selection guidelines for perpetual pavements based on the unified approach.

These objectives will be achieved in coordination with other research activities on similar topics. Specifically, our research will be coordinated among all members of the ARC with other ongoing activities at the Federal Highway Administration (FHWA), LCPC in France, University of Nottingham in Britain, and Delft University in the Netherlands.

Our proposed research plan will complement and be coordinated with the current work at FHWA. The results from the accelerated loading facility (ALF) of the FHWA will be extremely useful to our validation efforts. This is a well controlled experiment with different modified and unmodified binders and different pavement structures. Furthermore, the advances made by the FHWA on binder characterization will be very useful for our research. The FHWA has shown that the binder behavior is highly nonlinear and the differentiation among asphalt binders can only be accomplished through considering the influence of stress level on response. Our fatigue modeling framework considers the nonlinear response of asphalt binders and mixtures among other important factors such as aging and healing effects. Our modeling approach is applicable to asphalt binders, asphalt mastics, and mixtures. Therefore, we plan to develop testing protocols for these materials. Specifically, we will focus on the development of a simple method for the characterization of binder fatigue resistance. This method needs to be simple, efficient, and capable of being implemented into binder specifications. This is necessary given the shortcomings of the current Superpave system in properly characterizing asphalt binders. We strongly believe that the concepts that have already been developed for characterizing fatigue in asphalt mixtures can be adopted, with proper modifications, to characterize binder fatigue resistance.

EXPERIMENTAL DESIGN

The development of an experimental design will be among the initial subtasks of each work element. The experiment design will be communicated to the AOTR before the work is begun on each work element, and each experimental design or plan will be approved and/or developed by the project statistician, who is in our case Dr. E. S. Park of the Department of Statistics at Texas A&M. Dr. Park has a research appointment with TTI and is very familiar with the design of experiments in asphalt related research. She has served as team statistician on several asphalt related research projects including NCHRP Project 9-37, "Using Surface Energy Measurements to Select Materials for Asphalt Mixtures".

The TTI team will use the Buckingham PI theorem of experiment design to identify dimensional ratios of material properties to minimize the size of the experiment and maximize the information to be obtained from them. This approach was used successfully in many fields of mechanics such as fluid flow and aerodynamics.

WORK ELEMENTS

Category F1: Material and Mixture Properties

The work in this category will focus on determining material properties that are needed for the development of the unified model and micromechanics models.

Work Element F1a: Cohesive and Adhesive Properties

<u>Subtask F1a-1: Critical Review of Measurement and Application of Cohesive and Adhesive Bond Strengths (Continued in year 2)</u>

Adhesive and cohesive bond strengths are fundamental material properties that can be used to model crack growth in asphalt materials both in wet as well as dry conditions. Work of adhesion between the asphalt binder and the aggregate and the work of cohesion of the asphalt binders can be determined using their individual surface energy components. Initial studies conducted under the FHWA contract DTFH61-99-C-00022 (Fundamental Properties of Asphalts and Modified Asphalts) demonstrated the feasibility of using this approach to model fatigue crack growth in asphalt mixtures. In a recently completed NCHRP project 9-37 (Little and Bhasin 2006) test protocols to determine surface free energy components of asphalt binders and aggregates were developed. The project results also included parameters based on surface energy measurements that may be used to select combinations of materials that are more resistant to moisture damage. The impact of modification due to aging, addition of fillers, addition of polymers, and/or chemical additives on the work of cohesion or adhesion was addressed in limited detail in these and other previous studies. There is a need to critically review the existing methods with respect to determining viscoelastic properties and work of adhesion or cohesion for use with modified asphalt binders.

There is a difference between the magnitudes of work of adhesion or cohesion computed using the thermodynamics approach (surface energy) versus these quantities determined using mechanical tests (commonly referred to as practical or mechanical work of adhesion or cohesion). Existing literature provides detailed information on the various sources of this difference for elastic as well as viscoelastic materials. Examples of sources for this difference are energy dissipation due to plastic deformation and branching and coalescence of microcracks (Sharon et al. 1996). It is important to review and reconcile the source of these differences in order to improve the fatigue crack growth model for asphalt mixtures.

The detailed literature review will be continued from year 1 to address following areas relevant to the cohesive and adhesive bond strengths of materials:

i. Need for revision and/or improvement of existing methods to determine work of adhesion and cohesion for modified asphalt binders and recommendations for changes or improvements that may be required.
ii. Experimental and analytical methods to determine the work of cohesion or adhesion using mechanical tests, including approaches based on contact mechanics.
iii. Sources of differences between thermodynamic work of adhesion or cohesion and mechanical work of adhesion or cohesion, and methods to account for these differences.
iv. Acid-base scale to determine the surface free energy components of asphalt binders and aggregates and use of an alternate scale that may improve the sensitivity of the measured surface energy components and is consistent with the use of dissipated energy partitions applied to fracture mechanics and viscoplasticity.
v. Effect of oxidative aging on the surface free energy components of the asphalt binder.

During year 1 of this project, researchers from the Texas A&M University visited University of Nottingham and Imperial College in the United Kingdom as a part of the “Collaborating for Success through People” program sponsored by the United Kingdom. Researchers from the Imperial College, London, led by Professor Kinloch, have pioneered the development of several industry standards that are used to determine the practical work of adhesion and cohesion for different polymeric adhesives. Professors Little and Masad from Texas A&M University had a detailed discussion on the recently developed methodologies and experience related to the use of test methods to determine the practical work of adhesion and cohesion with Professor Kinloch and his team (Subtask F1a-4). During year 2 of this project and part of year 3, there will be an exchange of researchers from these Universities for durations ranging from one to twelve weeks. This research exchange, sponsored by the “Collaborating for Success through People” program of UK will greatly benefit the Asphalt Research Consortium, particularly for this work element.

Subtask F1a-2: Develop Experiment Design (Continued in year 2)

A detailed experiment design will be developed to accomplish the objectives identified in the work element F1a. The first part of this experiment design will be comprised of adaptation and use of test methods developed at the Imperial College, London for asphalt binders (in conjunction with tests from task M2a-1). The test method will be further refined after the results of preliminary tests using this methodology.

Subtask F1a-3: Thermodynamic Work of Cohesion and Adhesion (Continued in year 2)

The work of adhesion and cohesion can be computed using surface energy components of the asphalt binder and the aggregate. This subtask will evaluate existing protocols to determine surface energy of modified asphalt binders as well as asphalt mastics. The work of adhesion and cohesion for several different types of binders and binder-aggregate combinations will also be determined in this subtask. This information will be used in the subsequent subtasks to provide the mechanical work of adhesion and cohesion as inputs for the micro-mechanics and continuum fatigue model.

In summary, the following analytical and experimental elements are envisioned in this subtask:

i. Previous research at the Texas A&M University has led to the development of detailed test protocols to measure the surface free energy components of asphalt binders (Bhasin and Little 2006; Hefer et al. 2006). However, these protocols were developed based on neat asphalt binders. In year 1 of this project, existing protocols to determine surface energy components for modified asphalt binders and mastics were assessed. Preliminary tests were also conducted to determine the surface free energy components of polymer modified asphalt binders using the Wilhelmy plate method. Researchers were able to obtain smooth surfaces for polymer modified binders by separation of the polymer phase after it has physio-chemically interacted with the binder matrix. Researchers are currently evaluating the use of this methodology for asphalt mastics. This methodology will be further developed in year 2 and-results will be cross-examined using analytical methods and alternate experimental techniques such as the static sessile drop method.

ii. In year 2, the revised test protocol to measure surface free energy as well as guidelines to use and interpret these measurements for modified asphalt binders and mastics will be finalized.

iii. Measure surface free energy of selected unmodified and modified binders (including aged binders) and mastics using the Wilhelmy plate device. The recommended protocols from the aforementioned subtask will be used for these measurements. The common materials library for the ARC will be used to select binders for these measurements.

iv. Measure surface energy of selected unmodified and surface treated aggregates using the Universal Sorption Device (USD). A common example of surface treatment of aggregates that effects the aggregate-binder work of adhesion is application of hydrated lime slurry to the aggregate surface. The common materials library for the ARC will be used to select aggregates for these measurements.

v. Determine the thermodynamic work of adhesion and cohesion for different combinations of asphalt binders, mastics, and aggregates using their individual surface energy components.

Subtask F1a-4: Mechanical Work of Adhesion and Cohesion

Sources of energy dissipation on a larger scale, such as plastic energy and micro branching, also contribute to the work required for cohesive fracture in asphalt binders or mastics, albeit the energy dissipated from these additional sources is related to the work of cohesion due to surface free energy of the binder. The contribution of these secondary sources to the total work of adhesion and cohesion will be investigated in this subtask using a combination of analytical and experimental methods. The experimental methods will be developed in coordination with tasks under element F2a and M2a-1.

In summary, the following analytical and experimental elements are envisioned in this subtask:

i. Identify and develop protocols for one or two test methods based on the literature review from 1a-1 to determine the material viscoelastic properties and mechanical work of adhesion and cohesion.
ii. Determine the viscoelastic properties and work of cohesion and adhesion for different asphalt binders and binder-aggregate combinations using the selected test method(s).
iii. Develop a model to enable back calculation of the work of adhesion or cohesion from the mechanical tests, incorporating the influence of film thickness and viscoelastic effects.
iv. Reconcile the effect of scale and other energy dissipation mechanisms and develop the relationship between the thermodynamic parameters from subtask 1a-3 and the equivalent back calculated parameters from mechanical tests conducted in this subtask.
v. Develop framework(s) for the work of cohesion or adhesion with appropriate modifications so that it can be incorporated into the micromechanics or continuum damage models in subsequent tasks. This framework will be based on both thermodynamic measurements and mechanical tests.

This subtask will be conducted in conjunction with sub task M2a-1 for materials in dry condition. As described previously in sub task M2a-1, these experiments will combine the use of mechanical tests and advanced analytical techniques to determine the practical work of cohesion and adhesion for different materials. Also as mentioned before, this subtask will capitalize on the experience of research conducted at the Imperial College, London under an ongoing research exchange program sponsored by UK.

Subtask F1a-5: Evaluate Acid-Base Scale for Surface Energy Calculations

The surface free energy components of aggregates and binders are computed using adsorption isotherms and contact angles with different probe liquids. Thus far, these computations were made using surface energy values for probe liquids recommended as per the Good-van Oss-Chaudhary (GVOC) scale. The GVOC scale is based on the assumption that the acid and base components of surface energy of water are equal. Several researchers in the field of physical chemistry have pointed out that this scale introduces a bias which results in an apparently high magnitude for the base component and apparently low magnitude for the acid component of surface energy (Della Volpe and Siboni 2000). Alternate scales for the surface energy components of various probe liquids are also recommended in the literature.

In this subtask the work of adhesion and cohesion will be determined using surface energy components that are derived using different scales. This analysis will determine whether or not the use of a different scale can improve sensitivity of the computed surface energy components of asphalt binders and aggregates. This is especially important for the acid component of asphalt binders which are typically very small in magnitude but are significant contributors to the work of adhesion. This sub task will utilize the data from the Universal Sorption Device (USD), Wilhelmy plate and sessile drop devices obtained from other elements of this subtask as well as other subtasks.

<u>Year 2 Milestones for Work Element F1a</u>

i. A comprehensive document that summarizes the following: i) the differences between thermodynamic work of adhesion and cohesion versus practical work of adhesion and cohesion, ii) different experimental and analytical methods to determine the practical work of adhesion or cohesion using simple laboratory tests.
ii. Develop and experiment plan and conduct preliminary tests to determine work of adhesion and cohesion (in conjunction with work element M2a-1).

Work Element F1b: Viscoelastic Properties (Continued in Year 2)

The focus of this work element will be on developing experimental protocols and analysis methods to determine linear and nonlinear viscoelastic properties of the binder, mastic, and mixture.

As discussed later in work element F3c-1, one of the important inputs to the fatigue damage model is the rate of growth of dissipated fracture pseudo strain energy. The determination of this parameter necessitates separating the energy dissipated in nonlinear viscoelastic deformation from the energy dissipated in fracture damage. The difficulty in doing so stems from the fact that nonlinear viscoelastic deformation, plastic deformation and fracture damage are dependent on the stress level.

<u>Subtask F1b-1: Separation of nonlinear viscoelastic deformation from fracture energy under cyclic loading</u>

Cyclic loading is used in the testing of asphalt binders (dynamic shear rheometer), mastics (dynamic mechanical analyzer) and asphalt mixtures (cyclic axial or shear). It has been a challenge to use these tests to separate nonlinear viscoelastic from plastic deformation and fracture due to the following reasons: (1) the stress value could change within a load cycle from the linear response to the nonlinear response, (2) the stress varies radially within the specimen under shear loading, (3) the loading and unloading within each cycle causes energy to dissipate due to plastic deformation but permanent deformation is fully reversed within each cycle.

The nonlinear response will cause the viscoelastic properties (phase angle and modulus) to change within the cycle. In year 1 of this research, Schapery's nonlinear viscoelastic model was applied under the boundary conditions of cyclic loading to obtain functions for viscoelastic material properties within a loading cycle. This allows separation of the nonlinear response from the linear response predicted using properties measured at small stresses. The correct quantification and separation of non linear response is necessary to obtain an accurate estimate of damage that occurs during cyclic loading. This methodology developed in year 1 will be verified using select materials. Details of this methodology were presented in the quarterly report ending September 2007.

<u>Subtask F1b-2: Separation of nonlinear viscoelastic deformation from fracture energy under repeated and monotonic loading</u>

The continuum modeling of asphalt mixtures has relied on separating the strain into its viscoelastic and viscoplastic components. All available methods assume linear viscoelastic response, which makes the separation of the strain components straight forward (Huang et al. 2007). However, this assumption leads to erroneous decomposition of the strain components. In this subtask, we will develop a repeated loading-unloading testing protocol and analysis methods to separate the nonlinear viscoelastic and viscoplastic components. The mathematical basis for this subtask has been derived recently at Texas A&M University and presented to the expert task group in its meeting in Phoenix Arizona in February 2007. It relies on using statistical fitting for the unloading portion of the repeated test to determine the total permanent strain and one of the nonlinear viscoelastic parameters. These parameters are used in the mathematical form for the loading portion and fitted to the experimental measurements to obtain the remaining nonlinear viscoelastic parameters and the viscoplastic strain as a function of loading time.

<u>Major Findings from Year 1 for Work Element F1b</u>

A methodology was developed to identify the threshold value for the stress or strain amplitude that can be applied to a specimen without causing damage. A non linear viscoelastic model to characterize the response of the FAM subjected to cyclic loading was also developed (Details are included in the quarterly report ending September 2007). The model includes a damage parameter that can be monitored to quantify the evolution of damage with number of load cycles. The efficacy of the model was evaluated using limited data and the results are summarized in this report. On going work will extend the model to analyze the accumulation of damage with time within each load cycle.

<u>Year 2 Milestones for Work Element F1b</u>

i. Present the fully developed constitutive relationship to model the non-linear viscoelastic response of fine aggregate matrix (FAM) specimens subjected to dynamic loading. The model will be extended to the general three dimensional formulation.
ii. Conduct preliminary tests to support the model using select material specimens tested under a variety of dynamic loading conditions.

Work Element F1c: Aging

Oxidative aging changes binder composition. These changes have dramatic effects on binder (viscoelastic, cohesive, and adhesive) and mixture (viscoelastic, fracture, and permanent deformation) properties. Therefore, it is necessary to understand the material and microstructure factors that influence aging and the factors that govern the response of binders and mixtures to aging. The experiments and analyses will focus on characterizing the influence of aging on fundamental material properties that are included in the parameters of the models discussed in Category 3. Ultimately, the results must be able to provide insight to the asphalt microstructural model, the micromechanics model, and the unified continuum fatigue model and activities of this work element of Category 1 will coordinate with those of Category 3.

The planning and results of the above subtasks will be coordinated with other elements of the Consortium effort. As mentioned above, results that relate to fundamental binder and mixture properties will be communicated to the Micromechanics Model and Unified Continuum Fatigue Model elements. Results of the transport model of binder oxidation in pavements and on mixture parameters that maximize fatigue resistance will provide guidance on engineering mixtures to have enhanced pavement durability.

<u>Subtask F1c-1: Critical Review of Binder Oxidative Aging and Its Impact on Mixtures (Continued in year 2)</u>

This subtask will develop detailed objectives of this work element within the context of previous work and the objectives of the Consortium deliverables in the fatigue area (and other areas as appropriate). Pertinent prior work includes binder oxidation kinetics, binder hardening that results from oxidation, binder oxidation and hardening in pavements, and the effects of binder hardening on mixture properties. Additionally, effects of oxidation on binder cohesion and binder/aggregate adhesion will be reviewed and coordinated with activities in other work elements.

<u>Subtask F1c-2: Develop Experimental Design (Continued in year 2)</u>

A detailed experimental design will be developed to accomplish the objectives identified in subtask F1c-1 and to be carried out in subsequent subtasks, below. This subtask will include selecting binder and aggregate materials, mixture types and aggregate gradation, binder and mixture aging protocols, and test procedures for assessing the impact of binder oxidation on binder and mixture properties. Also, climate regions of interest for transport modeling, and the selection of relevant field sites for validating the transport modeling of binder oxidation will be selected.

<u>Subtask F1c-3: Develop a Transport Model of Binder Oxidation in Pavements (Continued in year 2)</u>

As an essential element in the process of modeling fatigue damage in mixtures and pavements, the oxidative aging of binders in pavements must be considered. A significant body of data is accumulating that oxidation of binders in pavements is an ongoing process and that it occurs to a significant depth below the surface. The rate at which this oxidation occurs in different climates and pavement types is a factor to understanding pavement performance. The oxidation rate of binders is accelerated exponentially with temperature, but also depends on the transport of oxygen to the binder. Data strongly suggest that if the accessible air voids in a pavement are sufficiently high, then the access of oxygen is not a limiting factor and that a model that relies solely on the pavement temperature might do very well at estimating binder oxidation rates in pavements. However, for pavements that have sufficiently restricted air voids, the transport of oxygen appears to be a significant factor, more in line with our expectations.

This subtask will address the development of a thermal and oxygen transport model for estimating binder oxidation in pavements. Such a model will require binder oxidation kinetics parameters (activation energies and oxygen reaction order values, plus early rate information), a model for calculating temperature as a function of time and depth in pavements, and a model for describing oxygen transport and diffusion to the binder.

The transport model will require fundamental material properties, including binder oxidation kinetics, diffusivities of oxygen in binders and mastics, and thermal diffusivities of pavements. It is likely that thermal diffusivities can be estimated quite well from existing measurements of pavement temperature as a function of time and depth, as can the impact of nationwide climate differences on pavement temperature. Oxygen diffusivities, however, will be measured as part of this subtask, as will some binder reaction kinetics parameters for which data are not yet available.

Such a model will provide calculations of binder properties in the pavement as a function of both time and depth, properties that can then be passed to the micromechanics and unified continuum fatigue models.

<u>Subtask F1c-4: The Effects of Binder Aging on Mixture Viscoelastic, Fracture, and Permanent Deformation Properties (Continued in year 2)</u>

Another critical element to understanding the impact of binder oxidation is the extent to which binder oxidative hardening impacts mixture, and thus pavement, properties. Recent data have shown that the hardening and embrittlement of binder that occurs as the result of oxidation causes dramatic decreases in mixture fatigue resistance under controlled-strain conditions. Furthermore, the data have shown that different mixtures can exhibit very significant differences in the extent to which binder hardening impacts this decline of fatigue resistance. Understanding these differences between mixtures is critically important to fatigue prediction. Furthermore, understanding the impact of binder oxidation on fatigue resistance and pavement durability in a controlled-stress environment must be better understood.

The objective of this subtask is to determine the fundamental mixture parameters that establish the extent to which fatigue resistance declines with binder oxidative hardening and thus the reasons that some mixtures are inherently more durable than others. Mixture parameters that likely affect fatigue resistance are binder composition, binder content, air voids content, aggregate gradation, and perhaps aggregate type. To the extent such parameters impact mixture fatigue, the fatigue problem is really a mixture/binder problem rather than simply a binder problem. Of course, the binder oxidation rate in pavements (Subtask F1c-3) will also impact pavement durability.

This subtask will conduct carefully designed experiments to determine the impact of binder oxidative hardening on fundamental mixture properties that govern mixture fatigue resistance, and for a variety of mixture parameters. The property measurement and the results will be coordinated with the efforts on the micromechanics and unified continuum fatigue models.

Subtask F1c-5: Polymer Modified Asphalt Materials

Polymer modification of asphalt binders offers unique opportunities for improving binder behavior, but also unique questions that must be better understood. Modifiers typically improve the elongational properties of binders and may improve their cohesive and adhesive strengths. However, oxidative aging of modified binders typically reduces the elongational flow improvement to the point that with enough aging, the modified binder behaves like the aged unmodified binder.

The interaction of the polymer modifier and the base asphalt binder appear to be critical in establishing the beneficial effects of the modifier and these interactions need to be better understood. Fluorescence microscopy imaging provides useful qualitative information on polymer-asphalt morphology and its changes with oxidative aging which, combined with measurements of binder rheology, mixture rheology, and mixture fatigue, can provide an improved understanding of polymer modification and its impact on pavement durability.

The work of this subtask will address polymer asphalt interactions and their impact on binder and mixture properties for a variety of modifiers and base binders and particularly as a function of oxidative aging. The work will provide important fundamental data for the asphalt microstructural model, the micromechanics model, and the unified continuum fatigue model.

Major Findings from Year 1 for Work Element F1c

Note: This section is more detailed than the section on "Major Findings in Year 1" in other parts of this work plan. This is because the details of major findings in other work elements were presented in the quarterly report dated September 30, 2007 and cited in this work plan. This was not the case for the work on aging, therefore a more detailed discussion of major finding in this area is presented here.

i. Based on a literature review targeting film thickness and the use of surface area factors to characterize mixtures from previous TxDOT Projects 0-4468 and 0-4688, a more sophisticated methodology is needed to characterize this important mixture parameter that may explain differences between mixtures in terms of their reduction in fatigue life with oxidation. The more advanced methodology will include the use of X-ray computed tomography (CT) to the limit of its resolution and theoretical modeling of particulate composites to obtain the distribution of binder thickness throughout the mixture. [Subtasks F1c-2, F1c-4].

ii. Dimensionless parameters including ratios of short-term to long-term healing energies, fracture energy to rate of fatigue damage accumulation, crack size at failure to binder film thickness, vertical to horizontal moduli, and possibly a parameter to capture accessible air voids may provide the basis for experimental design, although a preliminary investigation utilizing mixtures from previous TxDOT projects 0-4468 and 0-4688 showed that additional parameters will have to be evaluated to explain the differences in the decline of mixture fatigue life with oxidation. [Subtasks F1c-2, F1c-4].

iii. Mixture characterization of relatively thin specimens through axial testing is required on specimens cut from cores. This testing includes relaxation modulus master curves in tension and compression, damage accumulation rate in repeated direct tension, and tensile strength to facilitate selection of testing conditions. This testing of prismatic specimens has been successful in compression, and tensile testing is currently ongoing. [Subtask F1c-4].

iv. Crack growth index will be utilized as the mixture response parameter, following the analysis for fine-graded mixtures that is independent of mode of loading. [Subtask F1c-4].

v. Materials from the field validation sections currently monitored by WRI will be utilized. In addition, materials will be selected from previous TxDOT projects 0-4468 and 0-4688 to ensure longer time periods (and corresponding long-term fatigue distress) are captured for validation. In terms of aging, APT is not a viable option for model validation. [Subtask F1c-2]. A fairly simple pavement oxidation model has been developed based on three governing phenomena: (i) binder oxidation and hardening due to the oxidation, (ii) diffusion of oxygen through asphalt films and (iii) the proximity of air to the binder. Binder oxidation kinetics focuses on the chemical reaction properties of the asphalt binder and the resulting physical changes to the binder, i.e., viscosity change with the formation of carbonyl compounds, and as a function of temperature. Temperature plays a role through both the Arrhenius reaction rate and through the effect of temperature (without reaction) on physical properties such as viscosity. Second, the diffusivity of oxygen into asphalt binder (a strong function of asphalt binder viscosity) dictates how fast oxygen can penetrate into an asphalt binder and initiate the oxidation process. Because binder viscosity is a function of the binder oxidation state and temperature, the diffusivity also depends upon the oxidation state and temperature. Finally, the availability of oxygen to the binder (air voids size and the distance between air voids) is hypothesized to play an important role in the pavement oxidation model. Calculations using the PDE model (formulated in a cylindrical coordinate system) yield the oxygen partial pressure as a function of time and distance between two air voids, together with binder oxidation and hardening rates throughout the model pavement. These hardening rates as a function of position will be passed on to pavement performance prediction models. This PDE model has been solved in cylindrical coordinates at constant temperature. The kinetic data for five binders, available from the literature, were used to study the effects and sensitivity of the model parameters. The effect of the distance between two air voids on the oxygen partial pressure profile between the two air voids was assessed. [Subtasks F1c-1, F1c-3].

Year 2 Milestones for Work Element F1c

i. Identify important mixture parameters that govern decline in mixture fatigue life. [Subtasks, F1c-1, F1c-4].

ii. Test and analyze cores from selected field sections for one or two aging periods as materials are available from previous projects and for one aging period from new projects. [Subtask F1c-3].

iii. Perform tests on laboratory mixtures and field materials to verify testing procedure to obtain fatigue measurements on field cores. [Subtask F1c-4].

iv. Compare the binder oxidation model to literature pavement aging data. [Subtask F1c-3].

v. Initiate binder oxidation kinetics and diffusion studies on selected binder materials and binder mastics. [Subtask F1c-3].

Work Element F1d: Healing

Subtask F1d-1: Critically Review Previous Work on Healing under FHWA Contracts DTFH61-C-92-00170 and DTFH61-C-99-00022 (Continued in Year 2)

During previous FHWA contracts on Fundamental Properties of Asphalts and Modified Asphalts, DTFH61-92-C-00170 and DTFH61-99-C-00022, Texas A&M University hypothesized that healing of microcracks is related to the surface energy of the crack face. Intuitively, most healing is cohesive or within the mastic, instead of adhesive or between asphalt or mastic and aggregates faces. As a result the surface energies that affect healing are those of the binder and/or mastic. The existing data strongly demonstrate that higher total surface energies of the binder are related to improved healing. The data also convincingly indicates that healing is best in binders with high acid-base components of surface energy but that healing is impeded by a high Lifshitz Van der Waals surface energy component.

Previous work at Texas A&M has also shown that molecular morphology affects healing and that longer, less branched molecules promote healing as opposed to shorter, highly branched molecules. Texas A&M researchers have developed a model for healing rate that can be incorporated in the fatigue model. This model uses a Ramberg-Osgood function to represent the time rate of healing and its cumulative effect with time. This Ramberg-Osgood approach unites short-term (non polar) healing rate and long-term (polar) healing rate together with overall cumulative bond recapture capacity (ratio of polar to non-polar bond energies).

The healing mechanism will also be studied using the recently proposed approach that represents healing with the convolution integral form proposed by Wool and O'Connor (1981) for polymers. This form combines the effect of wetting (due to surface energy) when crack surfaces are pressed back together followed by diffusion and randomization. The diffusion and randomization processes are affected by molecular morphology.

In year 1 of this project, a detailed literature review on the mechanisms related to self healing in asphalt binders as well as methods to quantify healing was conducted. A framework to quantify healing and incorporate it in fatigue models was also developed. This information was presented in the quarterly report ending September 2007, and was also synthesized in other publications (Little and Bhasin 2007, Bhasin, Little et al. 2008). The literature review and refinement of this framework will continue in year 2.

Subtask F1d-2: Select Materials with Targeted Properties (Continued in Year 2)

A significant part of the research in the area of fatigue will utilize materials that are selected from the common material library for the Consortium project. However, in order to verify the elements of the healing mechanism, binders or mastics with a targeted range of properties will be required. This subtask is aimed at determining these properties for different asphalt binders and mastics as well as modifying the binders using model compounds or additives to achieve the targeted range of properties, as required. This will be achieved as follows:

i. Select binders and mastics to evaluate effect of surface energy on the wetting and healing of micro cracks. This will involve measurement of surface free energy components of different binders using the Wilhelmy plate device. Binders will be modified by addition of chemical additives and/or addition of model compounds to achieve variable surface characteristics of the asphalt binder. This process will ensure that the morphology of the asphalt molecules is not significantly altered.
ii. Select binders and mastics to evaluate effect of molecular morphology on diffusion and healing. This will involve measurement of surface free energy of different binders using the Wilhelmy plate device. Unlike subtask F1d-2, (i), the objective of this subtask will be to identify or formulate asphalt binders that have significantly different molecular morphology, compliance, and diffusivity, but similar surface energy characteristics. Important characteristics pertaining to the molecular morphology of the asphalt binders (e.g., average chain length, molecular weight distribution) will be determined in other tasks of this research project. This information will be used to blend different binders to achieve the desired differences. Previous research at the Texas A&M University has identified parameters such as methyl to methylene ratio, determined using the FTIR, as a parameter that reflects on the molecular properties related to healing. The selected or blended asphalt binders will be evaluated using this parameter.

This subtask was initiated in year 1 of this project. Molecular modeling software was used to model the healing response of different model asphalt binders. The objective of this modeling exercise is to conduct a parametric analysis of the compositional factors (e.g., chain length, distribution of phases, etc.) that have the most significant impact on the healing mechanism. This in turn will facilitate optimal selection of materials for this work element. One very reassuring discovery from the molecular modeling work was the magnitude of surface free energy obtained using molecular modeling is of the same order of magnitude as that measured using the laboratory tests such as the Wilhelmy plate method. This is important not only because surface free energy impacts fracture and healing from a fundamental perspective but also because our framework for the healing process is based on the convolution effect of wetting of the crack faces as they are pushed back in contact during the rest period and the molecular diffusion of molecules across the crack interface during and following the wetting process. The molecular modeling and material selection efforts will continue in year 2 of this project.

Subtask F1d-3: Develop Experiment Design (Continued in year 2)

Once the appropriate set of binders and additives are selected, an experiment design that will provide a statistically reliable assessment of the impact of surface energy (and its components), compliance, diffusivity, and molecular morphology will be developed in coordination with the project statistician, as described in the Experiment Design section. The materials incorporated in the experiment design will be based on the selections made in subtask F1d-2.

Subtask F1d-4: Investigate Test Methods to Determine Material Properties Relevant to Asphalt Binder Healing (Continued in year 2)

The propensity of an asphalt binder to heal over time can be considered as a time dependent function of material properties. The measurement of surface energy and its components will most likely be determined by the Wilhelmy Plate method, based on extensive earlier work. Pulse guided – nuclear magnetic resonance, PG-NMR, may be used to measure self diffusivity constants for the binder. However, other methods of assessing the morphology and diffusion and migration potential of molecular species will be investigated. The surface energy (wetting), compliance, diffusivity, and molecular morphology properties of the binders will be compared with the mechanical DMA quantification of healing. A comprehensive evaluation of healing that integrates properties such as compliance and bond energy will be conducted. The correspondence between the measured diffusion properties and the measured compliance will be determined. The most appropriate testing methodologies will be identified and recommendations for further development made in subtasks F2a and F2b.

In year 1 of this project, a test method using the DSR was developed to determine the intrinsic healing rate of the binder. Preliminary results from this method are consistent with the hypothesis for the healing mechanism developed in subtask F1d-1. Details of the test method and preliminary results were presented in the quarterly report ending September 2007. In addition, pilot tests using PG-NMR techniques to determine the self diffusion properties of binder molecules are in progress. Researchers are also developing methodologies using the molecular modeling techniques in order to obtain estimates of the self diffusion properties of the asphalt binder. Preliminary results related to these techniques will be included in the quarterly report ending December 2007.

The test methods in this subtask will be further developed in year 2. It is important to note that not all of the techniques evaluated or developed in this subtask are intended for routine use by practitioners in the future. However, some of these methods and tools allow the researchers to evaluate properties and/or validate the hypothesis relevant to the healing mechanism. This information will also be extremely useful in selecting candidates and developing a simple test method or analytical procedure to quantify the role of healing in asphalt mixtures on a routine basis.

Subtask F1d-5: Testing of Materials (Continued in year 2)

The binders and additives selected in subtasks F1d-2 and F1d-3 will be tested using the methods identified in subtask F1d-5 to determine their surface energy properties (total surface energy and non-polar and polar components of surface energy) and molecular morphology. These values will be compared with measurements of healing probably by using Dynamic Mechanical Analysis (DMA). In the DMA experiment the binder (neat or modified) will be mixed with a standard filler and fine aggregate. The sample will be subjected to cyclic, torsional loading in the DMA experiment. Multiple rest periods will be introduced and recovery of energy dissipated due to various mechanisms during these rest periods will be monitored as an indicator of healing. The objective will be to identify the effect of surface energy on the healing through the wetting mechanics and the effect of compliance and diffusivity as determined by molecular morphology through the diffusion and randomization mechanism.

Subtask F1d-6: Evaluate Relationship Between Healing and Endurance Limit of Asphalt Binders (Continued in year 2)

Subtask Lead: Carl Johnson

Introduction

During the last 10 to 15 years the understanding of healing and endurance limits of asphalt mixtures has advanced significantly. Research on binder fatigue and development of binder fatigue tests are relatively new and have not included two important aspects of fatigue: healing and endurance limits. It is expected that advancements in characterizing and modeling of healing and endurance limits of mixtures can be applied to fatigue measurements of binders in the dynamic shear rheometer (DSR). This task will focus on two main areas, applying methods developed for healing of mixtures to results of binder fatigue testing in the DSR, and developing methods for estimating the endurance limits of binders using the DSR.

A comprehensive plan for measuring healing potential of binders with and without modification using the DSR will be developed after a critical review of the advancements in mixtures and mastics. The data published on binder fatigue during the last few years will be gathered to introduce a binder fatigue model that allows an estimate of the effect of stress/strain on fatigue life and also the prediction of endurance limits. An attempt will be made to include healing in the endurance limit prediction model. The task will also include limited validation of the endurance limits and effect of modifiers on altering the limits. The work will be coordinated carefully with the other tasks of this area.

Relationship to FHWA Focus Areas

The fatigue work elements support the FHWA Focus Area of Optimizing Pavement Performance by providing a relationship between material property and pavement performance.

Hypothesis

Healing in asphalt binder greatly affects the fatigue performance of asphalt binders and the performance of asphaltic mixtures. The healing properties of asphalt binders have to be characterized to property predict the performance of the asphalt binders and asphaltic mixtures.

In addition, healing will be an important factor in establishing the endurance limit for asphalt binder and asphaltic mixtures.

Objectives

One of the objectives of this task is to include healing in the endurance limit prediction model. The task will also include limited validation of the endurance limits and effect of modifiers on altering the limits.

Experimental Design

The following tasks will be completed in order to achieve the objectives of this research effort:

i. Develop a protocol to measure healing of fatigue damage for asphalt binders. This task will include a comprehensive literature review of the worldwide literature on methods for measuring healing of asphalt mixtures and other viscoelastic materials. Based on the review, a set of testing protocols with potential to quantify healing of binders will be selected. Preliminary testing of a set of 4 binders will be conducted to evaluate the practicability and feasibility of the tests. The tests will be restricted to using the DSR and the BBR devices.
ii. Evaluate testing protocols. Further testing of 6 binders (2 unmodified and 4 modified) will be conducted to evaluate the practicability and feasibility of the tests identified in Task 1. The tests will also be restricted to using the DSR and the BBR devices. The best protocol will be defined by its ability to differentiate among binders, cost in terms of time and effort, repeatability, and simplicity of analysis. The outcome of this evaluation will be selected in coordination with other work elements on the unified fatigue damage model. In other words, the outcome should include parameters that can be used as input in the unified fatigue model.
iii. Evaluate factors affecting healing of binders. In this task, the factors known to affect healing, as identified in Task 1, will be used to develop a comprehensive experimental plan for testing and quantifying the change in healing due to variation of these factors. The factors will include, at a minimum, temperature, chemical composition, modification types, aging, loading rate, rest periods, and stress or strain used in testing. Statistical experimental design will be used to minimize the number of combinations.
iv. Evaluate possible surrogate measures. This task will compare the results from testing conduced in Task 3 with simple chemical, physical, or rheological properties already measured in binder surrogate fatigue testing (stress sweep), slope of the master curve, the m(60) value, and other measures that are already in the PG specification or can be an extension of the PG testing. This will be done to investigate whether healing can be estimated from other simple measures, eliminating the need for a healing-specific test.
v. Evaluate role of mineral surface in healing. Selected binders will be mixed with 3 types of mineral fillers (acidic, basic and neutral) to study role of mineral surface on healing results. Based on the results, limited testing of actual mixtures will be conducted to validate the effect of the mineral surface and define the importance of aggregate presence on healing.

vi. Make final recommendations for a binder healing test and specification parameter. Based on the results of Tasks 2 through 5, a final recommendation will be made regarding the practicality of including a healing test and specification parameter in practice. Guidelines will be developed for a test protocol and analysis method, and specification limits will be proposed. Suggestions for future research will be also listed.

Major Findings from Year 1

During year one, the materials and testing conditions for the plan were selected and are shown in table F1d-6.1. A testing plan was also developed and the proposed tests are shown in table F1d-6.2. During Year 1, a critical review of literature related to healing of asphalt mixtures and binders was conducted. The results of this were used to draft the conceptual outline.

Table F1d-6.1. Matrix of materials and conditions.

Neat Binders	PG64-22
Modifiers	SBS
	Elvaloy
	PPA
Mineral Fillers	Granite
	Ottawa sand
	Limestone
	Hydrated lime
	Cellulose

Table F1d-6.2. Proposed tests on asphalt binders and mixes.

Asphalt Binder and Mastics	Interrupted Cyclic Fatigue	Strain level	3%
			5%
			7%
		Frequency	5 Hz
			10 Hz
		# of Rest Periods	0
			1
			2
			5
			10
	Modified Resilient Modulus Test	Duration of Rest Periods	4 min
			8 min
			12 min
			16 min
			20 min
	Haversine Pulse Loading	Load Pulse Spacing	0 s
			1 s
			3 s
			9 s

The ultimate fatigue performance of a pavement relies on many factors, but the two that this study will focus on is the ability of asphalt binder both to resist damage from occurring and also to heal the damage that has already occurred. Fatigue performance of asphalt mixtures has been widely tested in the lab, but binder fatigue characterization is still in progress. This section will discuss two concepts that have been applied to mixtures and how they can be applied to binder testing.

1. Sinusoidal Cyclic Loading with the Inclusion of Rest Periods (RP's)

Typical fatigue testing, also known as time sweep testing, is performed by applying sinusoidal cyclic loading at a given frequency and controlled level for either a specified amount of time, or specified level of achieved damage (e.g., 50% loss of G*, max phase angle). The healing qualities of the material are typically measured by comparing the differences of the measured material properties between standard time sweep tests and those that have had rest periods introduced into them. It has been clearly shown that RP's increase the number of cycles that a sample can withstand before reaching its predetermined failure criterion. Below are two examples of this method:

a) *TTI's Method* (Kim et al. 2003; Song et al. 2005)

A standard strain-controlled time sweep is applied to the material until failure, in this case δ_{max}. Another time sweep test is then run with the addition of multiple RP's of predetermined duration spaced at equal intervals. The length of the interval depends on the ability of the material to withstand damage; weaker materials will be assigned shorter intervals in order to recover some of the accumulated damage. An example of these tests is shown below in figure F1d-6.1.

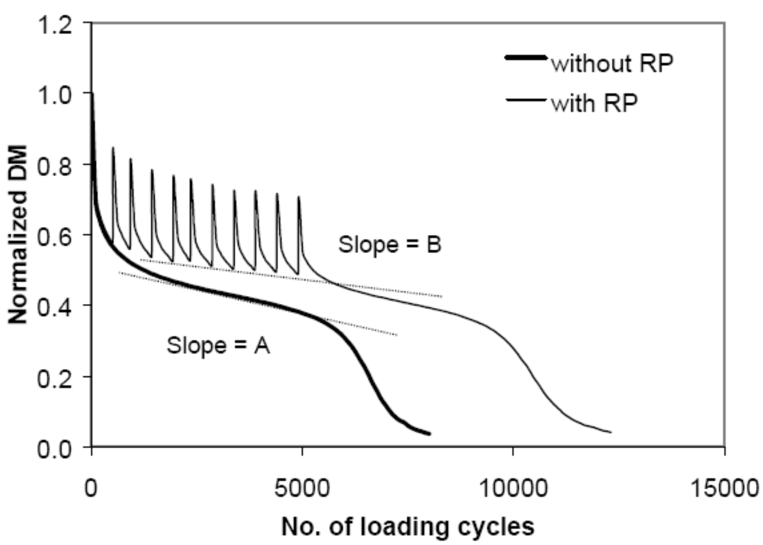


Figure F1d-6.1. Chart. Effect of microdamage healing due to rest periods.

The quantification of the material's healing index is then calculated using a parameter known as the Healing Potential Index (HPI):

$$HPI = \frac{A - B}{A} \tag{1}$$

Where *A* and *B* equal the absolute value of the slope representing microcracking speed (shown in figure F1d-6.1) with and without rest periods, respectively.

Performing this analysis method requires time sweep testing with and without rest periods. It also requires a predetermined failure criterion and a systematic way of determining rest period interval spacing.

b) *Baglieri's Method* (Baglieri 2007)

Similar to the previous method, this method involves measuring the comparison between time sweep tests with and without rest periods. However, the basis for comparison lies within measuring the Dissipated Energy Ratio (DER) over the course of the time sweep test. A standard stress-controlled time sweep is run in this case, and the DER is plotted for the duration of the test. Then, depending on the amount of damage in the specimen that the healing properties of the material to be evaluated, one RP is inserted into the time sweep at the desired level of damage (e.g., DER_{max}, 75% DER_{max}, 50% DER_{max}). The duration of this RP is equal to three times the duration of the time sweep test up until introduced RP, measured from the previous time sweep with no RP's. The test then resumes until the predetermined failure criterion is reached.

The Healing Index (HI) is calculated as follows:

$$HI = \left| \frac{W_{\mathrm{Re}load} - W_{Load}}{W_{Load}} \right| \tag{2}$$

Where W_{Load} is the dissipated energy per cycle at the end of the loading phase and W_{Reload} is the dissipated energy per cycle at the first cycle of the reloading phase.

Performing this analysis method requires time sweep testing with and without rest periods. It also requires a predetermined failure criterion, but the duration of the RP is determined as described above. The point at which the RP is introduced must be predetermined.

2. <u>Repeated Haversine Loading</u>

This method of fatigue and healing testing is derived from the method of determining resilient modulus of asphalt mixtures using the Superpave Indirect Tension test (IDT). Typically, a 0.1 second loading pulse is applied to the material, followed by a rest period of 0.9 seconds in order to simulate the action of traffic on a pavement. As the number of loading pulses increases, the internal structure of the material begins to accumulate damage and the specimen becomes unable to withstand additional loading. The testing can either be run to a specified number of cycles, or until a failure criterion is reached (e.g., 50% loss in dynamic modulus). The RP's are introduced either directly after the loading pulses by controlling the length of the repeated RP's, or after a certain number of loading cycles with standardized RP's during each cycle. An example of each is shown below:

a) *Carpenter's Method* (Carpenter and Shen 2006)

Rest periods using this method are controlled by adjusting the length of the RP directly after the pulse. Typically, a 0.9 sec rest period is applied after each 0.1 sec loading pulse; by changing the length of the RP, the material has more opportunity to heal accumulated damage.

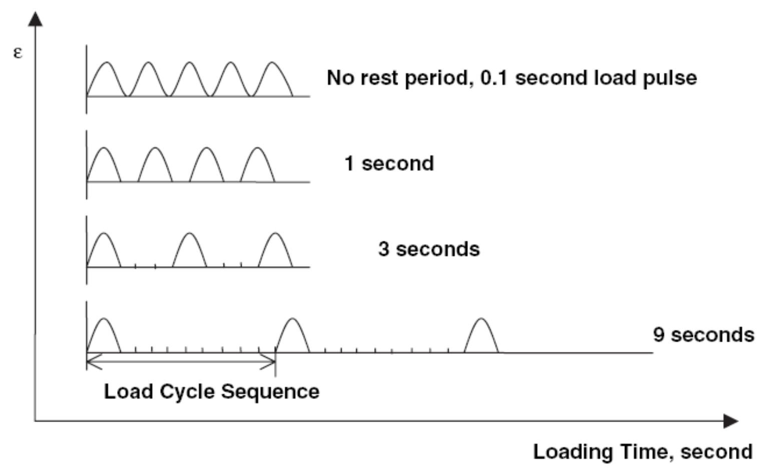


Figure F1d-6.2. Chart. Haversine load pulse sequence of fatigue-healing test.

By measuring number of cycles until failure (typically defined as 50% loss in stiffness) for each RP duration, a characteristic curve can be developed. This curve can be used to predict the duration of the RP needed to reach a predetermined number of cycles to failure; this idea can be extrapolated to the idea of a pavement's fatigue endurance limit. By lowering the strain level of the loading pulse, the duration of the RP needed to achieve the predetermined number of cycles to failure shortens. Once this duration reaches a level that is applicable to a desired traffic loading, the material can be engineered to perform within the expected loading levels. That is, pavement layer thicknesses can be calculated so that the asphalt concrete experiences strain levels at or below the material's fatigue endurance limit.

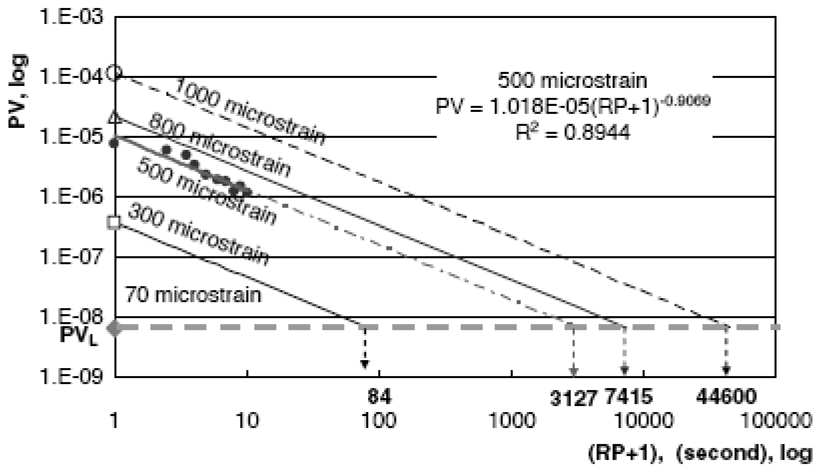


Figure F1d-6.3. Chart. Plot of PV versus Rest Period Duration + 1 (PV is a parameter derived from the inverse of N_f).

This method requires the ability to test using haversine loading, with the ability to adjust the duration between load pulses. The number of cycles to failure can be plotted against the duration of the RP's in order to evaluate the material's healing potential.

b) *Roque's Method* (Kim and Roque 2006)

This method uses the procedure set forth in AASHTO TP 31-94 to determine resilient modulus as its basis. In other words, the repeated haversine loading is standardized at 0.1 sec of loading with 0.9 sec of rest. Healing is evaluated by interrupting the loading cycles to include RP's of varying durations, then comparing the level of damage in the material before and after RP's. Damage is accounted for by measuring the deformation in the specimen against the number of loading cycles.

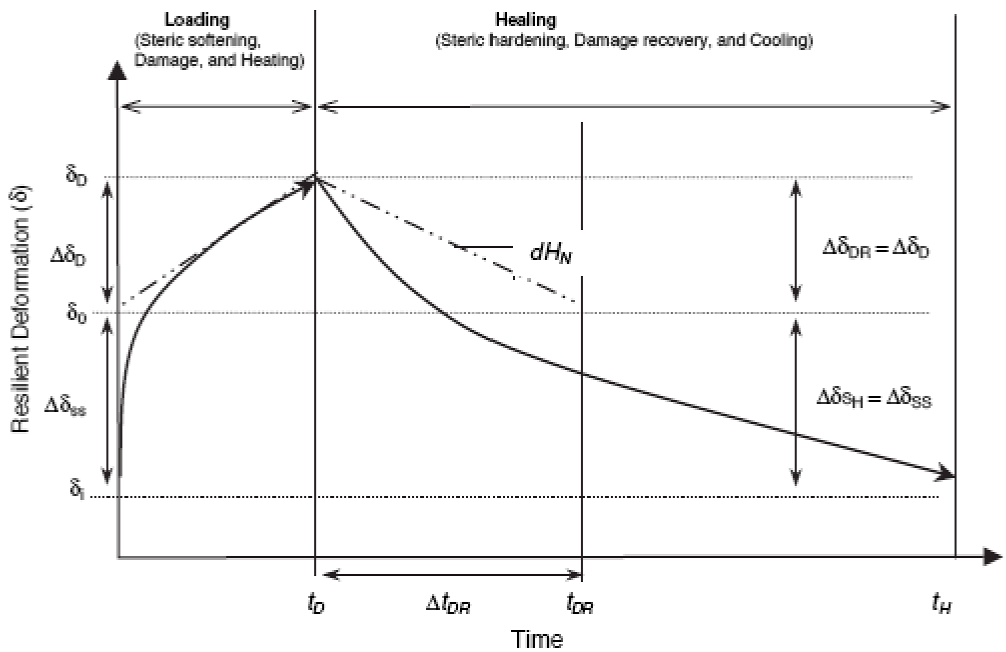


Figure F1d-6.4. Chart. Resilient deformations during loading and healing.

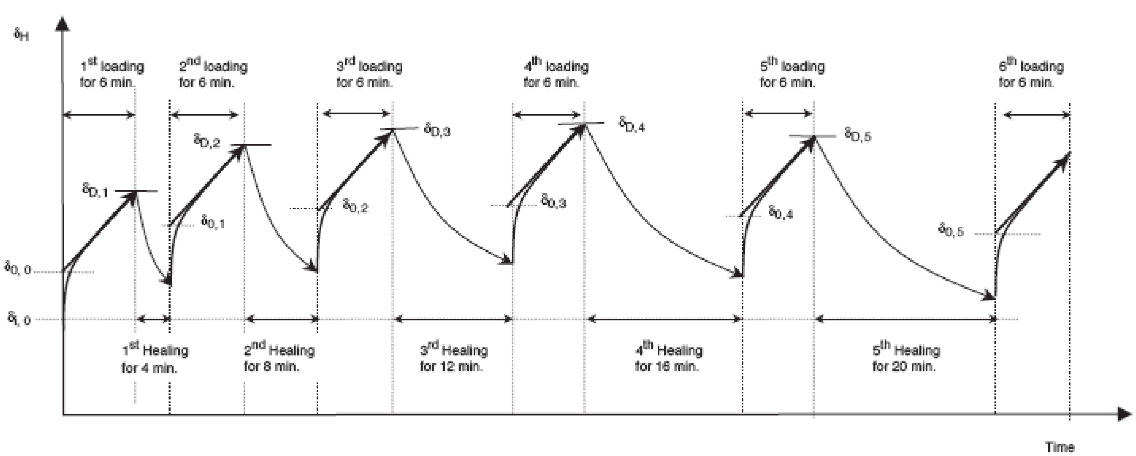


Figure F1d-6.5. Chart. Concept of repeated loads for determining damage recovery rate.

From Roque (Kim and Roque 2006), the healing characteristics are calculated as follows using the parameters as shown:

Net normalized damage:

$$(D_{NN,i}) = (\delta_{D,i} - \delta_{0,i-1})/\delta_{0,i-1} \qquad i = 1 \sim 5$$

Normalized damage:

$$(D_{N,i}) = D_{NN,i} + D_{NR,i-1} \qquad i = 1 \sim 5, D_{NR,0} = 0$$

Remaining normalized damage:

$$(D_{NR,i}) = D_{N,i} - H_{N,i} \qquad i = 1 \sim 5$$

Normalized damage recovery:

$$(H_{N,i}) = (\delta_{D,i} - \delta_{0,i})/\delta_{0,i-1} \qquad i = 1 \sim 5$$

Relative damage recovery:

$$H_{N,i}/D_{N,i} \qquad i = 1 \sim 5$$

With the relative damage recovery plotted with rest periods, the rate of normalized damage recovery (dH_N) was determined as the slope of a linear regression curve. Time to the full recovery of damage (Δt_{DR}) was then calculated by extrapolation of the regression curve (figure F1d-6.4).

To complete this analysis, haversine loading needs to be applied to the specimen at the standard 0.1 sec loading with 0.9 sec of rest per loading cycles. Testing can then be suspended at predetermined intervals in order to allow the specimen to heal, at which point the material's healing characteristics can be evaluated.

An experimental work plan was then designed by this team in order to evaluate prospective testing protocols and begin preliminary analysis on the factors affecting binder healing. A procedure for interrupted cyclic loading has already been completed, with an example of the data shown in figure F1d-6.6.

Further work still needs to be done in order to develop other test protocols, but the project will focus on evaluating the ability of the materials to heal applied damage, and how the level of damage in the material affects the healing potential of the materials.

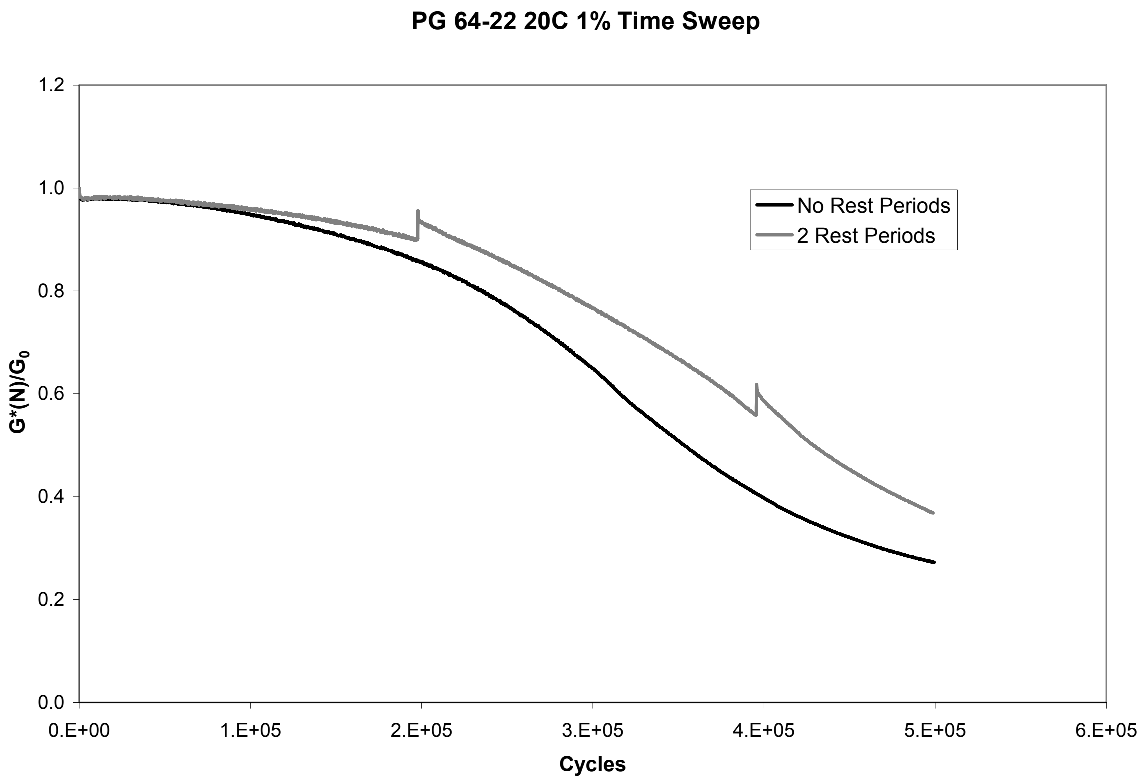


Figure F1d-6.6. Chart. Example data from interrupted cyclic loading procedure for asphalt binders.

Year 2 Work Plan

The experimental plan incorporates both the ability to evaluate proposed test methods as well as the ability to begin preliminary analysis on the factors affecting binder healing.

a. Development and evaluation of testing protocols

Further binder testing will be conducted to evaluate the practicability and feasibility of the tests identified in Task 1. The best protocol will be defined by its ability to differentiate among binders, cost in terms of time and effort, repeatability, and simplicity of analysis. The outcome of this evaluation will be selected in coordination with other work elements on the unified fatigue damage model. In other words, the outcome should include parameters that can be used as input in the unified fatigue model.

b. Evaluation of factors affecting the healing of binders

In this task, the factors known to affect healing, as identified in Task 1, will be used to develop a comprehensive experimental plan for testing and quantifying the change in healing due to variation of these factors. The factors will include, at a minimum, temperature, chemical composition, modification types, aging, loading rate, rest periods, and stress or strain used in testing. Statistical experimental design will be used to minimize the number of combinations. A general methodology for analysis is shown in figure F1d-6.7.

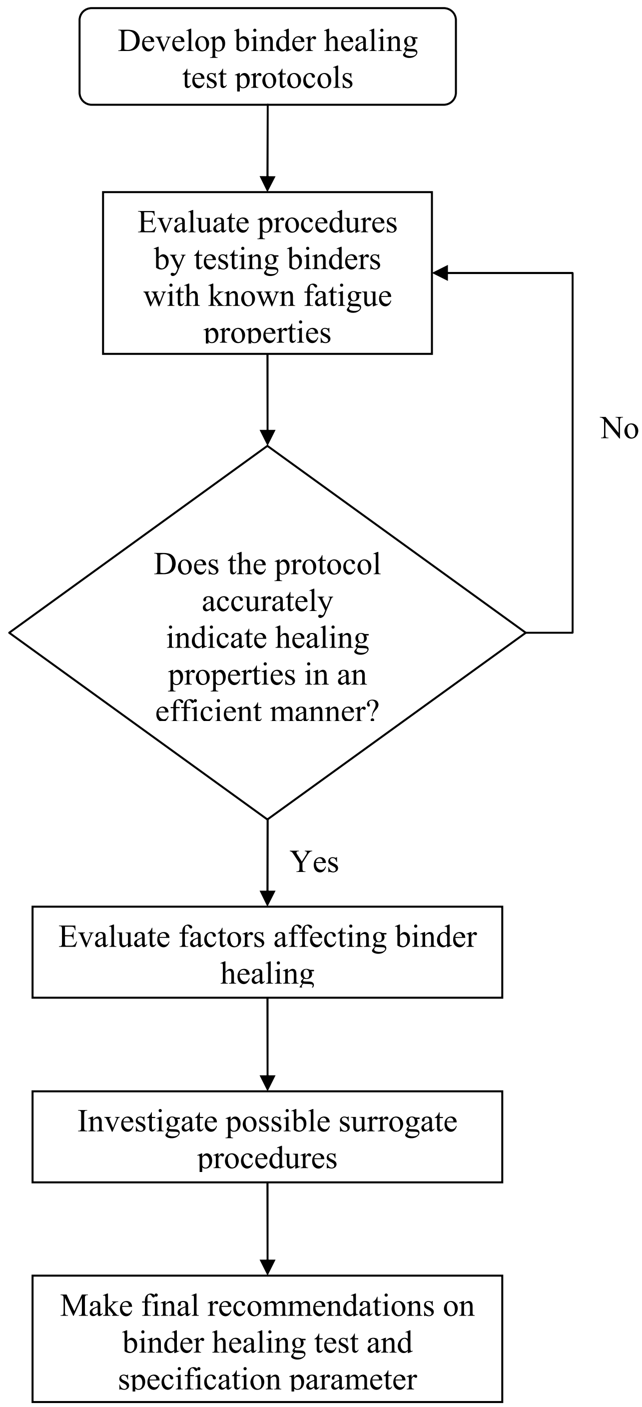


Figure F1d-6.7. Chart. Flow chart for the proposed research program.

Year 2 Milestones

- Complete report on review of literature
- Finalize test protocols for healing of asphalt binders
- Conduct the proposed tests to identify factors affecting the healing of asphalt binders

Budget

The estimated budget for this subtask is $350,000 over the five years. The work will be conducted by the University of Wisconsin-Madison.

Subtask F1d-7: Coordinate with Atomic Force Microscopic (AFM) Analysis (Year 2 start)

Subtask Lead: Troy Pauli

Introduction

Molecular ordering, irreversible energy dissipation and other asphalt compositional properties are important to the durability and fatigue properties of asphalt binders and asphalt-aggregate interactions. In this effort AFM imaging; friction and morphology, contact-force AFM, nanoindentation AFM, chemical-force AFM, etc. conducted in FP-III subtask 2-3, will be interpreted based on contact mechanics and statistical mechanics theories of irreversible energy dissipation at diffuse interfaces which will be adopted to describe and model the equilibrium composition and phase transformation stability of fracture, slow crack growth/crazing and self healing phenomena. Nanoindentation techniques may for example be adapted to measure stiffness and creep relaxation properties of asphalt binder material thin-films. The results that are obtained from these experiments will be compared between AFM methods and with other methods of analysis, including bulk thermal and rheological properties (DSC, DMA, and DSR). Furthermore, model development will be closely tied to nano-experimental techniques, where free energy expressions pertinent to the various molecular ordering events, (e.g., wax crystallization, Spinodal phase separation, and crazing and crack growth, etc.) will be investigated. These approaches are anticipated to lead to mathematical relations between the various molecular ordering events and the mechanical properties of the material based on fundamental physical and chemical theories of soft condensed matter. The mathematical relations developed will provide a better means of determining the performance properties of asphalts derived from different crude oil stocks and produced by different processing methods.

Theoretical Background

Heavy crude oil has historically been viewed by a majority of investigators as colloidal and/or polymeric in nature (Nellensteyn et al. 1933; Saal et al. 1939; Robertson et al. 2001). Although naturally occurring (the Trinidad Lake deposit for example), asphalt is generally defined as the residuum from the distillation of petroleum crude stocks. Heavier residua, such as asphalt, consist of a rather large number of different “petrol” organic compound (molecules) types (Barth 1962; Tissot and Welte 1978). These compound types vary in a complex manner in terms of composition; hydrogen-to-carbon ratio, shape, molecular weight or size, polarity, density, surface activity, etc. Furthermore, asphalt molecules are generally thought to range in character from that of non-polar waxy and oily type hydrocarbon molecules to condensed poly-aromatic sheet (graphite-like), heteroatom-containing molecules (Tissot and Welte 1978; Yen and Chilingarian 1994).

In the past couple of decades the compositional makeup of asphalt, which appears to correspond with a number of measured physical-mechanical properties, has been described in terms of a continuum nano-emulsion (Pal and Rhodes 1989; Sheu 2002; Sheu et al. 1991; Pauli and Branthaver 1998; Pauli and Branthaver 1999; Robertson et al. 2006). That is to say, asphalt may be described as a colloidal-like solution comprised of a molecular distribution (M.W., H/C ratio, density, etc.) of petrol-organic-chemicals, which also behaves much like a complex true solution mixture when defined specifically at temperatures above the material's glass transition temperature (Redelius 2000; Schabron et al. 2001), but also exhibits properties which act somewhat like an amorphous glass when specifically defined through and below the material's glass transition temperature (Turner and Branthaver 1997; Netzel et al. 1997; Netzel 2006).

Extended Irreversible Thermodynamics (EIT) Applied to Asphalt Composition-to-Mechanics: A Basis for a Theory of Petroleum Chemo-Mechanics. Mechanisms of micro/nanostructuring that have been observed in thin-films of asphalt samples were investigated by experimental techniques adopted from nano-science. This work is an attempt to develop analytical and computational tools applicable to prediction of fatigue cracking and healing due to a material's propensity for embrittlement due to oxidation compounded by moisture susceptibility. Experimental results demonstrated that the presence of micro-crystalline wax, investigated employing a thermal-cycle imaging technique (Robertson et al. 2005), tend to nucleate at the surface of these thin-film coatings to form what have been hypothesized to be "liquid crystals". Thus, it was hypothesized that the processes by which this phenomena occurs (e.g., hydrodynamic flow, diffusion, nucleation, buoyancy, etc.) coupled with surface oxidation could be an important contributor to the formation of cracks that appear at the surface of a pavement.

Unfortunately it was also observed that the presence of these "liquid crystal" wax moieties tended to obscure detection by AFM imaging techniques of other composition-moieties (classes of molecules) of these materials (e.g., asphaltenes, maltenes, and resins for example) in thin-film coatings that are more likely to be susceptible to oxidation and interaction with water than the waxy materials. Thus, in situ chromatographic methods of separating (contrasting) the various composition-moieties in asphalt thin-films was developed to observe other micro/nano-structures in order to further investigate their compositional and physical properties (and relationships) as they related to fatigue cracking and healing, propensity for oxidation embrittlement, and moisture susceptibility.

Non-equilibrium thermodynamic processes involving "dissipative structures" have been derived based on the theory of extended irreversible thermodynamics (EIT) originally formulated by Glansdorff and Prigogine (1971). Dissipative structures, which are defined for a thermodynamic state of a material far from equilibrium (e.g., phase transition phenomena, colloidal dispersion phenomena and process of energy dissipation associated with crazing and slow crack growth) (Wessling 1995), may be exploited to "project-out" changes in the micro/nanostructure of the system in order to predict the longevity of a material. Glansdorff and Prigogine originally proposed an inequality theorem that defines the entropy production at steady state under very general conditions. Under these general conditions, the flux-force relationship is considered to be non-linear, the Onsager reciprocal relationship is invalid (McQuarrie and Simon 1999), and phenomenological coefficients become time-dependent. The total entropy production, S_{total}, in an open system may then be defined as

$$S_{total} \equiv \dot{S}_{prod} = \int \sum_i J_i X_i dV \qquad \text{(F1d-7.1)}$$

where $J_i's$ are material property fluxes (e.g., concentration, surface tension and temperature gradients for example), $X_i's$ are the forces which drive these fluxes, where the sum of the flux-force pairs is defined over volume element dV.

The analysis that follows entails taking the time derivative of the total entropy production in order to develop stability conditions applicable to "dissipative structures" (Serdyukou 2004). The Glansdorff-Prigogine inequality theorem may then be stated by a cross partial derivative expressed as

$$\frac{\partial_X S_{total}}{\partial t} = \left| J_i \left[\frac{(X_i \partial x)}{\partial x} \right] \right|_0^x - \int_0^x \left[\frac{(X_i \partial x)}{\partial t} \right] \frac{\partial J_i}{\partial x} dx = - \int_0^x \left[\frac{(X_i \partial x)}{\partial t} \right] \frac{\partial J_i}{\partial x} dx \qquad \text{(F1d-7.2)}$$

Three conditions may be considered to define the total entropy production of a model binary system; 1) a hypothetical volume of length = x, which conducts heat where the flux-force is defined by $J_i = J_{U,}$ and $X_i \partial x = \partial(1/T)$, where the two ends of the volume are held fixed at $x = 0$ and $x = x$, and where $\partial(1/T)/\partial t = 0$, 2) a hypothetical binary solution exhibiting one-dimensional isothermal diffusion where the flux-force is defined by $J_i = J_i^D$ and $X_i \partial x = \partial(\mu_i / T)$, and $X_i = (-1/T)(\partial \mu_i / \partial x)$, and 3) a one-dimensional line tension and given surface of this volume where the flux-force is defined by $J_i = \dot{\boldsymbol{\varepsilon}}$, and $X_i \partial x = \partial(\gamma_i / T)$, where $X_i = (1/T)(\partial \gamma_i / \partial x)$ (Glansdorff and Prigogine 1971; Serdyukou 2004; Wessling 1995; McQuarrie and Simon 1999). An expression may then be derived for the time-rate-of-change in the total entropy production of a metastable binary mixture system,

$$\frac{\partial_X S_{total}}{\partial t} = - \int_{x=0}^{x=x} \frac{\rho \overline{C}_V}{T^2} \left(\frac{\partial T}{\partial t} \right)^2 dx - \int_{x=0}^{x=x} \frac{1}{T} \left(\frac{\partial \mu_i}{\partial t} \right)^2 \left(\frac{\partial c_i}{\partial \mu_i} \right)_{V,T,n_j} dx + \int_0^x \frac{1}{T} \left(\frac{\partial \gamma}{\partial t} \right) \frac{\partial \dot{\boldsymbol{\varepsilon}}}{\partial x} dx \le 0 \qquad \text{(F1d-7.3)}$$

where, at some given metastable state

$$\int_0^x \frac{1}{T} \left(\frac{\partial \gamma}{\partial t} \right) \frac{\partial \dot{\boldsymbol{\varepsilon}}}{\partial x} dx \approx \int_{x=0}^{x=x} \frac{\rho \overline{C}_V}{T^2} \left(\frac{\partial T}{\partial t} \right)^2 dx + \int_{x=0}^{x=x} \frac{1}{T} \left(\frac{\partial \mu_i}{\partial t} \right)^2 \left(\frac{\partial c_i}{\partial \mu_i} \right)_{V,T,n_j} dx \qquad \text{F1d-7.4)}$$

An expression for the interfacial surface free energy may then be derived as

$$\gamma = \int_{x=0}^{x=x} \left[\rho \bar{C}_V T \nabla_x T + \mu_i \nabla_x c_i \right] x dx \tag{F1d-7.5}$$

given molar heat capacity $\bar{C}_V$, density ρ, chemical potential μ_i, concentration c_i, strain rate $\dot{\boldsymbol{\varepsilon}}$, and temperature T. Thus, this derivation of surface free energy which develops at the interfaces of our hypothetical binary solution, as derived based on Glansdorff and Prigogine's theory of extended irreversible thermodynamics (EIT) (Glansdorff and Prigogine 1971; McQuarrie and Simon 1999; Serdyukou 2004; Wessling 1995) may be used to establish a thermodynamic basis for diffuse interfaces.

Phase-field models describe the dynamics of a diffuse interface associated with binary solution mixing, or crystallization and melting phenomena, usually treated in terms of kinetic rate equations that describe the rate of change of one phase of a material, φ, as it transforms into a second phase (i.e., liquid to solid transformation in solidification and crystallization processes, or crack-face openings, as two examples). The Cahn-Hilliard model of diffuse interfaces, derived, based on Cahn and Hilliard's original publications on the subject (Cahn and Hilliard 1958, 1959a and b; Cahn 1965] describes the free energy state which exists between two different materials or between two different phases of the same material defined in terms of a free energy functional, $\mathcal{F} = \mathcal{F}\left[f_0(\varphi), \nabla\varphi, \right]$, which is a composite function of a "local" free energy term, $f_0(\varphi)$, and a gradient "penalty" term, $\nabla\varphi$. In other words, the Cahn-Hilliard model assumes that some degree of mixing of materials or phases of a material tends to take place to a finite degree at any interface when temperature, and possibly strain effects are taken into consideration.

In metals solidification for example, phase-field models take into account the mushy zone that develops between the liquid and solid phases of an interface where a solidification front is being tracked with time as metal "crystal" formation takes place. This same type of approach may be applied to the description of the dynamics of wax crystal formation in asphalt thin-film coatings for example, or phase separation in a binary mixture of polymer and colloids (asphalt), or to describe the interface that develops between a crack void (space) in a brittle or viscoelastic material that is undergoing crack propagation.

Diffuse Interface Theory Applied to Asphalt-Polymer Spinodal Blends in nano-Thin-Film Chromatography. Diffuse interface theory/dynamics (Cahn and Hilliard 1958, 1959a and b; Cahn 1965] has become commonplace for defining the interfacial free energy contributions to material phases in the crystallization of salts and solidification of metals. In the field of polymer science for example, diffuse interface theory is exploited to develop phase-field models to study the interfacial free energy contributions to polymer crystallization (Kyu et al. 2000; Mehta et al. 2004a and b; Xu et al. 2005), polymer interaction with colloids (Sear 2000, 2002), and crazing and fracturing in polymer films (Buxton and Balazs 2004). Sear (2000, 2002) has utilized diffuse interface theory to study mixing and subsequent phase separation in polymer-colloid composite systems. According to this approach the polymer-colloid interfacial surface free energy may be initially expressed as

$$\gamma = \int \left[f(\varphi) + \mathbf{\kappa} (\nabla_x \varphi)^2 \right] dx \tag{F1d-7.6}$$

where the local free energy density, $f(\varphi)$, is defined as

$$f(\varphi) = \omega\left[\varphi_C(x)\right] - \omega^{(b)} - \mu_C\left(\varphi_C(x) - \varphi_C^{(b)}\right) \tag{F1d-7.7}$$

$f(\varphi)$ may be defined in terms of the number density of colloid particles present in the system, φ_C, the chemical potential of the colloid particles, μ_C, and a characteristic thermodynamic potential, ω, which is a function of the colloid particle number density and the activity of the polymer, a_P. If Cahn-Hilliard diffuse interface modeling is applied to these conditions, the interfacial surface free energy may eventually be derived as

$$\gamma = 2\int_{\varphi_C^{(P)}}^{\varphi_C^{(C)}} \sqrt{\mathbf{\kappa} f(\varphi)}\, d\varphi_C \tag{F1d-7.8}$$

Sear further suggests that if linear response theory is applied to this result, the gradient penalty term is then expressed as

$$\mathbf{\kappa} = \frac{k_B T}{12} \int \psi(r; \varphi_C, a_P) r^2 d\mathbf{r} \tag{F1d-7.9}$$

where $\psi(r; \varphi_C, a_P)$ defines a correlation function describing the potential field of the colloid particle fluid in the presence of the polymer. Based on this approach, it is observed that the stability of this type of mixture is sensitive to the average diameter of a colloid particle, σ, the chain length of the polymer, R_e, and the intermolecular distance between colloid and polymer particles, r, where the following results are found to hold;

$$\psi(r; \varphi_C, a_P) = -1 \quad @ \quad r < \sigma \tag{F1d-7.10}$$

$$\psi(r; \varphi_C, a_P) = a_P R_e^2 \sigma \left(\frac{\sigma}{r} \right) \quad @ \quad \sigma < r \le R_e \tag{F1d-7.11}$$

$$\psi(r; \varphi_C, a_P) = 0 \quad @ \quad r \gg R_e \tag{F1d-7.12}$$

Thus, it is observed that when large polymers (i.e., long chain length, high molecular weight) are combined with much smaller diameter colloidal particles, the mixture has a tendency to phase separate via spinodal decomposition (figures F1d-7.1 and F1d-7.2).

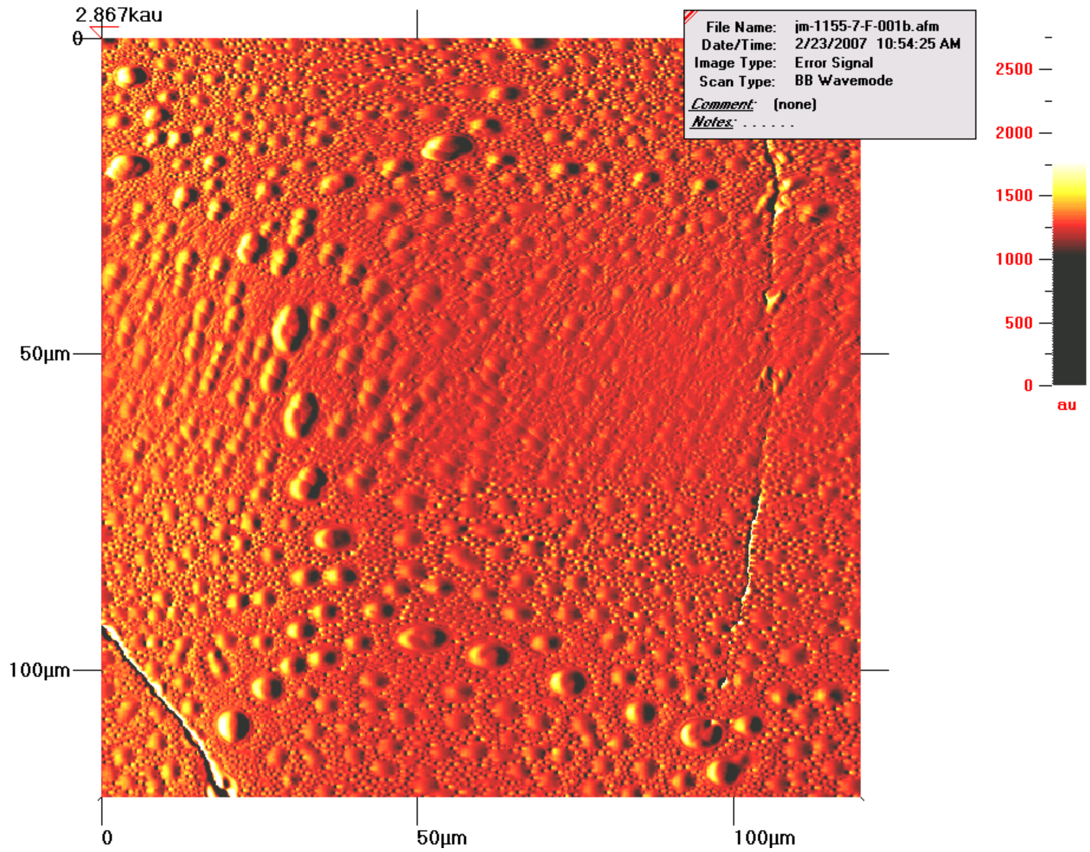


Figure F1d-7.1. AFM Wave-mode topography image: 50% by mass 13k polystyrene blended with 50% by mass AAD-1, ~0.5-µm thick film.

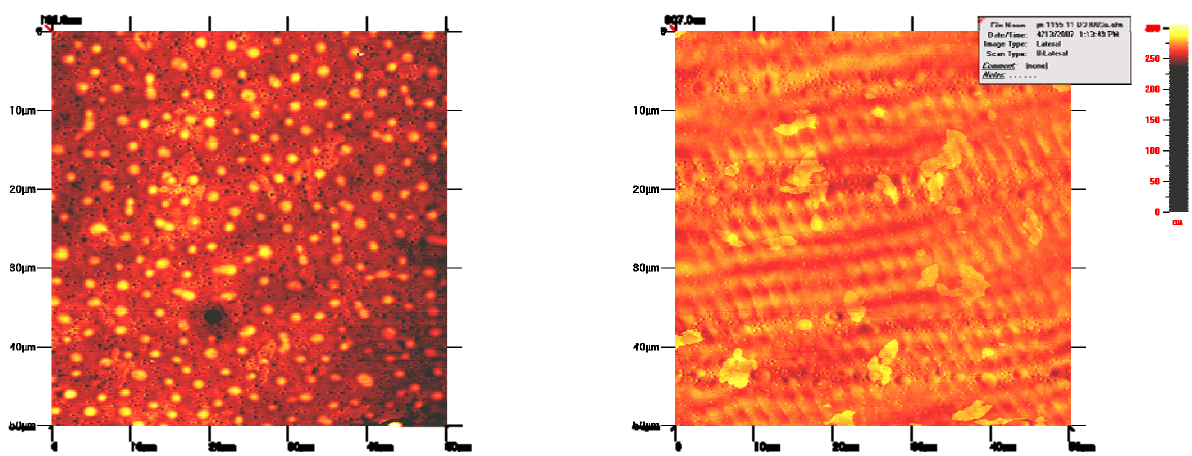


Figure F1d-7.2. Topography (left-hand) and lateral-friction (right-hand) image: 50% 13k polystyrene blended with 50% AAK-1, ~0.5-µm thick film.

Diffuse Interface Theory and Phase-Field Models Applied to Wax Crystallization in Asphalt and Asphalt-Polymer Spinodal Blends in nano-Thin-Film Chromatography. In work conducted at WRI, ion exchange chromatography has been utilized as a method of separating non-polar material from asphalt, resulting in a "lube-oil" like material that is eluted from the columns after separation of polar moieties has taken place. This material, commonly referred to as the neutral fraction is suspected to contain the majority of the crystallizable portion of asphalt, commonly referred to as wax. Neutral fraction materials recovered from the SHRP core asphalts, generated by fast ion exchange chromatography, were prepared as thin-film coatings (thickness = 1-µm to150-nm, 500-nm nominal) on glass microscope slides and then studied by intermittent-contact mode (WaveMode) atomic force microscopy. It is clearly observed from these studies that some form of complex re-ordering of molecular components takes place at the thin-film free surfaces as a function of time and temperature. Furthermore, the micro-structures that are observed at or near ambient temperature are easily described as the familiar "bumble-bee" micro-structures (Loeber et al. 1996). Wax re-crystallization in thin films of asphalt and asphalt fractions, could be modeled employing phase-field derivations (Kyu et al. 2000; Mehta et al. 2004a, 2004b; Xu et al. 2005), where the total free energy of crystal ordering,

$$\mathcal{F}_{\text{crystal}} = \int_V \left(f_0 + f_\nabla + f_\theta + f_\lambda + f_{\alpha\theta} \right) d\Omega \tag{F1d-7.13}$$

is derived in terms of the local free energy based on an asymmetric double well potential and potential field strength Φ_φ, defined as

$$f_0 = \Phi_\varphi \left[\frac{\varphi^2}{2} - \left(1+\zeta\right)\frac{\varphi^3}{3} + \frac{\varphi^4}{4} \right] \tag{F1d-7.14}$$

where φ is the crystal order parameter (non-conserved).

A free energy gradient "penalty" is further defined as

$$f_\nabla = \frac{\left(\boldsymbol{\kappa}\nabla\varphi\right)^2}{2} \tag{F1d-7.15}$$

which quantifies to what degree of "diffuseness" the interface is observed to exhibit.

For a crystal composed of a chain folded lamella with periodic undulations, a curvature elastic free energy term

$$f_\theta = \frac{1}{2}\left[\boldsymbol{\kappa}_\theta \left(\nabla\theta\right) + \varepsilon\left(\nabla^2\theta\right)^2 \right] \tag{F1d-7.16}$$

is added, where a free energy density of elastic deformation, i.e., the strain recovery potential associated with the deformation or volume contraction during crystallization is defined as

$$f_{\lambda} = \Phi_{\theta}\left[\frac{\theta^4}{2} - 4(\lambda_r - 1)\theta^2\right] \quad \text{(F1d-7.17)}$$

given

$$\lambda = \lambda_r \cos(\theta) \quad \text{(F1d-7.18)}$$

Φ_{θ} is defined as the elastic modulus, and θ is the angle of chain tilt of polymer molecules that comprise the lamella, and λ_r is the maximum recoverable strain.

Finally $f_{\alpha\theta}$ is the free energy due to coupling between the asymmetric double well potential and the tilt angle effects, expressed as

$$f_{\alpha\theta} = -\alpha\theta\left(\varphi - \varphi^2\right) \quad \text{(F1d-7.19)}$$

A time-dependent Ginzburg-Landau rate equation (Igor and Kramer 2002) for crystal ordering is then given as

$$\frac{\partial \varphi}{\partial t} = -M_{\varphi}\frac{\partial \mathcal{F}}{\partial \varphi} \quad \text{(F1d-7.20)}$$

$$\frac{\partial \varphi}{\partial t} = -M_{\varphi}\left[\Phi_{\varphi}\left(\varphi^2 - \varphi\right)(\varphi + \zeta) - \left(\boldsymbol{\kappa}_{\varphi}\right)^2 \nabla^2 \varphi - \alpha\theta(1 - 2\varphi)\right] \quad \text{(F1d-7.21)}$$

where the rate of change in the tilt-angle may be expressed as

$$\frac{\partial \theta}{\partial t} = -M_{\theta}\frac{\partial \mathcal{F}}{\partial \theta} \quad \text{(F1d-7.22)}$$

$$\frac{\partial \theta}{\partial t} = -M_{\theta}\left\{\Phi_{\theta}\theta\left[4(\lambda_r - 1) - \theta^2\right] - \boldsymbol{\kappa}_{\theta}\nabla^2\theta + \varepsilon\nabla^4\theta - \alpha\theta(1 - \varphi)\right\} \quad \text{(F1d-7.23)}$$

Figure F1d-7.3 depicts topography images of SHRP asphalts; AAK-1 and AAC-1, and maltenes and IEC neutral fractions of these two asphalts. Wax lamellas are readily observed in almost all of the images shown (particularly in the right hand images). Figure F1d-7.3 further depicts wax lamella, represented as the bright spots in the lateral-friction (right-hand) image. The theoretical model discussed herein, is one mechanism that may be used to describe wax "liquid crystals", lamellas, which tend to nucleate and crystallize at the top surface of an asphalt or asphalt fraction thin-film, most likely due to hydrodynamic flow and buoyancy, as well as to model the rippled structure that results.

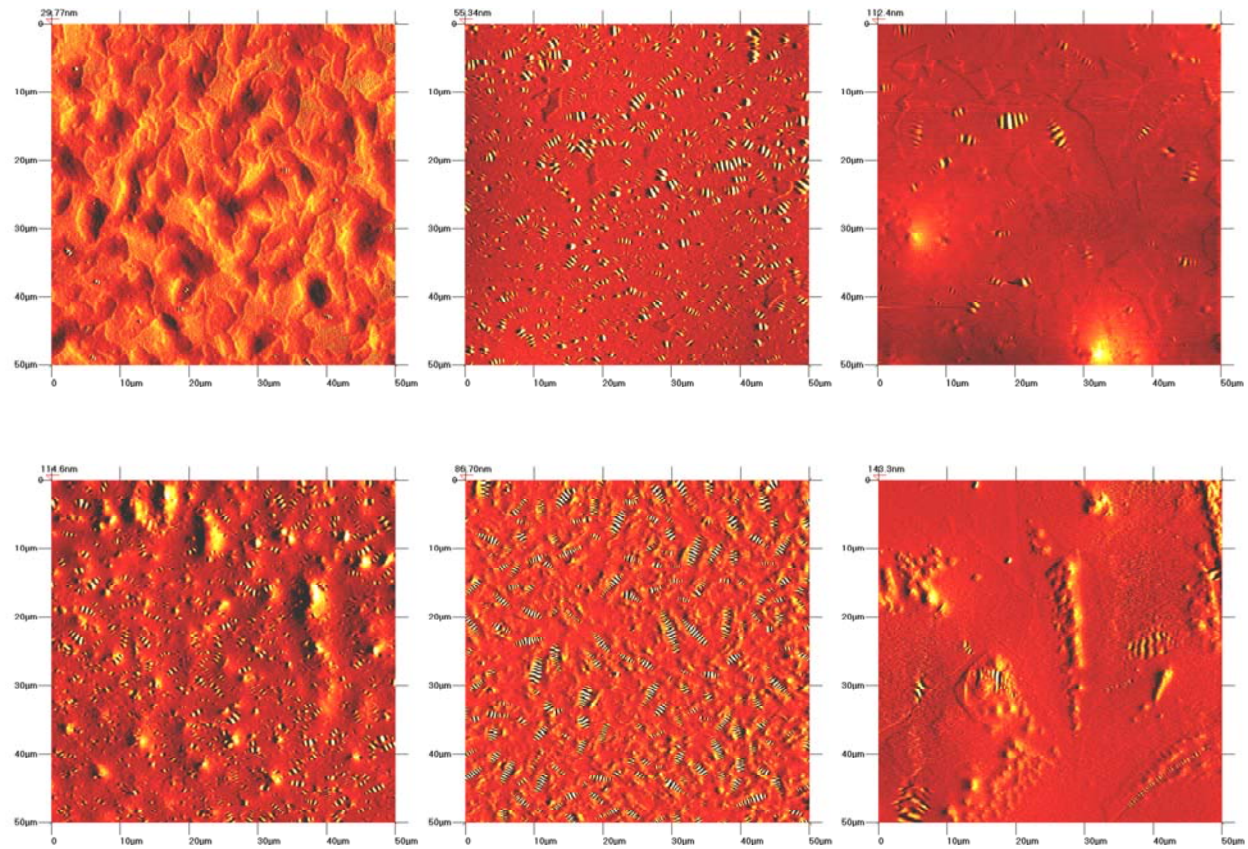


Figure F1d-7.3. AFM Wave-Mode topography images of two neat SHRP asphalts AAK-1 (top image set) and AAC-1 (bottom image set), (left-hand), and asphalt fractions; maltenes (middle) and IEC-neutrals (right-hand).

Fracture Modeling based on Phase-Field Models. Diffuse interface theories have also been adopted to describe fracture, crack growth and crazing phenomena that are observed in asphalt-polymer matrix thin-films. Phase-field models describing brittle fracture in hypothetical materials have been proposed (Buxton and Balazs 2004; Marconi and Jagla 2005; Hopper 1976; Eastgate et al. 2002; Henry and Levine 2004; Karma et al. 2001). These models are generally based on rate laws of phase transformations at an interface described by unbroken-to-broken states of the material, where one phase is defined by the intact material, and a second phase is defined by the void created at the crack interface. As an example (Eastgate et al. 2002), a total free energy functional, $\boldsymbol{\mathcal{F}}_{\text{fracture}}$, for the propagation of a crack may be defined as

$$\boldsymbol{\mathcal{F}}_{\text{fracture}} = \int_V \left(f\left(\varphi,\varepsilon\right) + \frac{w^2}{2}\left|\nabla\varphi\right|^2 \right) dV \qquad \text{(F1d-7.24)}$$

where

$$f\left(\varphi,\varepsilon\right) = \frac{h^2}{4}\varphi^2\left[\varphi_s\left(\varepsilon\right)-\varphi\right]^2 + \varphi^2 E\left(\varepsilon\right) \qquad \text{(F1d-7.25)}$$

is the local free energy density defined as a function of an interfacial order parameter, φ, and strain, ε, where $E(\varepsilon)$ is an elastic strain energy defined by

$$E(\varepsilon)=\frac{1}{2}\sigma_{ij}\varepsilon_{ij} \tag{F1d-7.26}$$

The components of a strain-field are further defined in terms of the following displacement vectors, u_i and u_j as

$$\varepsilon_{ij}=\frac{1}{2}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right) \tag{F1d-7.27}$$

The components of stress, σ_{ij}, are then defined as

$$\sigma_{ij}=\lambda\varepsilon_{mm}\delta_{ij}+2\mu\varepsilon_{ij} \tag{F1d-7.28}$$

where Lamb's constants, λ and μ, correspond to (are proportional to) the shear and bulk modulus', respectively. The total free energy functional is then fully expressed as

$$\mathcal{F}=\int_V\left(\frac{h^2}{4}\varphi^2\left[\varphi_s(\varepsilon)-\varphi\right]^2+\varphi^2\frac{1}{4}\left(\lambda\varepsilon_{mm}\delta_{ij}+\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\right)\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)+\frac{w^2}{2}\left|\nabla\varphi\right|^2\right)dV \tag{F1d-7.29}$$

Rate laws may then be defined for the rate of change in the phase-field parameter φ, and the displacement field, $\mathbf{u}$, expressed as

$$\frac{\partial\varphi}{\partial t}=-\nabla\cdot\left[-D\nabla\frac{\partial\mathcal{F}}{\partial\varphi}+\varphi\frac{\partial\mathbf{u}}{\partial t}\right] \tag{F1d-7.30}$$

and

$$\frac{\partial\mathbf{u}}{\partial t}=-\frac{1}{\eta}\left(\frac{\partial\mathcal{F}}{\partial\mathbf{u}}+\varphi\nabla\frac{\partial\mathcal{F}}{\partial\varphi}\right) \tag{F1d-7.31}$$

where the governing rate law is expressed as

$$\frac{\partial\varphi}{\partial t}=-\nabla\cdot\left[-\left(D+\frac{\varphi^2}{\eta}\right)\nabla\frac{\partial\mathcal{F}}{\partial\varphi}-\frac{\varphi}{\eta}\frac{\partial\mathcal{F}}{\partial\mathbf{u}}\right] \tag{F1d-7.32}$$

where η is the shear viscosity, and D is the diffusion constant.

Figure F1d-7.4 depicts a Spinodal-blend thin-film coating of 50:50 mass percent SHRP asphalt AAD-1 prepared with 13k polystyrene spin cast as a sub-micron thin film. These films, which initially exhibit crazing (i.e., figure F1d-7.4 depicts optical microscope images of Spinodal-blend thin-films containing AAD-1 prepared with 13k polystyrene) were re-imaged with AFT six months later, and were often observed to "heal" in spots based on the observation that the globular phases of the film had begun to reconsolidate in regions of the film where clean cracks had originally been observed. Thus, as the fracture phase-field modeling approach would suggest, crack opening and closing phenomena is likely due to flow and diffusion of mobile materials (molecules) present in the system. The modeling approach presented here essentially constitutes a starting point for future investigations on the topic of cracking and healing in idealized (simple) systems.

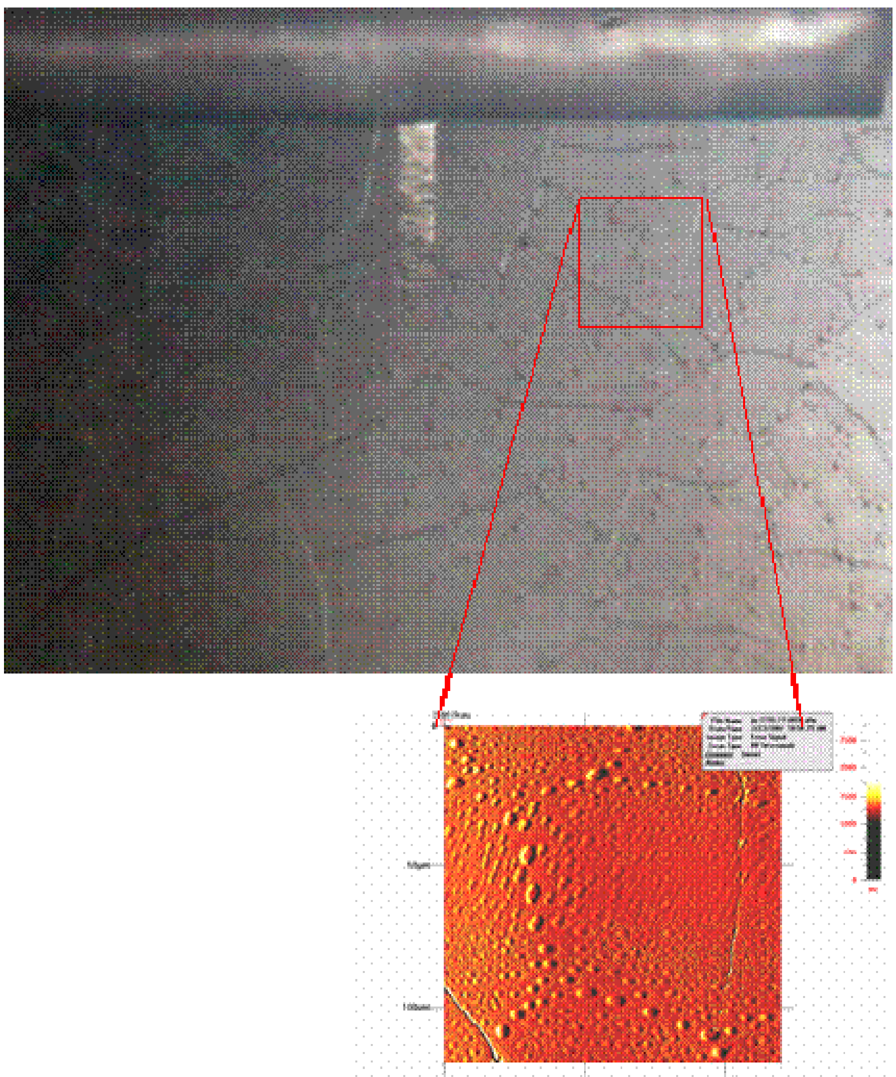


Figure F1d-7.4. Microscope image: 50% 13k polystyrene blended with 50% AAD-1, ~0.5-μm thick film.

The three models presented here demonstrate how the heterogeneity of a material results in a build up in stress in the system to promote crazing in these samples. Thus, application of this type of modeling approach may be exploited to study and quantify the compositional nature of crazed thin-film coatings to define mechanisms of fracture and self-healing in pavements. This may be ultimately accomplished by assuming the forward and reverse processes of the rate laws defined by equation F1d-7.32, summarized as follows

$$\begin{aligned} &\mathcal{J}_{\text{fracture}} = -\mathcal{J}_{\text{healing}} \\ &i.e., \left(\frac{\partial \varphi}{\partial t}\right)_{fracture} = \left(\frac{-\partial \varphi}{\partial t}\right)_{healing} \end{aligned} \qquad \text{(F1d-7.33)}$$

given the following functional relationships

$$\begin{aligned} &g\left(\mathcal{J}_{\text{fracture}}\right) = g\left(\mathcal{J}_{\text{composition}}\right) \\ &= g\left(\sum_{\text{i}} \mathcal{J}_{\text{i}}\right) = g\left(\mathcal{J}_{\text{crystalization}} + \mathcal{J}_{\text{flocculation}} + \mathcal{J}_{\text{acid-base paring}} + \mathcal{J}_{\text{oxidation}} + \cdots\right) \end{aligned} \qquad \text{(F1d-7.34)}$$

The utility of using the approach of dissipative structures to describe pavement failure is in its ability to extrapolate, or project-out changes in compositional properties of a material system as a function of time, temperature, and possibly moisture variations and reactions with oxygen, by taking into account, outside influential variables defining the total entropy production of the system. As a system changes, or evolves with time, the equilibrium state of the material changes, fluctuating throughout the life expectancy of the system, and then finds new equilibrium states that occur in between each of the dissipative state changes. In this manner, dissipative states, in addition to equilibrium states of the material, should then be considered in any model that attempts to predict performance of a material's life span.

In asphalt pavements for example, energy dissipation may be related to material viscoelastic relaxation, which is likely a process, in part, of molecular re-orientations. Viscoelastic relaxation, in turn, may be shown to be defined by the non-equilibrium thermodynamic flux-force approach. If this concept is exploited, then it may be hypothesized that many other factors which contribute to pavement failure may be taken into account, for example, oxidation rates, water uptake, moisture migration, contaminants such as fuels and oils, atmospheric pressure and temperature changes, just to name a few (equation F1d-7.34). Thus, a description of energy and matter dissipation mechanisms could be developed to model micro cracking and crazing mechanisms as they evolve with changes in material composition.

<u>Relationship to FHWA Focus Areas</u>

This work element is related to the following focus areas:

- Optimum Pavement Performance- Introducing methods for better characterization of neat asphalts.

- Advanced quality systems: Further development of test methods that are more related to actual pavement performance.

Hypothesis

Micro-fracture (crazing) and subsequent healing characteristics of an asphalt binder/mastic composite system depends on its bulk and surface physico-chemical properties, specifically phase transformation phenomena driven by composition gradients, thus, Cahn-Hilliard kinetics may be employed to model these phenomena.

Objectives

i) Develop experimental techniques that require the minimum amount of time and materials to quantify asphalt binder and aggregate surface physico-chemical and nano-mechanical properties based on nanotechnology. (e.g., nano-Thin-Film Chromatography/ Composition Analysis, nano-Mechanics, nano-indentation, nano-surface tensiometry, AFM solidification analysis, programmable dynamic wetting/spin-coating via Lubrication Theory, and programmable combinatorial-automated flocculation titrimetry (PC-AFT)) to be used as input in phase-field models.
ii) Develop correlations between image analysis data of spinodal-blend systems and asphalt physico-chemical data including mass fractions of asphalt fractions, and differences in chemical potentials of fractions to determine the compositional driving forces and gradients of asphalt binder.
iii) Develop approaches (Experimental) based on nanotechnology which lead to data-input for computational software (e.g., Virtual Asphaltic Concrete Testing Laboratory (VACTL) to model physico-chemical and chemo-mechanical properties of asphalt/aggregate (mastic) systems.

Experimental Design

In this subtask the preliminary job will be to conduct data analysis of a backlog of experimental results to determine physico-chemical properties of the systems discussed including chemical potentials phase separation phenomena to be fed back into the asphalt microstructure model discussed in Work Element F3a. The data generated from these analyses will then be incorporated into the chemo-mechanical models of asphalt and asphalt mastic structures.

Overall Work Plan

Sub-Subtask F1d-7.1: Conduct image analyses of pre-existing results (AFM imaging data of thermally cycled thin films, Spinodal-Blend Films, and asphalt fraction materials representing the eight SHRP core asphalts).

Sub-Subtask F1d-7.2: Determine asphalt compositional properties from image analysis data and preparation of a database of results.

Year 2 Schedule

Sub-Subtask F1d-7.1 will be conducted during the remainder of year 2 and into year three.

Milestones

Complete Sub-Subtask F1d-7.1 and submit a short report during Year 3.

Overall Schedule

Sub-Subtask F1d-7.1 will be conducted during the remainder of year 2 and into year three. Sub-Subtask F1d-7.2 will be conducted during the remainder of year 3.

References

Barth, E. J., 1962, *Asphalt Science and Technology*, Gordon and Breach Science Publishers, New York.

Buxton, G. A., and A. C. Balazs, 2004, Modeling of Dynamic Fracture of Polymer Blends Processed Under Shear. *Phys. Rev. B.*, 69, 054101.

Cahn, J. W., 1965, Phase Separation of Spinodal Decomposition in Isotropic Systems. *J. Chem. Phys*., 42(1): 93-99.

Cahn, J. W., and J. E. Hilliard, 1958, Free Energy of a Nonuniform System. I. Interfacial Free Energy. *J. Chem. Phys*., 28(2): 258-267.

Cahn, J. W., and J. E. Hilliard, 1959a, Free Energy of a Nonuniform System. II. Thermodynamic Basis. *J. Chem. Phys*., 30(5): 1121-1124.

Cahn, J. W., and J. E. Hilliard, 1959b, Free Energy of a Nonuniform System. III. Nucleation in a Two-Component Incompressible Fluid. *J. Chem. Phys*., 31(3): 688-699.

Eastgate, L. O., J. P. Sethna, M. Rauscher, T. Cretegny, C.–S.Chen, and C. R. Myers, 2002, Fracture in Mode I Using a Conserved Phase-Field Model. *Phys. Rev. E.*, 65, 036117.

Glansdorff, P., and I. Prigogine, 1971, *Thermodynamic Theory of Structure, Stability and Fluctuations*, Wiley-Interscience, division of John Wiley & Sons, Ltd., London.

Henry, H., and H. Levine, 2004, Dynamic Instabilities of Fracture Under Biaxial Strain Using a Phase-Field Model. *Phys. Rev. Lett.*, 93(10): 105504.

Hopper, R. W., 1976, Viscosity and Viscoelasticity of Two-Phase Systems Having Diffuse Interfaces. *Phys. Rev. Lett.*, 36(5): 289-292.

Igor, S. A. and L, Kramer, 2002, The world of the Complex Ginzburg-Landau Equation. *Rev. Mod. Phys.,* Vol. 74, No. 1, 99-143.

Karma, A., D. A. Kessler, and H. Levine, 2001, Phase-Field Model of Mode III Dynamic Fracture. *Phys. Rev. Lett.*, 87(4): 045501.

Kyu, T., R. Mehta, and H-W Chin, 2000, Spatiotemporal Growth of Faceted and Curved Single Crystals. *Phys. Rev. E.*, 61(4): 4161-4170.

Loeber, L., O. Sutton, J. Morel, J.-M. Valleton, and G. Muller, 1996, New direct observations of asphalts and asphalt binders by scanning electron microscopy and atomic force microscopy. *Journal of Microscopy*, 182(1): 32-39.

Marconi, V. I., and E. A. Jagla, 2005, Diffuse Interface Approach to Brittle Fracture. *Phys. Rev. E.*, 71, 036110.

McQuarrie, D. A., and J. D. Simon, 1999, *Molecular Thermodynamics*. University Science Books, Sausalito, CA.

Mehta, R., W Keawwattana, and T. Kyu, 2004a, Growth Dynamics of Isotactic Polypropylene Single Crystals During Isothermal Crystallization from a Miscible Polymeric Solvent. *J. Chem. Phys.*, 120(8): 4024-4031.

Mehta, R., W Keawwattana, A. L. Guenthner, and T. Kyu, 2004b, Role of Curvature Elasticity in Sectorization and Ripple Formation During Melt Crystallization of Polymer Single Crystals. *Phys. Rev. E.*, 69, 061802.

Nellensteyn, F. J., 1933, Theoretical Aspect of the Relation of Bitumen to Solid Matter. *Proceedings*, First World Petrol Congress, 2: 616-618.

Netzel, D. A., F. P. Miknis, J. C. Wallace, C. H. Butcher, and K. P. Thomas, 1997, Molecular Motions and Rheological Properties of Asphalts: An NMR Study, Chapter 2 in *Asphalt Science and Technology*, Usmani, A. M., Ed., Marcel Dekker, New York.

Netzel, D. A., 2006, Apparent Activation Energies for Molecular Motions in Solid Asphalt, *Energy & Fuels* 20: 2181-2188

Pal, R., and E. Rhodes, 1989, Viscosity/Concentration Relationships for Emulsions. *Journal of Rheology*, 33(7): 1021-1045.

Pauli A. T., and J. F. Branthaver, 1998, Relationship Between Asphaltenes, Heithaus Compatibility Parameters, and Asphalt Viscosity. *Petroleum Science and Technology*, 16(9&10): 1125-1147.

Pauli, A. T., and J. F. Branthaver, 1999, Rheological and Compositional Definitions of Compatibility as They Relate to the Colloidal Model of Asphalt and Residua. *American Chemical Society Division of Petroleum Chemistry Preprints*, 44: 190-193.

Redelius, P. G., 2000, Solubility Parameters and Bitumen. *Fuel*, 79: 27-35.

Robertson, R. E., J. F. Branthaver, P. M. Harnsberger, J. C. Petersen, S. M. Dorrence, J. F. McKay, T. F. Turner, A. T. Pauli, S.-C. Huang, J.-D. Huh, J. E. Tauer, K. P. Thomas, D. A. Netzel, F. P. Miknis, T. Williams, J. J. Duvall, F. A. Barbour, C. Wright, 2001, *Fundamental Properties of Asphalts and Modified Asphalts, Volume I: Interpretive Report*, FHWA-RD-99-212. U. S. Department of Transportation, Federal Highway Administration, McLean, VA.

Robertson, R. E., K. P. Thomas, P. M. Harnsberger, F. P. Miknis, T. F. Turner, J. F. Branthaver, S-C. Huang, A. T. Pauli, D. A. Netzel, T. M. Bomstad, M. J. Farrar, J. F. McKay, and M. McCann. "Fundamental Properties of Asphalts and Modified Asphalts II, Final Report, Volume I: Interpretive Report," Federal Highway Administration, Contract No. DTFH61-99C-00022, Chapters 1-4 submitted for publication, November 2005.

Robertson, R. E., K. P. Thomas, P. M. Harnsberger, F. P. Miknis, T. F. Turner, J. F. Branthaver, S-C. Huang, A. T. Pauli, D. A. Netzel, T. M. Bomstad, M. J. Farrar, D. Sanchez, J. F. McKay, and M. McCann. "Fundamental Properties of Asphalts and Modified Asphalts II, Final Report, Volume I: Interpretive Report," Federal Highway Administration, Contract No. DTFH61-99C-00022, Chapters 5-7 submitted for publication, March 2006.

Saal, R. N. J., W. Huekelom, and P. C. Blokker, 1939, Physical Constants of Asphaltic Bitumen Part 1. *Journal of the Institute of Petroleum*, 26: 29-39.

Schabron, J. F., A. T. Pauli, and J. F. Rovani Jr., 2001, Molecular Weight Polarity Map for Residua Pyrolysis. *Fuel*, 80: 529-537.

Sear, R. P., 2000, Phase Separation in Mixtures of Colloids and Long Ideal Polymer Coils. *Phys. Rev. Lett.*, 86(20): 4696-4699.

Sear, R. P., 2002, Interfacial Tension and Nucleation in Mixtures of Colloids and Long Ideal Polymer Coils. *Phys. Rev. E.*, 65, 062401-4.

Serdyukou, S. I., 2004, Generalization of the Evolution Criterion in Extended Irreversible Thermodynamics. *Physics Letters A*, 324: 262-271.

Sheu, E. Y., 2002, Petroleum Asphaltenes-Properties, Characterization, and Issues. *Energy & Fuel*, 16: 74-82.

Sheu, E., M. DeTar, and D. Storm, 1991, Rheological Properties of Vacuum Residue Fractions in Organic Solvents. *Fuel*, 70: 1151-1156.

Tissot, B. P., and D. H. Welte, 1978, Petroleum Formation and Occurrence A New Approach to Oil and Gas Exploration. Springer-Verlag, Berlin Heidelburg, Germany.

Turner, T. F., and J. F. Branthaver, 1997, DSC Studies of Asphalts and Asphalt Components. In *Asphalt Science and Technology*, A. M. Usmani, Ed., Marcel Dekker, Inc., New York, 59-101.

Wessling, B., 1995, Critical Shear Rate-The Instability Reason for the Creation of Dissipative Structures in Polymers. *Zeitschrift für Physikalische Chemie*, 191: S. 119-135.

Xu, H., R. Matkar and T. Kyu, 2005, Phase-field Modeling on Morphological Landscape of Isotactic Polystyrene Single Crystals. *Phys. Rev. E.*, 72, 011804.

Yen, T. F., and G. V. Chilingarian, 1994, *Asphaltenes and Asphalts 1. Developments in Petroleum Science, 40A*. Elsevier Science B. V., Copyright & Permissions Department, P. O. Box 521, 1000 AM Amsterdam, The Netherlands.

<u>Subtask F1d-8: Coordinate Form of Healing Parameter with Micromechanics and Continuum Damage Models (Continued in year 2)</u>

This subtask will be conducted in coordination with Work Elements F3b and F3c. The objective of this subtask will be to frame the healing property of asphalt binders and mastics, and if required the fine aggregate matrix, in a form that can be easily incorporated in the micromechanics model as well as the unified continuum fatigue model. This subtask will be critical to ensure that healing is appropriately incorporated along with other material properties as a part of these models.

<u>Major Findings from Year 1 for Work Element F1d</u>

A review of literature related to mechanisms and quantification of self healing properties was conducted (F1d-1). A frame work to model the healing process in asphalt materials was developed (F1d-1). A new test method that utilizes the DSR to determine the intrinsic healing function was developed. Results from this test method were compared to known values of healing for selected materials determined using the DMA (F1d-4). Key findings from the literature review, details pertaining to the framework to quantify healing, and preliminary results from the DSR based test method to quantify the healing process in asphalt materials were presented in detail in the Quarterly report ending September 2007 and synthesized in recent publications (Little and Bhasin 2007, Bhasin, Little et al. 2008).

<u>Year 2 Milestones for Work Element F1d</u>

i. Continue the development of test methods to measure material properties related to healing mechanism and extend these test methods to mastics.
ii. Refine framework to incorporate the net healing in a fatigue model.
iii. Measure material properties related to healing for select asphalt binders and mastics.

Category F2: Test Method Development

Work Element F2a: Binder Tests and Effect of Composition

Task Lead: Codrin Daranga

Introduction

A successful modification of an asphalt binder with a polymer is intended to improve one or more of the basic asphalt properties such as rigidity, elasticity, brittleness, durability, and compatibility – especially in-blend compatibility. An asphalt-polymer blend is considered compatible if the polymer is soluble in the asphalt cement or if it can be swollen by the asphalt oils without causing flocculation of the asphaltenes. Most polymer modifiers are used to enhance the rutting resistance of asphalt binders. When it comes to the influence of modifiers on fatigue resistance, some have a positive influence, while others can have a negative influence. It is to be expected that by adding more flexibility (increase in toughness) to the binder, fatigue resistance will increase. If, on the other hand, the modifiers will stiffen the material at medium and low temperatures, then a decrease in fatigue resistance is expected. The morphology of the polymers used as modifiers, as well as their chemical structure and affinities, play an important role on how the binder will perform in field applications. The flexibility of rubbers will bring toughness to the asphalt binder, possibly increasing its fatigue resistance. The hardness of waxes will improve rutting resistance properties. On the other hand, crystallinity promoted by rigid wax chains can diminish the fatigue life of asphalt binders and decrease their low temperature cracking resistance. Therefore, a fine balance needs to be maintained between flexibility and stiffness, between elastic and plastic domains within the asphalt binder, between the affinity towards polar compounds (e.g., mineral aggregate) and moisture damage resistance, etc. In addition to modifiers, aging can have a significant impact on fatigue. It is, however, not clear if aging has a negative effect on fatigue under all conditions of loading. For example, aging is expected to increase stiffness and strength but decrease ductility (flexibility). While increasing stiffness could have a positive effect on stress-controlled fatigue, reduced flexibility and toughness could have a negative effect.

Relationship to FHWA Focus Areas

This work element is related to the following focus areas:

- Optimum Pavement Performance: Introducing methods for better characterization of modified asphalts.
- Advanced quality systems: Further development of test methods that are more related to actual pavement performance.

Hypothesis

The hypothesis is that binder modification has a great impact on fatigue resistance of pavements. Aging of both modified and unmodified binders has its own impact on fatigue life. A fundamental understanding of how polymers interact with asphalt, and how aging and chemical modifiers control binder fatigue, can improve modifier selection process.

<u>Objectives</u>

This work element will focus on developing methods to estimate effect of modification and aging on fatigue resistance and provide a framework for selecting binders to reduce potential for inferior fatigue resistance. The framework will include polymer and asphalt chemistry as well as mechanical properties.

<u>Experimental Design</u>

The objective of this subtask will be addressed as follows:

i. Analyze Existing Fatigue Data on Polymer Modifies Asphalts (Year 1 start). Fatigue studies of unmodified, SBS and acid modified binders have been performed by UW-Madison in collaboration with FHWA for the last three years. Testing was performed using the dynamic shear rheometer (DSR), with three types of procedures of particular focus: stress sweep, stress-controlled frequency sweep, and stress-controlled fatigue. In addition, limited strain controlled testing was conducted. The DSR data was analyzed alongside direct tension data using principles of dissipated energy. This data set will be analyzed to identify most dominant trends in effects of polymers and aging on fatigue of binders. Some limited additional testing will be conducted to define the trends and provide a framework for the new testing plan.

ii. Select Virgin Binders and Modifiers and Prepare Modified Binder (Year 1 start). Based on the results of subtask 1, a complementary work plan will be developed. Modified binders will be prepared using two different "base" virgin binders and four modifiers (SBS rubber, Elvaloy®, Sasobit® wax, and a polyphosphoric acid modifier). In order to better examine the influence of the butadiene moiety along with the variation in ratio between the lengths of the butadiene and styrene blocks, more than one type of SBS will be tested. Every "base" binder will be modified using each of the chemical additives selected. Sample size to be produced will be determined taking into consideration the testing procedures that the materials will be subjected to.

iii. Subject Samples of Virgin and Modified Binder to Several Laboratory Aging Procedures. Samples from both the modified and unmodified types of binders will be subjected to lab aging techniques. This is done to enable the study of aging as a determining factor in the fatigue life of binders. Modified and unmodified binder samples will undergo RTFO and one or more PAV treatments.

iv. Collect Fatigue Test Data for All Samples. This task will concentrate on testing the previously prepared samples according to the work plan in Task 2.

v. Analyze Data and Propose Mechanisms by Which Aging and Modification Influence Fatigue of Binders. The objective of this task is to analyze all the collected data from the previous task. The focus will be on defining mechanisms by which modifiers and aging control fatigue at various conditions. The outlined mechanisms by which it is believed aging and modification affect fatigue life of binders will be used to develop guidelines for selecting modifiers and the tests required to qualify modifiers for improvement of fatigue life.

Major Findings from Year 1

During year one, the materials and testing conditions for the plan were selected and are shown in table F2a.1.

Table F2a.1. Matrix of materials and conditions.

Binders	Flint Hills PG 58-28	Mineral Fillers	Limestone
	Flint Hills PG 64-22		Sandstone
	Marathon PG 58-28	Modifiers	PG xx-34
	Marathon PG 64-22		D1101 Kraton SBS
Testing Temp	19° C		D1184 Kraton SBS
	25° C		Elvaloy AM
Storage time	0h		Elvaloy 4170
	24h		PPA 115
	72h		PPA105
Storage Temperature	135° C		OPA 85

Three binders (one neat, one SBS modified and one Elvaloy modified) were treated with polyphosphoric acid (PPA). The effect of PPA modification was then studied on storage time and presence of mineral filler. Notable results are as follows:

The starting materials are shown below:

- A1 PG 70-22 SBS Modified
- A5 PG 58-22 Neat
- B9 PG 64-28 Elvaloy Modified
- X 115 PPA (polyphosphoric acid)
- Y 105 PPA
- Z 85 OPA (ortho-phosphoric acid)

Table F2a.2 summarizes the PG properties for the starting asphalt binders included in this study. Note that the polymer modified binders were acquired already modified with unknown concentrations of the respective polymer modifiers.

Table F2a.2. PG grading of starting materials.

	A1 SBS PG 70-22		c.v.%	A5 Neat PG 58-22		c.v.%	B9 Elvaloy PG64-28		c.v.%
Original									
G*/sinδ (kPa)	@70°C	1.26	1.61	@58°C	1.12	1.66	@64°C	1.22	1.23
True Grade (°C)	**@1.00 kPa**	**72.5**		**@1.00 kPa**	**59.5**		**@1.00 kPa**	**66.3**	
RTFO									
G*/sinδ (kPa)	@70°C	2.43	0.20	@58°C	2.44	0.24	@64°C	2.76	0.77
True Grade	**@2.20 kPa**	**71.2**		**@2.20 kPa**	**58.9**		**@2.20 kPa**	**66.6**	
PAV									
G*·sinδ (kPa)	@13°C	4939	6.64	@16°C	3831	3.70	@07°C	4161	7.03
True Grade	**@5000 kPa**	**12.4**		**@5000 kPa**	**13.6**		**@5000 kPa**	**5.4**	
Stiffness (MPa)	@-18°C	267.0	2.12	@-18°C	273.3	10.76	@-24°C	258.3	6.45
True Grade	**@300MPa**	**-29.9**		**@300MPa**	**-29.4**		**@300MPa**	**-29.6**	
m-value	@-12°C	0.358	0.40	@-12°C	0.369	7.26	@-24°C	0.310	0.46
True Grade	**@0.300**	**-26.8**		**@0.300**	**-27.8**		**@0.300**	**-28.0**	
TEMP RANGE	**98.0**			**86.7**			**94.3**		

A small percentage of PPA (between 0.5 and 1%wt) raises the high PG grade of the binder by six degrees (one PG grade); 1.5 to 2% wt PPA will bring an additional PG grade raise. Figure F2a.1 shows the effects of the PPA content on the rheological properties of asphalt binders. The effect of increasing the high end of the PG grade is more pronounced on the polymer modified materials than on the neat binders, as indicated in table F2a.3.

There is also a surprising improvement on the low temperature grade of the binders.

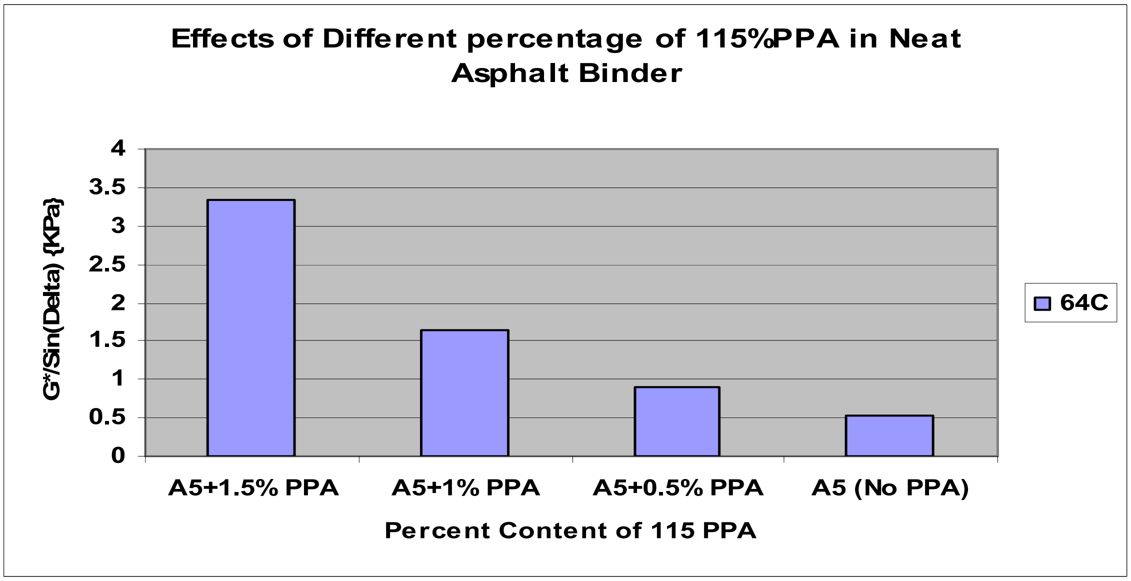


Figure F2a.1. Chart. Effect of PPA concentration on neat asphalt binder.

Table F2a.3. PG grading of binders after modification with 1% 105 PPA.

	A1 SBS PG 70-22		c.v.%	A5 Neat PG 58-22		c.v.%	B9 Elvaloy PG64-28		c.v.%
Original									
G*/sinδ (kPa)	@82°C	1.24	2.87	@64°C	1.25	0.79	@82°C	1.12	5.07
True Grade (°C)	**@1.00 kPa**	**84.7**		**@1.00 kPa**	**66.0**		**@1.00 kPa**	**83.3**	
RTFO									
G*/sinδ (kPa)	@88°C	2.86	3.73	@64°C	2.76	0.18	@88°C	2.68	8.31
True Grade	**@2.20 kPa**	**91.5**		**@2.20 kPa**	**66.0**		**@2.20 kPa**	**91.0**	
PAV									
G*·sinδ (kPa)	@13°C	4046	6.71	@13°C	4472	4.02	@07°C	4775	--
True Grade	**@5000 kPa**	**10.8**		**@5000 kPa**	**11.9**		**@5000 kPa**	**6.5**	
Stiffness (MPa)	@-18°C	200.7	1.39	@-18°C	222.0	3.82	@-24°C	231.0	6.45
True Grade	**@300MPa**	**-31.5**		**@300MPa**	**-30.4**		**@300MPa**	**-36.5**	
m-value	@-18°C	0.307	0.23	@-18°C	0.311	4.55	@-24°C	0.304	0.46
True Grade	**@0.300**	**-28.6**		**@0.300**	**-29.1**		**@0.300**	**-34.7**	
GRADE	**PG 82-28**			**PG 64-28**			**PG 82-34**		
TEMP. RANGE	**113.3°C**			**95.1°C**			**118.0°C**		

The storage experiment was performed at 135°C in closed containers for 24 and 72 hours. For all binders there is a definite trend of increased stiffness with increased storage time, as shown in figures F2a.2 and F2a.3.

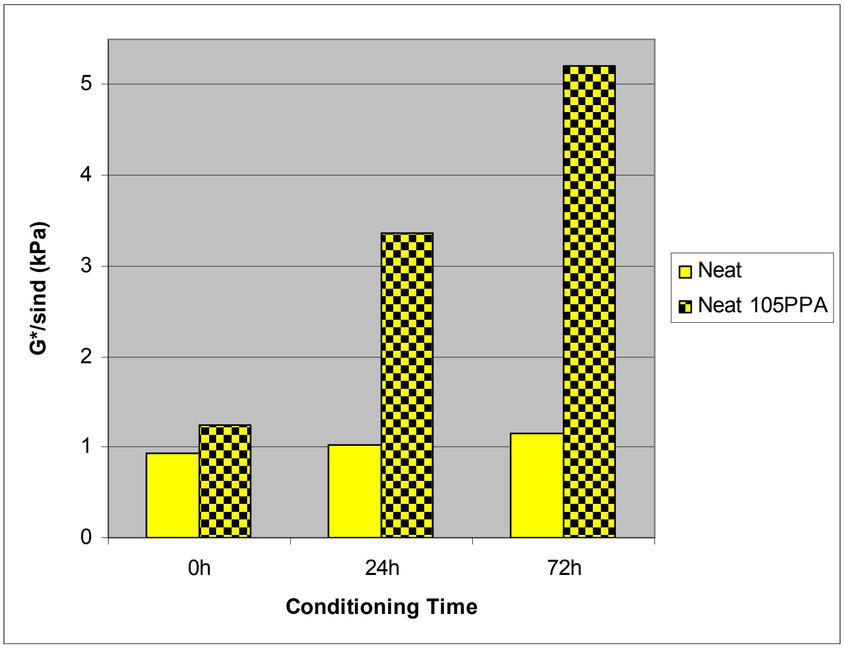


Figure F2a.2. Chart. Effect of conditioning on neat binder @ 135ºC.

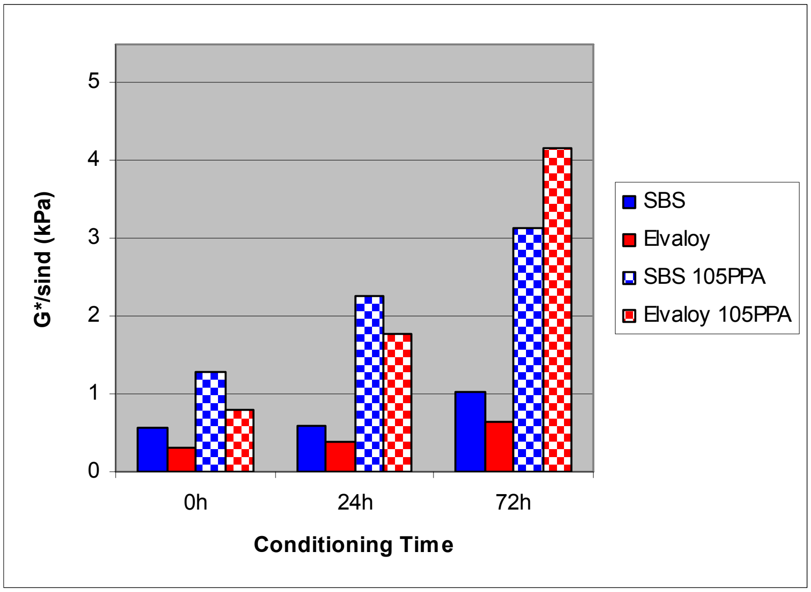


Figure F2a.3. Chart. Effect of conditioning on polymer modified binder @ 135ºC.

This trend is valid for both binders and mastics. As in the case of the high PG grade, this trend is more pronounced for the polymer modified binders than for the neat binder, as shown in figure F2a.4.

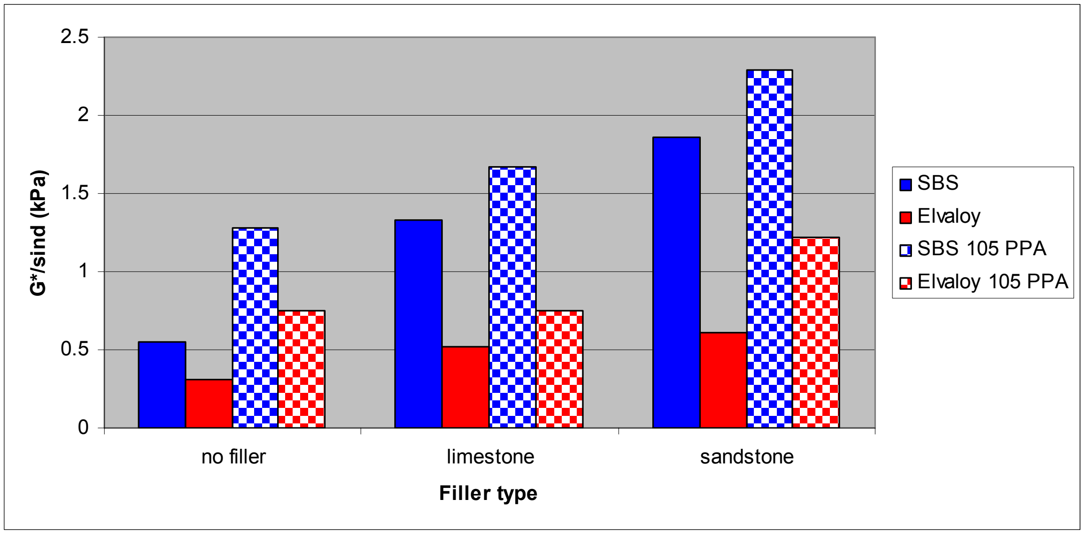


Figure F2a.4. Chart. Effect of filler on polymer modified binders.

In the case of the mastics, the presence of PPA does not seem to have as much of an effect as in the case of binders. However, the trend showing an increase in stiffness when PPA is added is still present.

The increase in stiffness observed in the presence of the PPA is greater than expected. One explanation could be the formation of a gel-like structure in the presence of an acid like PPA. In order to investigate this hypothesis, four samples of binders (two PPA modified and two without PPA) were subjected to stress sweep testing. If a gel-like structure is contributing to the increase in stiffness, then that structure would be expected to collapse under increasing shear stress. As shown in figure F2a.5, no evidence is seen of a gel like structure collapsing, which would indicate the absence of such a structure. However these are just preliminary results and investigation continues into this matter.

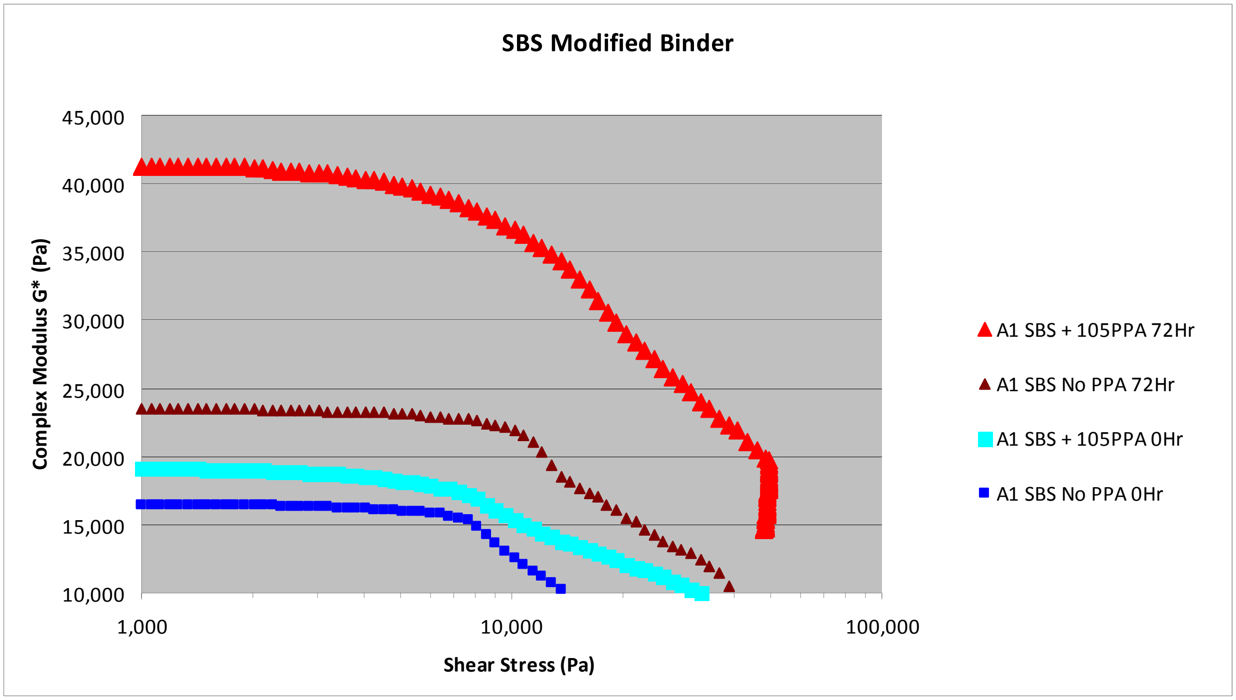


Figure F2a.5. Chart. Stress sweep test results on SBS modified binder with and without PPA, before and after 72 hours of conditioning @135 ºC.

Year 2 Work Plan

Stress sweep tests will be performed on these materials in order to asses their fatigue properties. Also the new monotonic test developed at University of Wisconsin-Madison will be performed. This will not only give a better picture of the influence of different modifiers on fatigue properties of binders, but also will help further validate the monotonic test.

The data analysis on this project will be focused on two main areas: rheological properties and damage resistance characterization.

The rheological properties investigation serves as a tool to classify and rank starting materials, as well as a monitoring tool during the modification and conditioning process. This is accomplished by measuring parameters such as $G^*/\sin\delta$, an indication of the rutting resistance of binders, as well as by performing Multiple Stress Creep Recovery tests on the binders. This will provide important information on how the modification of binders affects not only fatigue but also rutting performance of binders. The rheological properties will also be investigated on laboratory aged binders (Rolling Thin Film Oven and Pressure Aging Vessel) in order to cover the entire service temperature range for these materials. This is done knowing that aged binders usually have a shorter fatigue life than un-aged binders.

The damage resistance characterization part of the investigation will focus on classifying and ranking different modifiers and/or modification techniques based on their impact over the binder's ability to resist damage. This is mainly focused on fatigue damage, but it uses rutting damage control tests to maintain perspective on improving the overall binder properties. Figure F2a.6 depicts the research approach defined for this work element.

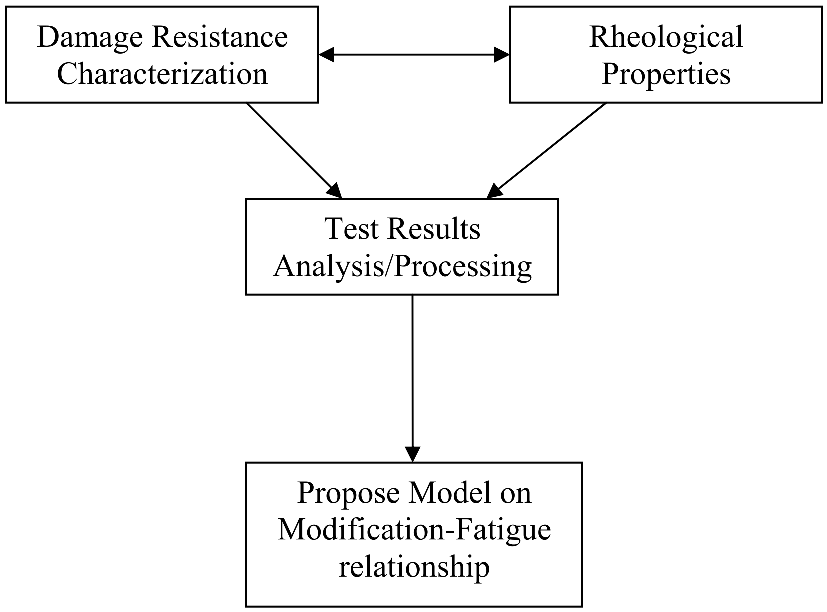


Figure F2a.6. Chart. Flow chart for research approach.

Year 2 Milestones

- Finalize the selection of binders and modifiers
- Subject modified binders to different aging procedures
- Start the fatigue tests on modified binders
- Start analyzing the test results

Budget

The estimated budget for this subtask is $425,000 over the five years. The work will be conducted by the University of Wisconsin-Madison.

Work Element F2b: Mastic Testing Protocol

This work element will be performed in close coordination with the Technology Development work area of this Consortium. Accordingly, some part of the budget for this work element has been allocated in the Technology Development work area.

The test protocol to determine mechanical properties of asphalt mastics and fine aggregate matrix (FAM) is an important component of the unified fatigue damage model. The test method will serve dual purposes of (i) validating the expected response of asphalt mastic or fine aggregate matrix based on fundamental material properties, and (ii) generating input that will be required for micromechanical or continuum fatigue model. Significant work has been done in the past at the Texas A&M University to develop the use of a Dynamic Mechanical Analyzer (DMA) to accomplish this. The objective of this subtask will be to detailed test protocol to generate parameters that will serve as inputs for the unified fatigue damage model. This objective will be achieved by accomplishing the following sub tasks.

Subtask F2b-1: Develop specimen preparation procedures (Continued in year 2)

The DMA has been used to measure the mechanical properties of asphalt mastic and Fine aggregate matrix (FAM). Different methods have been used for preparing DMA specimens for testing mastics and FAM. The mastic testing relies on preparing specimens with Ottawa sand, filler particles passing sieve # 200, and asphalt binder. An FAM specimen is comprised of asphalt binder and fine aggregates passing the #16 sieve including filler material (passing the #200 sieve). The Fine aggregate portion of the FAM typically follows the same gradation as in the complete asphalt mixture. The binder content for the FAM is determined based on a fixed filler to binder ratio by volume, based on a constant film thickness on aggregate particles, or based on an average film thickness computed using the complete asphalt mixture.

The procedures and relevant assumptions required to design the composition of the mastic and FAM specimens will be evaluated in this sub task. Standard design procedures will be recommended based on considerations that include percent of filler particles in the mixture, representation of the FAM phase in the complete asphalt mixture, validity of the assumptions used in the procedure, and practicality of compacting and preparing test specimens in the laboratory. The method for preparing and storing test specimens cored out of Superpave Gyratory Compacted (SGC) samples will also be evaluated and standardized.

In summary, this subtask will accomplish the following:

i. Compare and standardize the procedure to design the mastic and FAM specimens and ensure that they are representatives of the complete asphalt mixture.
ii. Evaluate and standardize the procedure to mix, compact, core, and store test specimens. The procedure will also provide for acceptable limits and tolerances in geometry and air voids in the test specimen.
iii. Assess ruggedness of the test method with reference to variability in specimen preparation and handling procedures.

Objectives (i) and (ii) were virtually completed in year 1 of this project. In year 2 of this project, emphasis will be on objective (iii). Also, joint efforts with Advanced Asphalt Technologies (AAT) will be made in the Technology Development area to accomplish objective (iii).

Subtask F2b-2: Document test and analysis procedures in AASHTO format

In year 2, emphasis will be on the development of a single unified document that describes various test protocols developed in other subtasks. Analytical methods to interpret test data and derive parameters of interest from these test procedures will also be documented along with user friendly software to conduct this analysis. More specifically, this subtask will provide detailed protocols to achieve the following from the test method:

i. Determine properties of the FAM required as input for micromechanics and continuum fatigue damage models as well as model crack growth in asphalt mastics and mixtures. For example, procedures developed in subtask F1b to determine the linear and non linear viscoelastic properties will be refined for use with FAM and documented in this subtask.
ii. Determine fatigue cracking life of FAM with and without rest periods. For example, procedures to assess the fatigue and healing characteristics of FAM developed in subtask F1d-5 will be standardized and documented.

Major Findings from Year 1 for Work Element F2b

The procedure for design and preparation of FAM test specimens for use with DMA was further refined. The new design procedure allows the use of a FAM that is an exact representation of the asphalt mixture without the coarse aggregates. The test procedure to prepare and test FAM specimens using the DMA was documented in AASHTO format.

Year 2 Milestones for Work Element F2b

i. Document the test and analytical procedure in a standard format to obtain specific properties of the FAM using DMA, such as determination of the non linear viscoelastic parameters and fracture parameters.
ii. Assess ruggedness of the test method with reference to variability in specimen preparation and handing procedures. This task will be conducted in collaboration of with AAT in the technology development area.

Work Element F2c: Mixture Testing Protocol

This work element will be performed in close coordination with the Technology Development work area of this Consortium. Accordingly, some part of the budget for this work element has been allocated in the Technology Development work area.

This work element is intended to develop a mixture testing protocol that will be able to generate mixture parameters of interest for the continuum model with the most optimal level of laboratory testing. The primary characteristics of the comprehensive testing protocol are as follows:

i. Repeated loading that allows separating the nonlinear viscoelastic, viscoplastic and damage components.

ii. Different stress levels, temperatures and loading rates in order to determine the linear viscoelastic response, nonlinear viscoelastic response, plastic deformation, and fracture.
iii. Different stress states (tension and compression) in order to determine the model's parameters under various loading conditions.
iv. Different confinement levels in order to determine the dependency of model's parameters on confinement.

It is realized that a comprehensive testing protocol might be too elaborate for routine use for mixture design and evaluation. Therefore, we will seek the development of surrogate tests that can potentially lead to determine the necessary model parameters. This, however, can only be done once the comprehensive testing protocol is developed and used to test a variety of mixtures. We will conduct sensitivity analysis using the measurements from the comprehensive testing protocol to determine the parameters that has the significant influence on the mixture performance. It is possible to find that some of the model parameters vary within a small range and they do not have significant influence on performance. These parameters will be assigned fixed values in the model, and reduce the testing steps that are used to determine these parameters.

Year 2 Milestones for Work Element F2c

i. In the initial phase of this work element, fatigue tests will be conducted using select mixtures in repeated load direct tension mode. The fatigue test will follow protocols similar to those developed for FAM using the DMA with the exception of the mode of loading. The test data will also be analyzed using the similar analytical methods as those developed and used for the analysis of fatigue data with the DMA. This analysis will provide non linear viscoelastic and fracture parameters for the full mixture, analogous to the parameters for the FAM determined using the DMA.
ii. In addition, researchers will also develop a protocol for axial testing in both tension and compression of prismatic HMA specimens cut from cores with relatively thin HMA layers. This will facilitate laboratory evaluation of cores from test sections. Three different characterization tests including tensile strength, relaxation modulus in both tension and compression, and repeated tension testing are envisioned.

Work Element F2d: Tomography and Microstructural Characterization

X-ray CT is a nondestructive test to capture the internal structure of materials. Various applications of this method are discussed by Masad (2004). The X-ray CT step up at Texas A&M University includes two separate systems placed in the same shielding cabinet. The mini-focus system has a 350 kV X-ray source, while the micro-focus system has a 225 kV X-ray source. The required X-ray source power increases as the specimen thickness and density increase, while the micro-focus system can achieve a better resolution than the mini-focus system.

The researchers at Texas A&M University have developed methods for identifying of cracks and their dimensions. Also, they developed mathematical functions of the anisotropic distribution of damage, and statistical functions of these cracks based on size and shape characteristics. The X-ray CT will be used to verify the predictions of the developed models by monitoring evolution of damage at various loading conditions. This is valuable in order expand the model's verification beyond the typical macroscopic measurements to detailed microscopic measurements.

X-ray CT imaging will also be used to obtain microscopic images that are needed for the micromechanical models discussed in Category 3. As discussed later, it is possible to use X-ray CT to capture images at high resolution and then use image processing techniques in order to combine these images for detailed micromechanical analysis.

<u>Subtask F2d-1 (new addition): Micro scale physio-chemical and morphological changes in asphalt binders under relaxation, fatigue loading, and healing conditions</u>

In addition to the X-Ray CT imaging, an experimental methodology to evaluate micro scale physio-chemical and morphological changes in asphalt binders in different stress states will be developed. The primary motivation for introducing this subtask is to better understand the physio-chemical and morphological changes associated with the following four processes:

i. relaxation,
ii. plastic deformation and fatigue crack initiation,
iii. fatigue crack propagation, and
iv. healing

This subtask will assist in understanding the nature of viscoelastic creep, crack nucleation and propagation and healing and the relationship of these phenomena to the physio-chemical properties of asphalt binders. This information can also be used to ensure that the material property measurement and modeling aspects of this research are in line with the physically observed micro scale damage phenomena. The following is a brief description of the methodology that will be used in order to conduct this investigation.

The experimental set up consists of a thin film of asphalt binder on a glass or crystal substrate (figure F2d-1.1). The substrate is clamped onto a mini loading frame that contains a piezoelectric actuator. The piezoelectric actuator is calibrated to apply normal deflection of up to 130 microns on the bottom of the glass or crystal substrate via a hemispherical contact to ensure line loading. Tensile strain on the surface of the asphalt binder film is generated by subjecting the substrate to flexural stresses. The magnitude of tensile strain can easily be computed and controlled by the adjusting the amount of normal deflection applied by the piezoelectric actuator. By varying the applied voltage field, the surface of the binder film can be subjected to a static tensile strain in order to monitor relaxation behavior or a cyclic tensile strain in order to monitor crack nucleation, initiation, and healing behavior. It is also possible to extend the test to a direct tension of shear mode, if required, at a later stage.

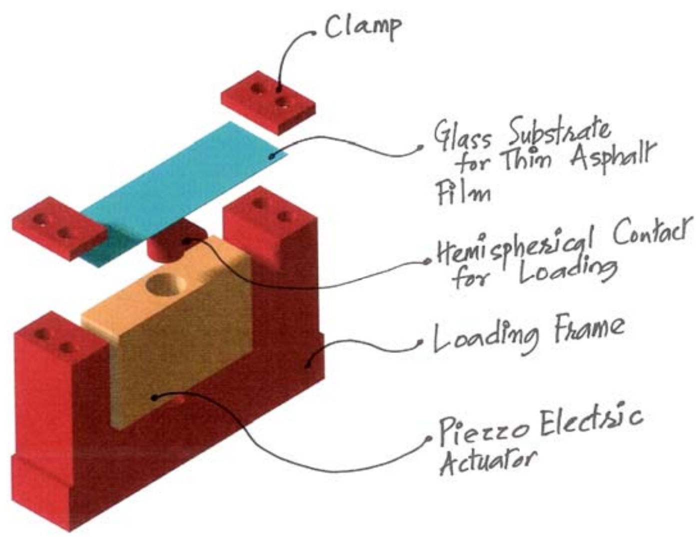


Figure F2d-1.1. Diagram. Isometric representation of the mini loading frame.

The small size of this loading frame (figure F2d-1.2) makes it possible for it to be used in-situ with a variety of microscopic techniques such as optical microscopy, FTIR, and atomic force microscopy. This device is in the design and fabrication stage.

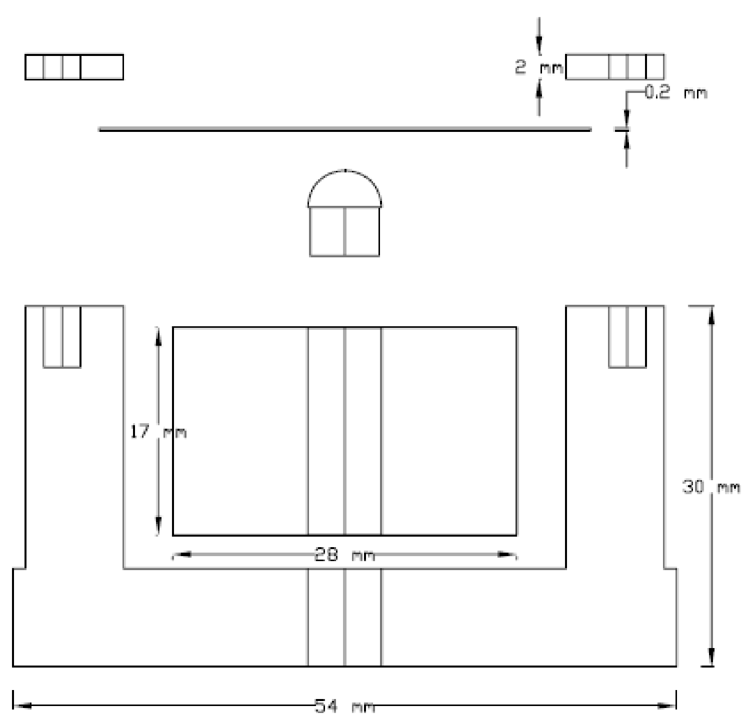


Figure F2d-1.2. Diagram. Front view of mini loading frame with key dimensions.

The micro scale chemical changes and morphological changes in the region of the highest tensile stresses can be recorded using FTIR and atomic force microscopy. In an earlier study, Little et al. (1994) presented the proof of this concept by demonstrating the relaxation behavior of different functional groups in thin films of asphalt binders subjected to shear stresses. It is envisaged that this device and methodology will provide invaluable insight into the understanding of relaxation, crack propagation, and healing in asphalt binders and mastics.

<u>Year 2 Milestones for Work Element F2d</u>

i. Complete the development of the prototype test apparatus and procedure to evaluate the micro scale physio-chemical and morphological changes in asphalt binders under relaxation, fatigue loading, and healing conditions.
ii. Conduct preliminary tests on selected asphalt binders.
iii. X-ray CT will be used to capture damage in mastic specimens at a high resolution (10 microns/voxel) to verify the predictions of the fracture models.

Work Element F2e: Verification of the relationship between DSR Binder Fatigue Tests and mixture fatigue performance

The current Superpave Binder fatigue parameter has been shown to be insufficient as a predictor of pavement fatigue performance. Recent studies have shown that $G^*\sin\delta$ values obtained from binders used in mixes correlate poorly to laboratory mixture fatigue testing. Progress has been made during the last few years to introduce a more meaningful fatigue parameter for binders, but the extent to which the new test and the parameters derived from it relate to mixture and pavement performance is yet to be determined. The lack of correlation between the binder $G^*\sin\delta$ and performance could be attributed to many factors among which the use of the actual conditions of stress and strain experienced by binders in typical mixtures and the reliance on small strain testing are the most important missing factors.

Recent studies have clearly shown that response of binders to repeated cyclic loading show damage accumulation behavior that cannot be predicted by the few initial cycles used to measure $G^* \sin \delta$. Also, modeling of the strain distribution within the mix has shown that the binder can experience strain levels as high as 90 times those experienced by the mix. By testing binders within the linear viscoelastic region, it is likely that the current specification is not addressing the actual behavior within the mix. These high strains may be indicating that fatigue failure of pavements is, in part, due to the non-linear behavior and subsequent stiffness reduction of binders within the mix.

This work element will focus on comparing binder fatigue results to fatigue performance of mixtures measured in the lab and also pavement fatigue of full scale experiments such as the FHWA-ALF results. The work will include imaging of mixtures to estimate ranges in stress and strains, conducting testing under various loading conditions that mimic the mixture testing of the full scale experiments, and development of specification limits and criteria. The work element will be coordinated with other tasks in the Consortium project and also with activities of NCHRP on fatigue. The work is essential for developing an understanding of the role of the binder in fatigue resistance, and in the development of a unified model for fatigue damage. The following tasks will be completed in order to achieve the objectives of this research effort.

Subtask F2e-1: Evaluate Binder Fatigue Correlation to Mixture Fatigue Data (Year 1 start)

Data has already been collected on mixture fatigue performance in the laboratory as part of the Pacific Coast Conference on Asphalt Specifications. In this task, the binders used in that study will be tested at various strains and temperature conditions in order to evaluate the results as indicators to mixture fatigue. This will be done using a standard fatigue procedure in the dynamic shear rheometer. The strain levels used for binder testing will be chosen based on the results of the strain distribution modeling research. Number of cycles to failure for the binders (based on the same failure criterion used for mixture testing) will be compared against the same results for mixtures and evaluated for significance.

Subtask F2e-2: Selection of Testing Protocols

Variables relevant to the binder-mix relation, such as asphalt content in the mix, mixture stiffness, and strain and stress levels in the binder domain will be selected and controlled for the testing. Refined binder fatigue protocols that incorporate these conditions will be integrated into the testing plan. The binder and mixture testing will include controlled strain and controlled stress, adding the surrogate stress sweep test for binder testing. Binder test methods will also include limited use of torsion cylinders consisting of binder-sand mixtures for better representation of thin film behavior tested in the DSR. Utilization of the binders used for the FHWA-ALF study will be incorporated into testing for comparison to the fatigue performance results from that study.

Subtask F2e-3: Binder and Mixture Fatigue Testing

Standard fatigue and surrogate stress-sweep testing will be performed on binders and binder-sand torsion cylinder mixtures. Mixture fatigue testing will be performed using axial cyclic fatigue testing in a servo-hydraulic test frame on gyratory samples prepared in the lab. Images of the cross sections of the mixture samples will be taken for analysis of strain distributions.

Subtask F2e-4: Verification of Surrogate Fatigue Test

Data collected during the stress sweep testing of the binders and binder-sand mixtures will be compared to the traditional fatigue testing as well as results from the FHWA-ALF study to verify the stress sweep as a suitable surrogate test for fatigue.

Subtask F2e-5: Interpretation and Modeling of Data

Results from all binder and binder-sand mixture testing will be correlated to the results from gyratory compacted mixture sample testing to evaluate the contribution of binder fatigue characteristics to the fatigue performance of the mixtures. Results from mixture imaging will verify the ranges of stresses and strains experienced by the binder phase.

A few approaches will be explored to characterize the fatigue behavior of asphalt binder and fundamentally evaluate the effects of asphalt binder on asphaltic mixtures. The hypothesis is that the damage evolution in asphaltic mixture is a function of fatigue performance of asphalt binder, as well as other components of asphaltic mixtures. The team will employ the mechanistic approaches for either asphalt binders or asphaltic mixtures and identify the most effective approach for asphalt binder. The approaches that the team is evaluating are as follows:

a. Dissipated Energy. The way to characterize the point when fatigue damage occurs is shown by using the concept of change in the dissipated energy per cycle. A binder can be subjected to cyclic loading for a determined number of cycles without showing fatigue damage. During this stage, the energy dissipated per loading cycle remains constant. However, if the binder continues to be loaded and unloaded, a point is reached when it does not dissipate the same amount energy per cycle any longer. This is a sign of fatigue damage. This behavior can be clearly shown using a parameter called Dissipated Energy Ratio (DER) (Bahia et al. 2001).
b. Viscoelastic Continuum Damage Mechanics (VECD). VEDC uses the correspondence principle and the concept of pseudo strain to characterize the damage. Without damage, the stress and pseudo strain curve overlaps the line of equality. The curve that deviates from the line of equality indicates damage. The stress and pseudo strain is then regressed to get C and S which are internal damage parameter (Kim et al. 1997). The C and S curve can be used to predict the fatigue life of a material under a specific testing condition.
c. Dissipated Pseudo-strain Energy (DPSE). Masad et al. derived relationships for the energy dissipated due to damage in viscoelastic materials. These relationships were based on the concept of dissipated pseudo strain energy as pioneered and presented by the works of Little, Kim and Lytton in a number of studies. The derivation relies on calculating the dissipated energy that reflects the change in the apparent phase angle due to damage (W_{R1}), and the dissipated energy due to change in the apparent modulus (W_{R2}). The crack initiation and propagation are obtained based on the change of dissipated pseudo-strain energy.

Subtask F2e-6: Recommendations for Use in Unified Fatigue Damage Model

The results from the previous task will be used to aid in the development of the unified fatigue damage model by providing a more efficient method of evaluating fatigue characteristics of binders, as well as an increased understanding of the behavior of the binder phase within mixtures and its contribution to fatigue performance.

Major Findings from Year 1

During Year 1, the materials and testing conditions for the plan were selected and are shown in table F2e.1. A testing plan was also developed and the proposed tests are shown in table F2e.2.

Table F2e.1. Matrix of materials and conditions.

Neat Binders	PG58-28	Aggregates	Limestone
	PG64-22		Granite
	PG70-22		
Modifiers	SBS	Mix Designs	E-10
	Elvaloy		
	PPA		
	Sasobit		
Mineral Fillers	Limestone	Testing Temp	31 ºC
	Granite		25 ºC
	Ottawa sand		19 ºC

Table F2e.2. Proposed tests on asphalt binders and mixes.

Asphalt Binder	Time Sweep (TS)	Strain level	3%
			5%
			7%
		Frequency	1 Hz
			5 Hz
			10 Hz
	Monotonic Test (MT)	Shear Strain Rate	30%/min.
			45%/min.
			60%/min.
	Stress Sweep (SS)	Strain level	3%
			5%
			7%
		Frequency	1 Hz
			5 Hz
			10 Hz
Mix	Cyclic Test (CT)	Strain level	600 microstrain
			1000 microstrain
			1400 microstrain
		Frequency	1 Hz
			5 Hz
			10 Hz
	Monotonic Test (MT)	Constant Cross-head Rate	12.5 mm/min.
			25.4 mm/min.
			38.1 mm/min.
			50.8 mm/min.

Since the start of Year 1 work plan, the team has extensively evaluated two aspects of fatigue for asphalt binder: (a) a surrogate test for fatigue of asphalt binder, and (b) the application of viscoelastic continuum damage mechanics to asphalt binder. The major findings are briefed here.

a. Surrogate test for fatigue of asphalt binder.

A surrogate test is desired to substitute the time-consuming time sweep test for rapid characterization of fatigue performance of asphalt binder. The team developed a monotonic shear test using the DSR. A constant strain-rate, 45% per minute in this case, was applied to the specimen until the stress reached the peak level and dropped. The fracture energy was calculated under the stress-strain curve up to the peak stress level. It was found that fracture energies of ALF asphalt binders (three replicates for each binder) highly correlated with the field performance of these binders at ALF site, as shown in figure F2e.1.

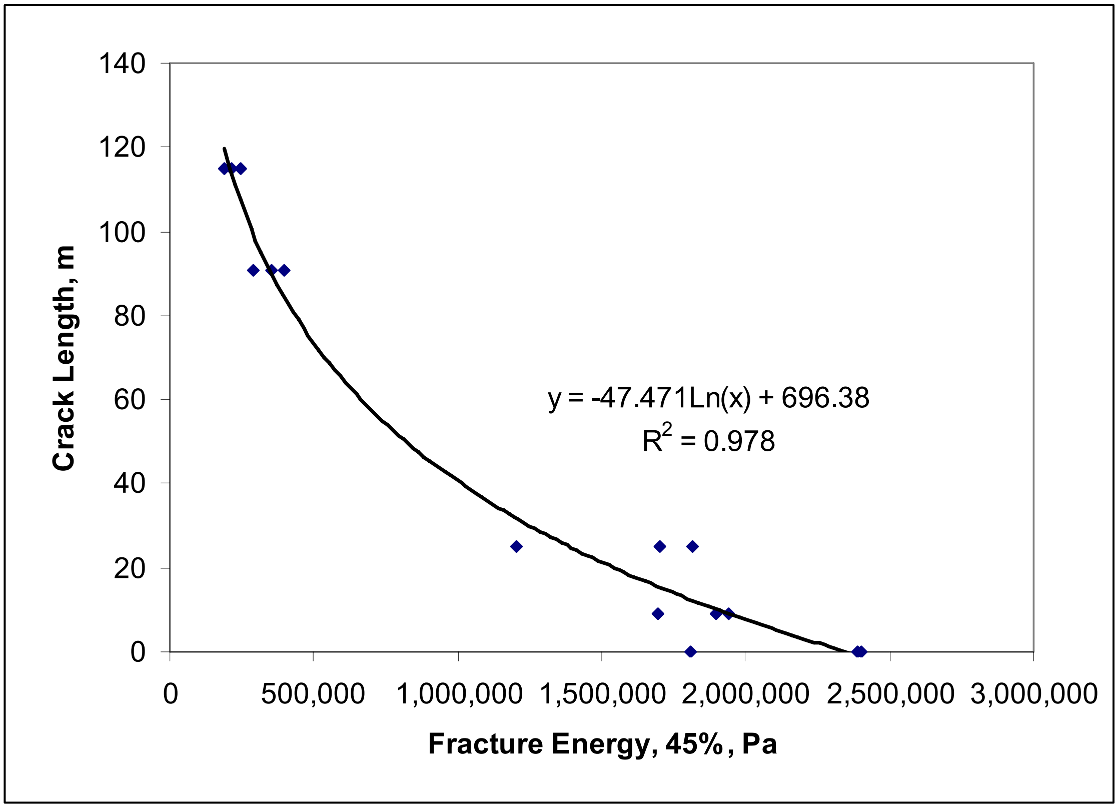


Figure F2e.1. Chart. Correlation of fracture energy and field performance of asphalt binders.

This observation indicates that the constant strain rate test has the potential to be a surrogate test for fatigue of asphalt binder. The fracture energy from the constant strain rate test of asphalt binder could be a good indicator of fatigue performance of asphalt binder. The team will further evaluate the repeatability and ruggedness of this test.

b. Viscoelastic Continuum Damage (VECD) Mechanics

Viscoelastic continuum damage mechanics were employed to characterize the asphalt binders. Frequency sweep and monotonic constant-strain rate tests were conducted using

DSR. The complex moduli of asphalt binders were obtained from frequency sweep test and converted into relaxation moduli. The relaxation moduli were fitted into the Prony series and used for pseudo strain calculation. The pseudo strain was then used to obtain pseudo stiffness, C, and damage parameter, S. Three strain rates were used for each asphalt binder. It was found that the VECD approach could eliminate the effects of different strain rate. The C vs. S curves for three strain rates collapsed, as shown in figure F2e.2. The C vs. S relationship can be used to predict the fatigue life of asphalt binders. This demonstrated that VECD has the potential to be used for asphalt binder, as well as asphaltic mixtures which have been reported by Kim et al. (1997). The cyclic fatigue test data for these binders will be analyzed to evaluate of the effectiveness of VECD on the binders.

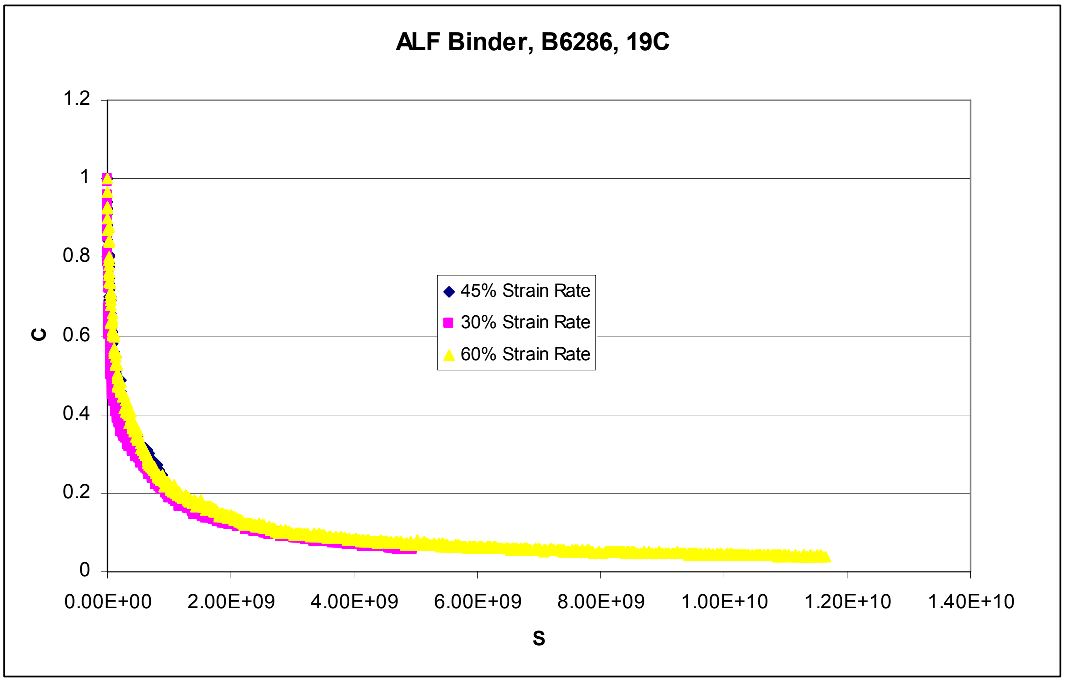


Figure F2e.2. Chart. C vs. S curves for asphalt binder.

Year 2 Work Plan

During Year 2, the team will continue to evaluate different approaches for fatigue performance of asphalt binder, especially the VECD mechanics. The Year 2 work plan consists of two major parts: a detailed experimental plan and an evaluation of the effectiveness of different analytical approaches based on the experimental results.

The test results will be analyzed using different analytical approaches. These analyses will determine the fundamental properties of asphalt binder that govern the damage resistance to fatigue. In addition, the team will strive to quantify the relationship between the damage properties of asphalt binders and those of asphaltic mixes. For instance, the damage parameter of S in VECD can be an input to the fatigue life of asphaltic mixes.

Figure F2e.3 depicts the research approach defined for this work element.

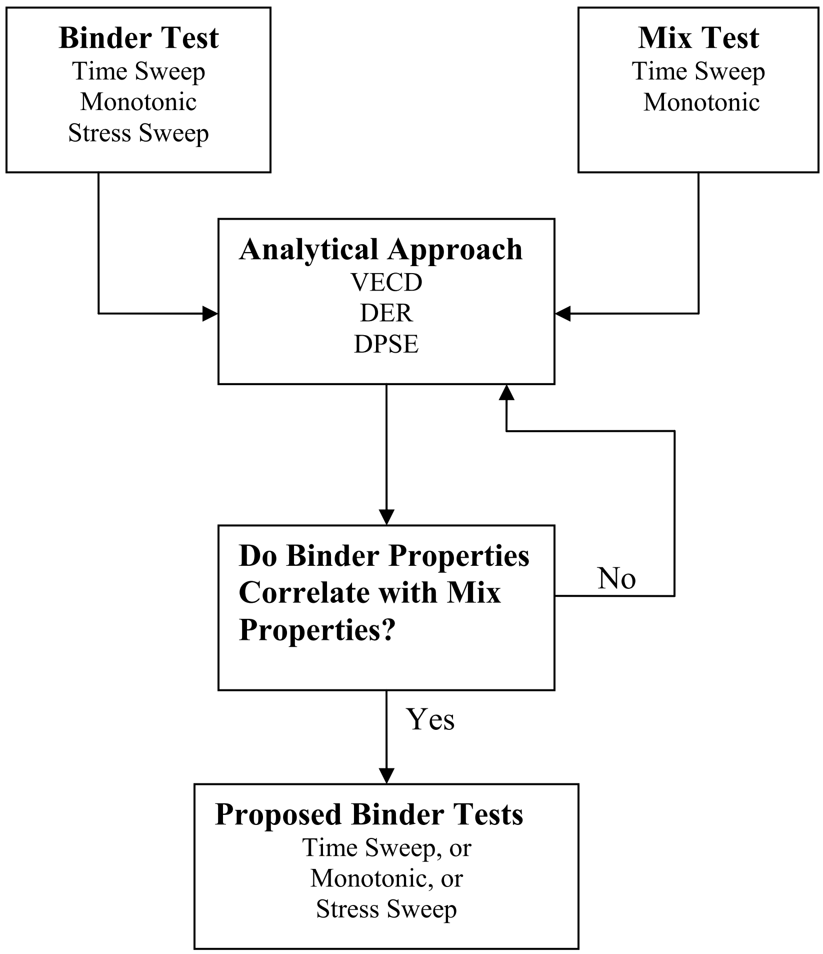


Figure F2e.3. Chart. Flow chart for research approach.

Year 2 Milestones

- Complete report on review of literature for fatigue of asphalt binders and asphaltic mixtures
- Finalize material selection and experimental plan
- Conduct the proposed tests on asphalt binders and prepare for mix tests
- Select the analytical approach for further evaluation

Budget

The estimated budget for this subtask is $425,000 over the five years. The work will be conducted by the University of Wisconsin-Madison.

Category F3: Modeling

Work Element F3a: Asphalt Microstructural Model (Year 2 start)

Introduction

In investigations of asphalt pavement performance developed in the mid-part of the past century (Hveem 1943), failure modes were often attributed to the "chemical action" of the binder (Robertson et al. 2001). Hence, four properties of the binder materials were deemed critical to the quality of a pavement. The properties (Hveem 1943) that were thought to be most crucial to pavement performance were (1) consistency, (2) durability, (3) curing rate, and (4) resistance to water. First and foremost, consistency relates to the flow properties of asphalt, whereas durability relates more to the change in consistency of asphalt materials, usually as a function of temperature and time, for example the changes in material properties brought about as a result of oxidative age hardening. On the other hand, cure rate may be associated with the resistance of an asphalt-aggregate mixture to "set" during construction, producing mixtures that may shove during compactive-rolling, considered to be "tender" or subject to permanent deformation immediately following construction. Finally, asphalt pavement quality was and still is thought to rely heavily on its resistance to water, which directly relates to moisture damage resulting from stripping for example.

Today, at the start of the twenty-first century, all of the aforementioned modes of failure are still intensively investigated due to a lack of a comprehensive understanding of the material properties and fundamental mechanisms of action that relate to asphalt pavement longevity and/or tendencies toward premature failure. It is for this reason that the pursuit of a cooperative asphalt composition "microstructure" modeling approach should be initiated.

Predictive models of material properties and reliability are used routinely in the pharmaceutical, metals, and semiconductor industries, because quantitative theory based on fundamental materials science has been successfully applied to these materials. Why can't we do this yet with asphaltic concrete? One answer may be that asphaltic concrete is a complex material comprised of several different "types" of components, including the asphalt-bitumen "binder" or "glue" (i.e., heavy residual distillate from crude oil), the aggregate (typically limestone or granite), complex binder-aggregate interactions, and any number of chemical additives. Furthermore, the binder undergoes chemical reactions and physical phase changes during temperature excursions at many length scales, including down to the nanometer scale. The aggregate, as it packs together with binder, ranges from a few tens of micrometers to 15 mm or so in size. To further compound the issue, loading of the pavement slab by traffic and environmental conditions (seasonal changes in temperature and impact of moisture) is random and difficult to characterize but contribute significantly to pavement failure. The only way to handle the simultaneous chemistry and microstructure development of the binder as it interacts with the aggregate and additives/modifiers, over many length scales, is to have a computer model of the whole material system, linking and based on fundamental chemistry, physics, and mechanics of the asphalt-binder molecular composition interacting with the aggregate mineralogy. This kind of model for asphaltic concrete does not now exist, but if it did exist, it would have enormous importance for academics studying pavement performance, state DOTs, and the paving industry.

Relationship to FHWA Focus Areas

This work element is related to the following focus areas:

Pavement Design and Analysis: This work will contribute to further refinement of the MEPDG Design Guide by providing fundamental understanding of the physico-chemical nature of asphalt-binder as it relates to pavement performance.

Optimum Pavement Performance: A more fundamental understanding of the physico-chemical nature of asphalt-binder will to a better characterization of modified asphalts.

Environmental Stewardship: A more fundamental understanding of the physico-chemical nature of asphalt-binder will to a better characterization of warm mix asphalts and recycled asphalt pavement technologies.

Integration of Mix Design into Pavement Design: A more fundamental understanding of the physico-chemical nature of asphalt-binder will help produce modified binders, composite binders of desired properties and develop mixes of truly super performing pavements.

Hypothesis

In the asphalt pavement community, as in any scientific/engineering community, technical problems arise. After a lot of frantic work, short-term fixes for these problems are found, and the problem is solved – for the present. But because of the empirical nature of these fixes, these solutions are only short-term and the problem arises again, albeit in another form. Thus, a comprehensive and rigorous description of the molecules present in heavy residua and their associated interactions with each other and with foreign materials is ultimately needed to develop a model that directly relates the material's physico-chemical properties to the bulk mechanical properties that predict the material's propensity to bind aggregate, polymer, fillers, etc., when used as the gluing agent in pavement construction applications. Such a chemo-mechanical model would then be very useful for predicting the performance of these materials in roadway construction applications.

A wealth of experimental evidence indicates that asphalt binders, which are composed of complex petrol-organic molecules, are capable of dynamic structural changes, including phase separation, flocculation, crystallization, and melting. In the past two decades, several powerful computer modeling methods have been developed that are capable of simulating/predicting these kinds of phenomena, and we expect that these models can be used to help predict material softening and embrittlement pertinent to pavement performance. As Mehta et al. (2004a) have shown, there are well-established ties between phase field model parameters and the properties of the system that may be obtained by upscaling thermodynamic and kinetic properties obtained from molecular mechanics models of the asphalt binder, such as viscosity, composition-dependent free energies, interfacial free energies, and elastic moduli.

To realize this vision of a fundamental predictive model of asphalt concrete properties, a multiscale, multiphysics approach will be applied to the problem through cooperative interaction between several different research entities. At the largest length scales, asphalt concrete is a suspension of randomly shaped aggregate particles in a complex viscoelastic suspension. A modeling endeavor of such a complex material as asphalt binder will rely heavily on cooperative theoretical approaches grounded in molecular mechanics/dynamics simulations, non-equilibrium statistical mechanics (Glansdorff and Prigogine 1971) (i.e., rate dependent thermodynamic phase-field models [Cahn 1965; Cahn and Hilliard 1958, 1959a and b]) and continuum mechanics conducted at multiple scales including molecular/ nano, micro, meso and macro scales. To be successful, this approach needs to bring together scientists and engineers to undertake these tasks.

Objectives

The preliminary objective of the proposed research is the development of molecular-based, chemo-mechanical, and continuum mechanical models capable of predicting the mechanical performance of unmodified asphalts, polymer-modified asphalts, and full binder-aggregate systems. The ultimate goal of the research line proposed, far beyond the scope of this proposal, is the design of new composite materials, governed by the mechanical demands of the end users, industry, and the general public. This multi-scale, chemo-mechanical approach can be generalized to the solution of other problems in civil, chemical, materials, and mechanical engineering.

Asphaltic concrete provides an important example of a material whose properties are governed by hierarchical scales. Viscoelastic properties of neat asphalts are influenced by crude oil source (Petersen et al. 1994) through their detailed molecular compositions (nm). Microstructural phase domains are induced by blending asphalt with polymer modifiers (μm). Adding sand particles and fine aggregates leads to “mastic” with yet different rheology (0.1mm). This mastic binds together mm-to-cm aggregate particles (i.e. rocks) to form a pavement.

The chemistry within asphalts is rich and still poorly-defined, while desired macro scale properties are well-posed. Over the past two decades, pavement design has been advanced by incorporating well-defined experiments into material specifications (Superpave approach (Kennedy et al. 1994)), and by applying numerical models, such as the Mechanistic-Empirical Pavement Design Guide (ARA Inc. 2004). The current and rather limited understanding of the quantitative aspects of the interplay among chemical, physical, and mechanical phenomena involved in pavement performance currently inhibits developing a fully mechanistic approach. For example, Superpave lab methods for defining “good” asphalts for use in the field often fail when applied to polymer-modified asphalts (Shenoy 2002). Quantifying and incorporating such chemical effects, with increasing guidance from computation, will be crucial for rational and targeted design of high-performance asphaltic concrete, particularly as petroleum sources of asphalt raw materials become scarcer due to decreasing supplies worldwide.

The idea of chemo-mechanical coupling, for example, is in itself not new and is, for instance, readily accepted in biomechanical systems and Portland cement concrete (Ulm 2003). The combination of diverse chemistry, time-dependent phase behavior, slow oxidation, and long-term creep and deformation makes the chemo-mechanics of asphalt concrete a new and bold research challenge, with application to other systems that share those traits, such as filled polymers.

On small scales, the complex chemical composition of asphalts (> 10^5 molecular species [Wiehe and Liang 1996]) limits the extent to which well-defined experiments can explain observed properties. Asphalts of different chemical composition exhibit vastly different rheological properties, for example. The controlled boundaries of a computation enable effects of composition to be probed without the complexities of measuring single molecule properties within a complex mixture. Computations will help to identify and understand the anticipated formation of globular clusters of molecules that seemingly act together when observed from the next higher length scale (in analogy to Bader's "Atoms in molecules" concept [Bader 1990]). Only sophisticated computational tools at all scales can guide the observer to the presence of strong correlations that identify emerging collective behavior.

Each link between length scales in asphalt materials is best made using computational methods. Asphalt effects over individual length scales have been studied previously, though the fields that arise at each scale lack a unified framework for sharing their results. Advantages at each scale have not yet been leveraged to overcome the disadvantages of models at other scales. For example, stress transmission calculations on mm to m scales require functional forms and parameters to incorporate simplified damage models (Sadd et al. 2004). Models of asphalt-polymer-particle interactions over μm length scales are capable of describing the microstructural evolution over moderate time scales and potentially can provide the required inputs. Such phase field models rely, however, on appropriate functional forms for the free energy as a function of some well-defined order parameter. Molecular scale simulations are capable of providing the relative probabilities for different orderings, based on the interaction energies among the different molecules found in asphalt, a polymer, and/or at an interface.

Chemo-Mechanics Application to Constitutive Modeling of Pavement Structures. Complex suspensions can be modeled, for example, using Dissipative Particle Dynamics (DPD) models (Sims and Martys 2004) if the rheological properties of the asphalt binder phase can be predicted as input. Therefore, much of the modeling work should concentrate at the scale of 1 μm to 100 μm, where much of the binder properties are determined by its microstructure. At these length scales, computational modeling would be applied to three challenges: (1) Understanding the molecular interactions that lead to the development of the observed microstructure elements, (2) understanding and quantitatively predicting the changes in the microstructure of asphalt binder as a function of time and under a variety of environmental conditions, and (3) relating that microstructure to important engineering properties, such as the time-dependent consistency and curing rate. To model the structural evolution of asphalt binder, molecular simulations will provide direct links between the nm-scale characteristics and intermolecular forces of individual molecules and the larger scale "coarse-grained" structures. Phase field models will then be used to simulate the formation, growth, and morphology of, for example, micro-crystalline wax that appears under thermal cycling. Recently, there have been good ideas put forth that help with the qualitative understanding of the general shape and undulations of these crystals (Mehta et al. 2004a), which can be developed further for the much more complicated asphalt chemistry. The main challenge will be to make the simulations quantitatively accurate by employing more realistic free energy models in larger-scale three-dimensional systems.

Virtual Asphaltic Concrete Testing Laboratory. Our ultimate vision is to build a multiscale model, tentatively entitled the Virtual Asphaltic Concrete Testing Laboratory (VACTL). It will be designed to simulate, based on the known chemistry, physics, and mechanics of the constituent components, the development of molecular constituent microstructures and physical properties as an asphaltic concrete mixture is prepared and cured and then degraded. Property calculation, like mechanical properties related to water permeability and surface forces, will be an integral part of the VACTL.

The vision of a VACTL is now needed in this field for several reasons. First, much has been learned at the fundamental chemistry and physical level about bitumen over the last 20 years, and especially over the last 10 years or so. Second, in that same time range, computers have become enormously more powerful. Third, this kind of integrated project is already being carried out for portland cement and concrete, in the Virtual Cement and Concrete Testing Laboratory (VCCTL) (Bullard et al. 2004; Bentz et al. 2006), which began development in 2001. In the last six years of work, the software has gone through six versions and is approaching its goal, the same goal that the VACTL would have: simulation of microstructure and properties with known chemistry and physics, so that many tests can be carried out in the computer rather than the laboratory. For asphalt, there is probably less known about the basic chemistry of bitumen than there is for Portland cement, which might imply a longer development time. However, the lessons learned in the VCCTL will help speed the VACTL development time.

The VACTL, by being based on fundamental physico-chemical and chemo-mechanical theories, can be used to solve these problems fundamentally. Many of the problems that arise in a complex material like asphaltic concrete have to be solved with basic science, or they will occur again. Once this basic understanding is attained, generated by the use of the VACTL, it will allow one to be very practical in solving problems, and will save money by not having to continually re-solve recurring problems.

Use of a reliable, well-validated VACTL will help select materials, predict performance, and suggest rehabilitation schedules and approaches. When new materials and pavement technologies are introduced, VACTL will be able to help predict long-term performance and identify potential service life problems, a far better prospect than discovering problems empirically as they occur. The VACTL will be especially useful in playing out "what-if" scenarios, helping to design new materials and processes and optimizing old materials and processes.

Thus, we intend to tap into the world-class expertise in phase field modeling at NIST's Center for Theoretical and Computational Materials Science (CTCMS), and will utilize large-scale parallelized implementations of these models for the tasks at hand. Through these phase field models, we expect to determine the volume fraction and size distribution of micro-crystalline wax domains as a function of time, asphalt binder composition, and thermal cycling history.

Validation of the phase field modeling results will come from experimental techniques on idealized materials, such as syndiotactic polypropylene, asphalt binder thin films like those investigated by researchers at WRI, and computational techniques such as molecular dynamics simulations (URI) which determine temperature-dependent changes in the relaxation rates of single molecules within model asphalt systems to estimate changes in physical and rheological properties like shear viscosity. Using principles of finite element models of viscoelasticity in combination with differential effective medium theory (DEMT), we will establish and validate models for the rheological properties of asphalt binder, akin to the Pal and Rhodes model (Pal and Rhodes 1989), in terms of important binder composition parameters and thermal history. With these continuum models of binder rheology, we will complete the upscaling to the largest scales of asphalt concrete using DPD models of rheology.

Digital Specimen, Digital Test and Digital Mix Design Techniques. Traditional materials characterization methods apply macroscopic testing to evaluate the stress-strain relation and other properties of construction materials such as asphalt concrete. With support from the Partnerships for Innovations Program, the project team has developed the Digital Specimen and Digital Tester techniques to characterize the microstructure of materials and simulate their behavior. The approach uses X-ray Computerized Tomography to reconstruct the three-dimensional digital representation of the microstructure (Digital Specimen) of a physical specimen of construction material, and to perform various simulations of the behavior of the material on the digital specimens (Digital Test) using modeling and computational techniques. It has a number of significant advantages over the traditional approaches including a) integration of failure mechanism at the microscopic level to gain better understanding of material behavior for guiding mix designs in such as material selection and compatibility assessment; b) allowing performing different digital tests on the same digital specimen to optimize mix designs that will offer balanced properties in strength and resilience and avoid problem mixes to be placed in roads; c) visualization of the entire failure process microscopically during digital test; and d) offering potential to directly integrate mix design into pavement structure design. The project has developed multiple functional digital specimen and digital test techniques (Wang et al. 2007a, b and c; Fu et al. 2007; Zhang and Wang 2007) for testing asphalt concrete for strength, resiliency, and durability and will further investigate the possibility of using the technology with other construction materials. While these tools are initially developed for modeling the permanent deformation properties of asphalt concrete, with change of the failure criteria, they can be adapted to model the fatigue properties. In addition, representation of irregular aggregate particles and simulation of the mixing process will allow the mix design process to be completely simulated. The Virginia Tech work and the NIST work together will place a solid foundation for the integration into a VACTL.

<u>Experimental Design</u>

This research proposal represents collaboration among six groups at five institutions. M. Greenfield (URI CHE) specializes in molecular simulations of asphalts, polymers, and liquids. E. Garboczi (NIST) is a physicist experienced in modeling µm-to-mm scales of Portland cement concrete and J. Bullard (NIST) is a materials scientist with expertise in phase-field approaches. N. Kringos (Delft) and L. Wang (VT) are experts in mechanics with civil and mechanical engineering backgrounds, respectively. T. Pauli (WRI) is a team leader in asphalt materials science. In several instances, student and post-doc participants will conduct research at URI, NIST, Virginia Tech and Delft; the latter adds an international component to the overall research. Efforts are required in each field, connecting research methods in order to achieve a seamless virtual asphalt design environment.

On a molecular scale, asphalts have traditionally been described as a multicomponent colloidal system, with polar asphaltene molecules dispersed in nonpolar maltenes through the amphiphilic behavior of moderately polar resins (Petersen et al. 1994). More recent studies have reinterpreted these descriptions because the microstructures cannot be observed. They instead describe asphalts as multicomponent mixtures that lack such a precise microstructure (Petersen et al. 1994); asphalts remain a stable mixture due to a balance among dispersion, pi-pi, polar, and hydrogen bonding forces. Disrupting any of these forces by diluting with a solvent with particular Hansen solubility parameters leads to phase separation, such as asphaltene precipitation (Redelius 2004).

Asphalts constitute complex systems because their chemical and physical structure allows for different properties and orderings emerging over different length scales. A molecular realization of asphalt over a 1-10 nm scale includes a collection of asphaltene, resin, and maltene molecules, with overall disorder tempered by nearest-neighbor ordering that occurs due to molecular geometry (Zhang and Greenfield 2007a). These orderings can rearrange over molecular time scales at high temperature, while they are predicted to remain unrelaxed (and thus glass-like) over microsecond to second time scales at progressively lower temperatures (Zhang and Greenfield 2007b). Over micrometer scales, asphalts can exhibit different phases, particularly in asphalt/polymer mixtures (Masson et al. 2003). Over μm to mm scales, nonpolar and polar asphalt phases and polymer phases interact with < 75 μm particles to form mastics. Micromechanical and rheological models have been used to calculate the modulus and compliance of the composite system (Kim and Little 2004; Buttlar et al. 1999). Different results for different aggregates indicate chemical effects for polar systems, such as hydrated lime (Kim and Little 2004). Specific adsorption of polar components will alter the phase behavior within the bulk asphalt by shifting the distribution among asphaltene/resin/maltene. Over mm and larger scales, the different phases can dissipate energy to different extents, leading to different stress responses and thus system-specific storage and loss moduli. Changes in modulus and flow over long time scales (years) then impact pavement performance as a result.

The macro-scale properties and characteristics of many engineered systems are the mechanical manifestations of physic-chemical interactions over a wide range of length and time scales (figure F3a.1). Molecular interactions and structure control nanometer and nanosecond behavior, cooperative effects such as self-organization and the formation of distinct phases give rise to micro and mesoscale properties, and interdependences among meso- and larger scale structures affect the large-scale and long-time response, which relate directly to the engineering properties and performance of the materials system.

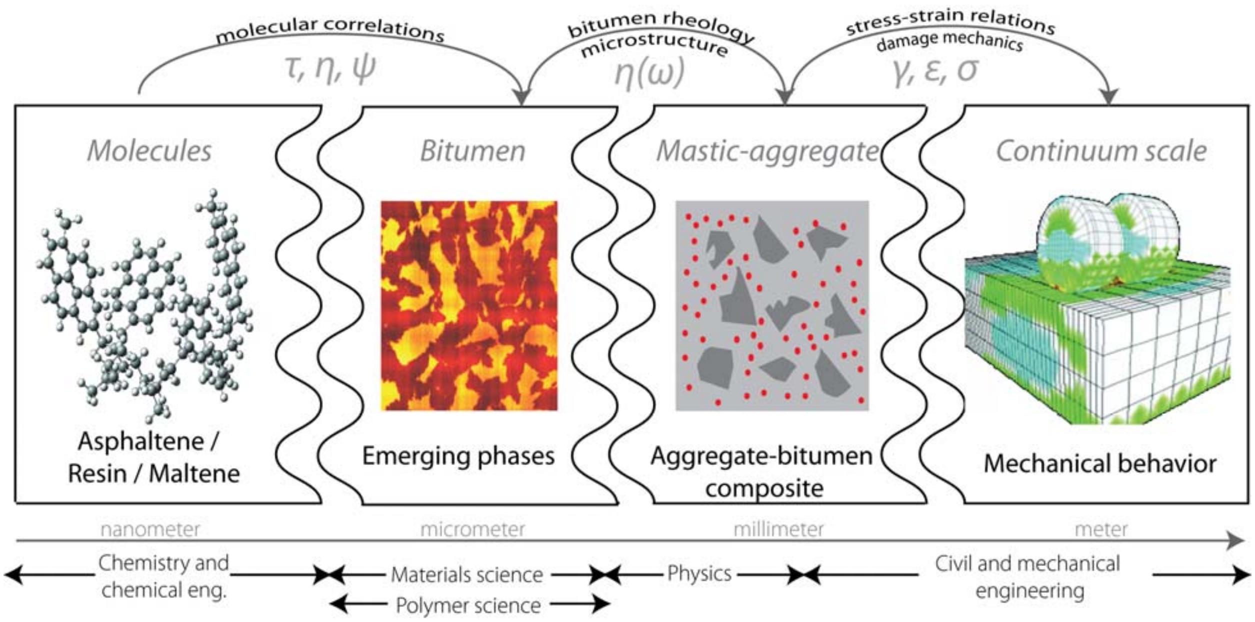


Figure F3a.1. Depiction of the research approach defined for this work element.

The term *chemo-mechanics* refers to the direct coupling of the chemistry of a material system to its mechanical properties. These effects of chemical modifications, phase domains, and aging on macroscale engineering attributes are indicated by arrows between scales.

Two ingredients are required to construct a successful sequential multiscale model. First, it is necessary to have a priori and complete knowledge of the fundamental processes at the lowest scale involved. This knowledge or information can then be used for modeling the system at successively coarser scales. Second, it is necessary to have a reliable strategy for encompassing the lower-scale information into the coarser scales, and vice versa. The key attribute of the sequential approach is that the simulation at a higher level critically depends on the completeness and correctness of the information gathered at the lower level, as well as the efficiency and reliability of the model at the coarser scale.

The properties of interest and research methods required in this project span several disciplines in engineering and science. Modeling the mechanistic links across scales is necessary for demonstrating understanding of complex chemo-mechanical properties in asphalts. Thinking in terms of computer models will guide each stage in the proposed work. The scales and disciplines map to the expertise of the research team.

- **chemical engineering / chemistry (nm)** – How do single-molecule dynamics impact the rheological properties of a multicomponent chemical system?

  Asphalts differ in the mass fraction distribution among asphaltenes, polar and naphthalene aromatics (resins), and saturates. Changes in asphaltene chemistry, such as alkane branch length and aromatic core size, affect single-molecule relaxation rates and thereby provide the <u>origin</u> of chemo-mechanical effects. Coupling of chemical effects will quantify (using molecular dynamics simulations) how molecular changes affect shear modulus *G* and viscosity η, as inferred from stress-stress correlation functions and rotational relaxation times τ (Zhang and Greenfield 2007b). The micrometer-level structure will inspire a choice of order parameters (Mehta 2004a), ψ; and related probability distributions will be averaged over the molecular simulations. Simple models will quantify the simulation results and provide guiding equations and parameters for the phase field models.

- **materials science / chemistry (μm)** – What equilibrium solid phases coexist? How are the phase domains controlled by surface vs. bulk interactions?

  In the context of the phase-field approach, the lower scale knowledge is in the form of ab initio or classical free energies $F(\psi)$ and the coarse-grained model is a continuum model. However, direct ab initio calculations of crystal phase free energy and of the excess free energies of the interfaces between phases are impractical using the currently available computational power. Therefore the mixed-space cluster expansion methodology (Wolverton 2000) shall be explored for its capability to extend the direct *ab initio* calculations of the energetics of several molecules to obtain the thermodynamic properties (bulk free energies and interfacial free energies) of systems with hundreds of thousands of molecules. If successful, this approach should yield the bulk free energies of the various equilibrium phases as a function of composition and temperature, as well as the interfacial free energies between coexisting phases. These are the key material data needed to construct a phase field model for the kinetics of structure evolution at the micrometer scale, so we can expect a smooth bridging of length scales by this approach. Free energies $F(\psi)$ obtained from the classical simulations will be tested for amorphous phases.

- **polymer science (μm)** – How do polymer modifier microphase structures that develop depend on the chemistry and polarity of the original asphalt?

  Computational tools using self-consistent field theory will be used to determine polymer microstructure and domain sizes (μm), based on molecular energetics (nm). This is similar to phase-field modeling.

- **physics (μm-mm)** – How are the micrometer-scale physical and phase properties connected with properties over longer length scales?

  The micrometer-scale properties and phases of the asphalt, along with the size and shape distribution of the finest aggregates, must be combined computationally to give the properties of the mastic phase that is input into the mm-m scale computations. The composite problem encountered is a viscous/viscoelastic matrix filled with elastic aggregate particles, with surface absorption between the matrix and the aggregates that can possibly alter the local properties and phase structure of the asphalt. Both viscous flow properties and mechanical properties must be supplied to the next level. Viscous flow properties will be computed with dissipative particle dynamics (DPD) techniques (Martys 2005), modified for a viscoelastic matrix using smooth particle hydrodynamics techniques. Mechanical properties will be computed using finite element methods adapted for micromechanical applications at the micrometer scale (Roberts and Garboczi 2002).

- **civil and mechanical engineering (mm-m)** – What mechanical properties emerge for an asphalt–aggregate pavement system? Two complementary multiscale approaches shall be utilized for simulating the macro scale response of asphalt concrete to link common pavement distress behaviors such as rutting, cracking, stripping, etc., with chemo-mechanical results from smaller length scales.

  In one approach (TU Delft), the macroscopic properties are derived from a microscopic description of the response of the individual components of the mix by utilizing homogenization techniques. A unit cell element of the material is considered and assumed to contain sufficient number of aggregate particles embedded in a mastic matrix. The homogenization procedure consists of three stages. First, a kinematic localization procedure assesses the directional average displacement field in terms of the macroscopic strain tensor. Next, local constitutive equations are introduced to relate both kinematic and static directional average variables. Finally, an averaging procedure is built to infer the macroscopic stress tensor from the distribution of directional average forces between neighboring particles in contact. The local behavior is described properly using elaborate elasto-visco-plastic constitutive laws to relate the local normal and tangential forces to the local normal and tangential relative displacements. The macroscopic behavior is the result of the multiplicity of intergranular contact conditions in various mechanical states.

  In the second approach, asphalt materials are classified as particle-reinforced composites, since they are characterized by a stone-based microstructure that is cemented together by a binding medium (mastic). To accommodate the previous smaller length scale information, we propose to use a computational modeling scheme based on finite element simulation. This will be achieved by modeling the interactions between individual aggregates within the composite using a network of specially created finite elements. For this case, the network finite element model will yield the usual general equation (Sadd 2005), $[K]\{U\}=\{F\}$, where [*K*] is the stiffness matrix, $\{F\}$ is the loading vector, and $\{U\}$ is the nodal displacement vector. Our previous work (Sadd et al. 2004) incorporated damage behaviors into the stiffness matrix to account for inelastic and failure mastic behavior. This process produced a stiffness matrix that was dependent on a series of damage parameters d_i as $[K]=[d_1,d_2,\cdots]$. For the proposed work, previous information from studies at smaller scales (such as mastic rheology and aging properties) will be fed into [*K*]. In this fashion, all previous length scale studies will contribute to the macro-modeling. Specially developed elements can be conveniently created using user defined element subroutines within packages like ABAQUS. Macro-stresses and deformation at the meter scale can then be obtained from standard averaging procedures.

  Finally, asphalt concrete is heterogeneous and composed of aggregates and binder of distinct properties. The interfaces between the two different constituents demonstrate behavior different from either of the constituents and often control the overall failure properties of the mixture due to imperfect bonding. Currently in asphalt mechanics, these interfaces are modeled as perfect bonding (continuous displacements and normal stresses for example), and zero interface thickness (ignoring the interface structure). Enhancements could include the characterization of the interface structure into modeling, and use of molecular dynamics to come up with a constitutive model for the interface. A realistic interface between aggregate and asphalt binder might have micro voids in between. The percentage of these micro voids by volume or area fraction of the total interfacial zones or areas represents the degree of imperfectness. The micro voids are typically of sizes ranging from 100 nanometers to 1 micrometer and can be characterized with Atomic Force Microscope. Fatigue cracking, and moisture damage often initiate from the interfaces.

Most FEM (Finite Element Method) simulations use phenomenological models formulated within the frameworks of continuum mechanics including elasticity, viscoelasticity, plasticity and viscoplasticity. Material constants of these models are usually characterized using macroscopic mechanical testing. For the interfaces that are of 100-nanometer scale, these tests are extremely difficult; this is the main reason for the lack of an interface model so far. In addition to the constitutive modeling of the stress-strain relation of the interfaces, the strengths of the interfaces contributed by friction and cohesion are also difficult to determine using macroscopic tests. How to separate friction from cohesion contribution to the interface strength is even more challenging using the current macroscopic approaches.

Overall Work Plan

Subtask F3a-1: *ab* initio Theories, Molecular Mechanics/Dynamics and Density Functional Theory Simulations of Asphalt Molecular Structure Interactions
Subtask Lead: Greenfield

Sub-subtask F3a-1.1. **Specify desired asphalt compositions and chemistries for testing multiscale asphalt modeling effort (large cluster simulations) (URI, WRI)**

A required input for beginning this task is information about the properties of asphalts from the different crude oil sources that are of interest in the chemomechanical asphalt model development effort. Properties of most interest are SARA speciation and elemental analyses (C:H ratio; alkane to aromatic carbon ratios, particularly if available within each SARA fraction; mass fractions C, H, S, N, O; etc.) for each asphalt/crude oil source of interest.

- Literature search on well-defined resin-type molecules available commercially.
- Hansen solubility parameter estimation for asphalt components.
- Composition calculations to determine concentrations (i.e. the number of each type of molecule present in a model asphalt) that represent crude-specific SARA data and elemental analyses.

Sub-subtask F3a-1.2. **Develop algorithms and methods for directly linking molecular simulation outputs and phase field inputs (URI, NIST)**

- Literature review of multi-scale simulations that bridge molecular perspectives and phase field approaches.

- Explore various upscaling formalisms to bridge between molecular-scale properties and coarse-grained phase-field model parameters.
- Derive/compile equations relating material properties (cohesive energy, molar volume, etc.) to phase field model parameters.

Sub-subtask F3a-1.3. **Obtain temperature-dependent dynamics results for model asphalts that represent asphalts of different crude oil sources (URI)**

- Assess effects of differences in asphalt chemistry and chemical environment among asphalt crude sources by altering asphaltene chemistry and composition balance among asphaltene, resins, and saturate concentrations in model asphalts.
- Quantify changes in dynamics by conducting extensive molecular dynamics simulations of model asphalt systems to estimate rotational relaxation times of asphaltene molecules.
- Relate changes in temperature-dependent rotational relaxation time to viscosity and mechanics results for these various asphalt compositions.

Sub-subtask F3a-1.4. **Simulate changes in asphalt dynamics after inducing representations of chemical and/or physical changes to a model asphalt (URI)**

- Augment oxidation-prone sites on asphaltene and resin molecules with oxygenated groups (e.g. carbonyls). Then probe effects of oxidation on nanometer-scale dynamics by determining rotational relaxation time in this changed chemical environment. Physical changes can correspond to composition shifts, such as loss of saturate due to wax formation.

Sub-subtask F3a-1.5. **Molecular mechanics simulations of asphalt-aggregate interfaces (VT)**

For nano scale simulations using MD (Molecular Dynamics), a recently developed innovative technique called Atomistic-Scale Finite Element Method (AFEM) (Liu et al. 2004a) will be adopted. The AFEM formulation is based on the observation that FEM and MD share the common ground that energy minimization leads to equilibrium configuration in materials. AFEM achieves considerable reduction in computation time while maintaining the same level of accuracy as the conventional conjugate gradient method. Another advantage is that AFEM can be seamlessly coupled with FEM permitting multiscale simulations combining nano and macro elements.

Even with the use of AFEM, MD simulation still has limited capabilities in terms of time and length scales. In parallel with AFEM, another novel and ingenious technique called Virtual Internal Bond (VIB) Model (Gao 1996; Gao 1997; Gao and Klein 1998) will be applied. VIB is a systematic approach to derive the continuum strain energy from the energy stored in the atomic bonds by averaging over the bond orientations and distribution. VIB models significantly extend the capabilities of nanoscale simulations to handle large-scale problems under longer time scales by averaging and homogenizing the interactions at the atomic level. Thus, a combination of discrete MD and continuum VIB simulations will ensure that the behavior of rock minerals (aggregates), binder and interfaces can be investigated over a wide range of scales. MD simulations will be used to investigate detailed atomic interactions and validate results of VIB models, while VIB models will be used for simulations of larger models.

The overall objective of this sub-subtask is to use MD, AFEM, and VIB simulations to come up with a macroscopic constitutive model of the stress–strain relationship for the interfaces and to implement the model on a FEM code following similar approach by Wang and Wang (2006). It has the following two components.

- **Molecular Dynamics (MD) Simulation and Homogenization Method Development (VT)** MD simulation is a technique to compute the equilibrium and transport properties of classical many-body systems where the motion of the particles (i.e. atoms and molecules) obey the laws of classical mechanics through the interatomic potential function (see Liu et al. 2004b for an excellent overview of computational nanomechanics and materials). The motion of a particle system is given as:

$$m_i \frac{d^2\mathbf{r_i}}{dt^2} = \mathbf{F}_i \qquad \text{(F3a-1.6.1)}$$

where $\mathbf{r}_i$ is position of the i^{th} particle and m_i its mass. The force $\mathbf{F}_i$ acting on a particle is calculated from the interatomic potential function U_{ij}:

$$\mathbf{F}_i = \sum_{j(i \neq j)} \mathbf{F}_{ij}\ ,\ \ \mathbf{F}_{ij} = -\nabla U_{ij} \qquad \text{(F3a-1.6.2)}$$

Several interatomic potential functions are currently available for MD simulations of different materials. One of the most widely used is the Lennard-Jones (LJ) potential. Another popular model that has been used for a great variety of atomistic processes and systems is the Morse potential. In the simulations of rock minerals, we will use the two-body interatomic potential function in the simulation of several types of clay minerals. This function consists of a combination of several potentials including Coulomb (attractive or repulsive), Born-Meyer-Higgins short-range repulsion (which originates from Pauli's exclusion principle), van der Waals and Morse terms:

$$\begin{aligned} U_{ij}(r_{ij}) = & \frac{z_i z_j e^2}{4\pi\varepsilon_o r_{ij}} + f_o\left(b_i + b_j\right)\exp\left[\frac{a_i + a_j - r_{ij}}{b_i + b_j}\right] - \frac{c_i c_j}{r_{ij}^{\ 6}} + D_{ij}\exp\left(-\beta_{1ij} r_{ij}\right) \\ & + D_{2ij}\exp\left(-\beta_{2ij} r_{ij}\right) + D_{3ij}\exp\left\{-\beta_{3ij}\left(r_{ij} - r_{ij}^*\right)^2\right\} \end{aligned} \qquad \text{(F3a-1.6.3)}$$

In the above equation, r_{ij} is the distance between two particles located at $\mathbf{r}_i$ and $\mathbf{r}_j$; z_i is the charge of the i^{th} ion; ε_o stands for the dielectric constant of vacuum; f_o is a constant for converting units; D_{ij} and β_{ij} are the depth and shape factors in the modified Morse term, respectively; r_{ij}^* is the equilibrium distance between atoms; and *a*, *b* and *c* are material parameters. We will use the potential in equation (F3a-1.6.3) as a generic potential, modify and calibrate it with terms relevant to different minerals and asphalt binder.

To increase computational efficiency, we will adapt the AFEM technique recently developed by Liu et al. (2004a) and the Virtual Internal Bond (VIB) model developed by Gao (1996, 1997), and Gao and Klein (1998) for homogenizing atomistic response. The major effort in this consortium is to refine the preliminary development currently being carried out in a joint project between VT and NIST.

- **Nanoscale Simulations of Rock Minerals (aggregate) -Binder Interfaces (VT)** Using the AFEM and VIB models and computer programs we are currently developing, we will perform nanoscale simulations of rock minerals, asphalt binder, and rock mineral-binder interfaces. The major goals of the nanoscale computations are to develop a constitutive model and failure criteria for aggregate-binder interfaces. A secondary goal is to develop a library of AFEM and VIB models of several commonly occurring rock minerals (aggregates) and binder for macroscopic comparisons. For the MD simulation, we will employ both *NPT* (constant number of particles N, pressure P, and temperature T) and *NVT* (constant number of particles N, volume V, and temperature T) ensembles to simulate the stress-strain response of rock minerals and binder. The velocity scaling method will be used to control temperature, while the pressure is maintained by controlling basic cell parameters. Three-dimensional periodic boundary conditions will be used to reduce the number of particles in the simulation. In the *NPT* ensemble, pressure is applied to the modeled cell in the direction of uniaxial compression, tension or shear and strains are calculated by averaging the ensemble deformation. In the *NVT* ensemble, simulations are carried out by changing the sizes and shapes of the modeled cell and the average stresses are obtained. For interfaces between constituents, we will use the technique developed by Depondt (2002), which essentially consists of stacking two blocks or chains of particle ensemble one on top of the other and applying a constant force or velocity on the top assemblage. Li et al. (2003) has successfully used this technique to explain the origin of stick-slip phenomenon in NiAl. We note that rock mineral surfaces are not purely planar at the nanoscale and nanoscale roughness will be included in the simulation. The end results of these simulations will be the ensemble stress-strain relation or the constitutive response. VIB will be used for larger scale simulations while AFEM will be used for detailed atomistic simulation including the effects of defects on the bond distribution. The simulations will be calibrated against available experimental data. We will consider several minerals other than quartz and calcite and PG64-22 binder. The percent micro voids will be taken into considerations through effective stress and effective strain and average strength.

<u>Sub-subtask F3a-1.6.</u> **Modeling of fatigue behavior at atomic scale (VT, NIST)**.

Based on the developments and refining additional to the NSF project by VT and NIST, we will perform nano-scale simulations to understand the mechanism of fatigue and healing. Although tremendous research efforts have been devoted to the investigation of fatigue behavior of asphalt concrete the understanding of fatigue at microscopic and nano scale is very much limited. Fatigue life of a specimen is currently determined at 50% reduction of the modulus. A scientific basis is needed for better understanding the fatigue and healing mechanism and interpretation of the currently experimental data. **This task will be achieved in the third year**.

<u>Sub-subtask F3a-1.7.</u> **Modeling of moisture damage (VT).**

Moisture damage has several mechanisms including excess pore water pressure, and chemical-mechanical coupling. When water penetrates into the micro pores at the interfaces between binder and aggregates, the excess pore water pressure mechanism and the chemical-mechanical coupling mechanism may have to be considered together. Nano mechanics simulations will present a basis for understanding the mechanisms of moisture damage and the coupled phenomena of moisture damage and fatigue. **This task will be achieved in the fourth year**.

<u>Sub-subtask F3a-1.8.</u> ***ab initio* Calculations of Asphalt Molecular Structures and Correlation to Experimental Physico-Chemical Properties of SHRP Asphalts (WRI-TUDelft)**

This sub-subtask will focus on the identification of asphalt molecular structures representative of molecular classes of materials present in paving grade asphalts, where *ab initio* calculations of free energy (i.e., states of chemical potential and conformations) of single molecules and small clusters of asphalt and asphalt fraction molecular structures will be considered. The calculations performed at this level will be very fundamental in terms of the computational chemistries employed. The intent here is to identify the types of molecular structures and dominate interactions; e.g., dispersive, H-bonding, π-π, and change-transfer, representative of dimer, trimer, etc., molecular clusters, and the associated energy values that best correlate with experimental observations such as UV-VIS, IR and NMR spectroscopes of actual heavy crude oils and chromatographic fractions of heavy crude oils. Theoretical chemistry models will include Hartree-Fock self-consistent field theory, and Møller-Plesset perturbation theories employing electron correlation interaction and Density Functional Theory.

- Determine molecular structures and interaction energies (specifically chemical potentials) of molecules that are representative of asphalt and asphalt fraction (SARA fractions for example) that are also specific to a given crude source.
- Derive thermodynamic free energies and chemical potentials of molecular and phase states specific to a select set of crude oils from molecular structures and interaction energies.
- Correlate calculated data with experimental data generated in Nanotechnology subtask 2-3 in the FP-III contract, e.g., SARA fractions, IR and NMR spectra analyses.

Subtask F3a-2: Phase-Field Modeling of Asphalt Molecular Moieties
Subtask Lead: Bullard

Sub-subtask F3a-2.1: **Derive phase field model expressions for colloidal nano-emulsion phase separation thermo-kinetic processes (NIST)**

This sub-subtask will focus on application of phase field models to simulate the stability and time-dependent mesostructure of colloidal emulsions, which are analogs to asphalt binder systems. By formulating the bulk and gradient energy terms in terms of the system's constitutive variables (i.e. order parameters), one can obtain predictions of phase separation, coarsening, and phase topology in emulsions as a function of temperature and bulk composition. The work plan begins with deriving the generic form for the free energy functional, including the number and type of relevant order parameters that are required to provide a sufficiently detailed picture of the structural evolution of nano-emulsions. From that point, computational algorithms for phase-field models will be employed, taking advantage of fast Fourier transform (i.e., spectral) methods for computational efficiency. Much of the algorithm development has been done already by other investigators, and we will leverage that work here. Finally, and even more importantly, we must be in a position to incorporate realistic values for the thermo-kinetic properties (enthalpy of mixing, interface free energy, molar volumes, etc., and their temperature dependence) that determine the exact form of the free energy functional for the system under consideration. Therefore, a critical component of the work in Year 2 will be to begin developing a rational way to upscale molecular-scale information to the phase field model (subtask F3a-1).

- Determine number and class of order parameters needed to simulate nano-emulsion structure evolution. Derive/compile equations relating material properties (enthalpy of fusion, surface energy, molar volumes, etc.) to phase-field model parameters for the mobility coefficients in the TDGL equations, the interface gradient coefficient tensor, and the local free energy scaling parameter.
- C/C++ coding, debugging, and testing of 2-D and quasi-3-D phase-field model for nano-emulsion phase separation.
- Conduct simulations of nano-emulsion phase separation and coarsening in a quasi-3-D thin film system. Predict volume fraction of emulsion and size distribution of emulsion domains as a function of time and temperature. Compare predictions to experimental observations using atomic force microscopy. Adjust parameters in free energy functional to agree with experiment.

Sub-subtask F3a-2.2: **Derive phase field model expressions for wax crystallization thermo-kinetic processes (NIST)**

The spirit of this sub-subtask is much the same as sub-subtask F3a-2a that is, applying phase field modeling methods to understand and predict the structural evolution of asphalt binder as a function of composition and environmental variables. In this sub-subtask, phase field models will be used to investigate the nucleation, growth, and shape of wax crystallite domains that can form in asphalt binders. These crystallites can have a profound impact on mechanical properties (e.g. viscosity, workability, elastic moduli, and binder/aggregate adhesion). The exact form of the free energy functional will be different in this case than in sub-subtask F3a .2.1, but the phase field implementation is essentially the same once the free energy functional is derived. Here, as before, a critical aspect of this work will involve obtaining realistic values for the thermo-kinetic properties of the material system. These include the enthalpy of mixing, molar volumes, interface free energy *and its anisotropy*, the viscoelastic compliance of the waxy phase (thought to be responsible for observed buckling due to misorientation of accreting molecules), and the temperature dependence of these parameters. Our approach will be the same as in sub-subtask F3a-2.1, i.e. to begin developing a framework for upscaling molecular-scale properties that are obtained as part of subtask F3a-1.

- Literature review of phase-field modeling of polymer-colloid composites and for surface energy and curvature elasticity of wax-like crystallites.
- Construct thermodynamically consistent and chemically realistic free energy functionals for implementation in phase field models of nano-emulsion structure evolution and wax crystallite formation and growth.
- Design, develop and debug C/C++ phase field model, and benchmark the model against theoretical results for grain growth, Ostwald ripening, phase separation kinetics, and crystal growth anisotropy.
- Develop and exercise formalism for upscaling molecular properties (structure, chemical potentials) from molecular-scale calculations to corresponding coarse-grained free energy parameters in phase field models.
- Conduct simulations of wax crystallization in a quasi-3-D thin film system. Predict volume fraction, size distribution, and ripple frequency of the wax domains as a function of time and temperature. Compare predictions to experimental observations using atomic force microscopy. Adjust parameters in free energy functional to agree with experiment.

<u>Subtask F3a-3: Phase-Field and Continuum Mechanical (Finite Element) Modeling of Asphalt Binder, the Unified Chemo-Mechanical Model of Asphalt Binder</u>
Subtask Lead: Niki Kringos

<u>Sub-Subtask F3a-3.1.</u> **Conduct phase field simulations for micro-crack initiation-propagation and self-healing processes (TU Delft and WRI)**

Laboratory experimental evidence clearly indicates the beneficial effects of rest periods in restoring the stiffness and strength characteristics of asphaltic samples subjected to fatigue loading. There is consensus among researchers that currently available cracking failure prediction models grossly underestimate asphalt concrete pavements field life. It is commonly accepted that the reason for this discrepancy is the exclusion of healing effects from design calculations.

- Experimental and analytical approaches will be carried out to investigate the mechanisms leading to the initiation, propagation and healing of damage in asphalt concrete pavements. One of the major goals of this investigation is the development and finite elements implementation of a triaxial, strain rate sensitive, history and temperature dependent constitutive model which enables the accurate incorporation of the healing capacity of the material.

- By postulating a multiplicative decomposition of the deformation gradient and an additive decomposition of the Helmholtz free energy function, an elegant formulation is obtained for the three dimensional elasto-visco-plastic response of asphaltic concrete materials by systematic exploitation of the Clausius-Planck local dissipation inequality. The healing of the bituminous material is simulated via a phase field model, utilizing a modified version of the Cahn Hilliard and Flory-Huggins equations. The characterization and visualization of the kinetics of the phase separation of the bitumen will subsequently be performed via Atomic Force Microscopy and Nano-Indentation experiments. The model will be implemented in the finite element code CAPA-3D. Results of the utilization of CAPA-3D will include the simulation of cracking of asphaltic concrete mixes and the associated self-healing capability under the appropriate environmental and mechanical conditions.

NOTE: This work will be conducted as part of the ISAP consortium on Chemo-mechanics of Bituminous Materials

Subtask F3a-4. **Overall integration for multiscale modeling (VT, NIST, URI, TUDelft and WRI)**

While modeling at the nano scale certainly presents insights for understanding the behavior of asphalt binder and aggregate-binder interfaces, a multiscale simulation approach will provide direct applications in material selection, mix design and performance predictions. Developed methods in Subtasks F3a will be integrated into a multiscale simulation tool for realistic applications. The nano-scale modeling techniques will be integrated into the digital specimen and digital test techniques to perform simulations of performance tests of mixtures. **This task will start in the third year and requires about two years to accomplish**. There might be some overlap with the development of nano-scale modeling techniques in timing.

Subtask F3a-5. **Experimental verification and validation (VT, NIST, URI TUDelft and WRI)**

The overall modeling techniques will be verified and validated through demo project. In the demo project modeling predictions will be compared to experimental measurements to provide feedback for modeling enhancements or revision. **This task will start in the fourth year and requires about one year to accomplish**.

Year 2 Milestones

In year 2, four asphalts of different crude source dependent “molecular types” will be identified based on variation in chemical composition (e.g., asphaltene/maltene compatibility, wax content, elemental composition including SARA characteristics), and rheological properties. Molecular “representations” of these “systems” will be developed and preliminary models representing scaling from molecular to microstructural phase-dependent traits will be derived, this will include a simple colloidal emulsion system. Wax crystallization phases will be developed in the second and third year. Two aggregate types will also be identified and MD simulations conducted to model interfaces of at least four combinations of asphalt-aggregate systems. Toward the end of year 2, input parameters derived from molecular to phase-field scales will be implemented into continuum models to simulate the stress concentrations induced by the developing microstructural phases.

Overall Schedule

Work Element F3a: Microstructural Modeling	Year 2 (4/08-3/09)				Year 3 (4/09-3/10)				Year 4 (04/10-03/11)				Year 5 (04/11-03/12)				Team
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	
Subtask F3a-1: *ab initio* Theories, Molecular																	
Sub-Subtask F3a-1.1. Specify desired asphalt compositions and chemistries for testing multiscale asphalt modeling effort (large cluster simulations).																	URI, WRI
Sub-Subtask F3a-1.2. Develop algorithms and methods for directly linking molecular simulation outputs and phase field inputs								D									URI, NIST
Subtask F3a-1.3. Obtain temperature-dependent dynamics results for model asphalts that represent asphalts of different crude oil sources								D									URI
Sub-Subtask F3a-1.4. Simulate changes in asphalt dynamics after inducing representations of chemical and/or physical changes to a model asphalt								D									URI
Sub-Subtask F3a-1.5. Molecular mechanics simulations of asphalt-aggregate interfaces								D									VT
Sub-Subtask F3a-1.6. Modeling of fatigue behavior at atomic scale								D									VT, NIST
Sub-Subtask F3a-1.7. Modeling of moisture damage													D				VT
Sub-Subtask F3a-1.8. *ab initio* Calculation of asphalt molecular structures and correlation to experimental physico-chemical properties of SHRP asphalts																	WRI, TUDelft
Subtask F3a-2:Phase-Field Modeling of Asphalt Molecular																	
Sub-Subtask F3a-2.1. Derive phase field model expressions fro colloidal nano-emulsion phase separation thermo-kinetic processes						D											NIST
Sub-Subtask F3a-2.2 Derive phase field model expressions for wax crystallization thermo-kinetic processes								D									NIST
Subtask F3a-3: Phase-Field and Continuum Mechanical (Finite Element) Modeling of Asphalt Binder, the Unified Chemo-Mechanical Model of Asphalt Binder																	
Sub-Subtask F3a-3.1. Conduct phase field simulations for micro-crack initiation-propagation and self-healing processes							D										TUDelft, WRI
Subtask F3a-4: Overall Integration for Multiscale Modeling															M		ALL
Subtask F3a-5: Experimental Verification and Validation															F,JP		ALL

Deliverable codes	Deliverable Description
D: Draft Report	Report delivered to FHWA for 3 week review period.
F: Final Report	Final report delivered in compliance with FHWA publication standards
M&A: Model and algorithm	Mathematical model and sample code
SW: Software	Executable software, code and user manual
JP: Journal paper	Paper submitted to conference or journal
P: Presentation	Presentation for symposium, conference or other
DP: Decision Point	Time to make a decision on two parallel paths as to which is most promising to follow througjh
(blue)	Work planned
(orange)	Work completed
(gray)	Parallel topic

Year 2 Schedule

Work Element F3a: Microstructural Modeling	Year 2 (4/08-3/09)												Team
	4	5	6	7	8	9	10	11	12	1	2	3	
Subtask F3a-1: *ab initio* Theories, Molecular													
Sub-Subtask F3a-1.1. Specify desired asphalt compositions and chemistries for testing multiscale asphalt modeling effort (large cluster simulations).													URI, WRI
Sub-Subtask F3a-1.2. Develop algorithms and methods for directly linking molecular simulation outputs and phase field inputs													URI, NIST
Subtask F3a-1.3. Obtain temperature-dependent dynamics results for model asphalts that represent asphalts of different crude oil sources													URI
Sub-Subtask F3a-1.4. Simulate changes in asphalt dynamics after inducing representations of chemical and/or physical changes to a model asphalt													URI
Sub-Subtask F3a-1.5. Molecular mechanics simulations of asphalt-aggregate interfaces													VT
Sub-Subtask F3a-1.6. Modeling of fatigue behavior at atomic scale													VT, NIST
Sub-Subtask F3a-1.7. Modeling of moisture damage													VT
Sub-Subtask F3a-1.8. *ab initio* Calculation of asphalt molecular structures and correlation to experimental physico-chemical properties of SHRP asphalts													WRI, TUDelft
Subtask F3a-2:Phase-Field Modeling of Asphalt Molecular													
Sub-Subtask F3a-2.1. Derive phase field model expressions fro colloidal nano-emulsion phase separation thermo-kinetic processes													NIST
Sub-Subtask F3a-2.2 Derive phase field model expressions for wax crystallization thermo-kinetic processes													NIST
Subtask F3a-3: Phase-Field and Continuum Mechanical (Finite Element) Modeling of Asphalt Binder, the Unified Chemo-Mechanical Model of Asphalt Binder													
Sub-Subtask F3a-3.1. Conduct phase field simulations for micro-crack initiation-propagation and self-healing processes													TUDelft, WRI
Subtask F3a-4: Overall Integration for Multiscale Modeling													ALL
Subtask F3a-5: Experimental Verification and Validation													ALL

Deliverable codes	Deliverable Description
D: Draft Report	Report delivered to FHWA for 3 week review period.
F: Final Report	Final report delivered in compliance with FHWA publication standards
M&A: Model and algorithm	Mathematical model and sample code
SW: Software	Executable software, code and user manual
JP: Journal paper	Paper submitted to conference or journal
P: Presentation	Presentation for symposium, conference or other
DP: Decision Point	Time to make a decision on two parallel paths as to which is most promising to follow througl
(blue)	Work planned
(orange)	Work completed
(grey)	Parallel topic

Budget

	Year 2	Year 3	Year 4	Year 5	Total
URI	76,000	76,000	76,000	76,000	304,000
VT	76,000	76,000	76,000	76,000	304,000
NIST	59,000	93,000	93,000	93,000	338,000
WRI/TUDelft	52,000	93,000	93,000	93,000	331,000
Total	263,000	338,000	338,000	338,000	1,277,000

References

ARA Inc., 2004, Guide for mechanistic-empirical design, Technical Report 1-37A, NCHRP.

Bader, Richard F. W., 1990, *Atoms in Molecules*. Oxford University Press.

Bentz, D. P., E. J. Garboczi, J. W. Bullard, C. F. Ferraris, and N. S. Martys, 2006, Virtual testing of cement and concrete, in *Significance of Tests and Properties of Concrete and Concrete-Making Materials*, Joseph Lamond and James Pielert, eds., ASTM STP 169D.

Bullard, J. W., C. F. Ferraris, E. J. Garboczi, N. S. Martys, and P. A. Stutzman, 2004, Virtual Cement and Concrete, in *Innovations in Portland Cement Manufacturing*, Chapter 10.3, J. I. Bhatty, F. M. Miller and S. H. Kosmatka, eds., Portland Cement Association, pp. 1311-1331.

Buttlar, W. G., D. Bozkurt, G. G. Al-Khateeb, and A. S. Waldhoff, 1999, Understanding asphalt mastic behavior through micromechanics. *Transp. Res. Rec.*, 1681: 157-1690.

Cahn, J. W., 1965, Phase Separation of Spinodal Decomposition in Isotropic Systems. *J. Chem. Phys*., 42 (1), 93-99.

Cahn, J. W., and J. E. Hilliard, 1958, Free Energy of a Nonuniform System. I. Interfacial Free Energy. *J. Chem. Phys*., 28 (2), 258-267.

Cahn, J. W., and J. E. Hilliard, 1959a, Free Energy of a Nonuniform System. II. Thermodynamic Basis. *J. Chem. Phys*., 30 (5), 1121-1124.

Cahn, J. W., and J. E. Hilliard, 1959b, Free Energy of a Nonuniform System. III. Nucleation in a Two-Component Incompressible Fluid. *J. Chem. Phys*., 31 (3), 688-699.

Depondt, Ph., 2002, A One Dimensional Model of Friction at Nanometric Scale. *Surface Science*, 501: 112-124.

Fu, Y. R., L. B. Wang, and M. Tumay, 2007, Quantification and Simulation of Particle Kinematics and Local Strains in Granular Materials Using X-ray Tomography Imaging and Discrete Element Method. *Journal of Engineering Mechanics*, In Press.

Gao, H., 1996, A Theory of Local Limiting Speed in Dynamic Fracture. *Journal of the Mechanics and Physics of Solids*, 44: 1453-1474.

Gao, H., 1997, Elastic Waves in a Hyperelastic Solid Near Its Plane Strain Equibiaxial Cohesive Limit. *Philosophical Magazine Letters*, 76: 307-314.

Gao, H., and P. Klein, 1998, Numerical Simulation of Crack Growth in an Isotropic Solid with Randomized Internal Cohesive Bonds. *Journal of the Mechanics and Physics of Solids*, 46: 187-218.

Glansdorff, P., and I. Prigogine, 1971, *Thermodynamic Theory of Structure, Stability and Fluctuations*, Wiley-Interscience, division of John Wiley & Sons, Ltd., London.

Hveem, F. N., 1943, Quality Tests for Asphalts – A Progress Report. *Proceedings, Association of Asphalts Paving Technologists*, 15: 111-152.

Kennedy, T. W., G. A. Huber, E. T. Harrigan, R. J. Cominsky, C. S. Hughes, H. Von Quintus, and J. S. Moulthrop, 1994, SHRP-A-410, *Superior performing asphalt pavements (Superpave):*

The product of the SHRP Asphalt Research Program, National Research Council, Washington, DC.

Kim, Yong-Rak, and D. N. Little, 2004, Linear viscoelastic analysis of asphalt maltics. *J. Mater. Civ. E.*, 16: 122-132.

Li, B., P. C. Clap, J. A. Rifkin, and X. M. Zhang, 2003, Molecular Dynamics Simulation of Stick-Slip. *Journal of Applied Mechanics,* 90(6): 3090-3094.

Liu, B., Y. Huang, H. Jiang, S. Qu, and K. C. Hwang, 2004a, The Atomic Scale Finite Element Method. *Computer Methods in Applied Mechanics and Engineering*, 193: 1849-1864.

Liu, W., E. G. Karpov, S. Zhang, and H. S. Park, 2004b, An Introduction to Computational Nanomechanics and Materials. *Computational Methods in Applied Mechanics and Engineering*, 193: 1529-1578.

Martys, N., 2005, Study of a dissipative particle dynamics based approach for modeling suspensions. *J. Rheol.*, 49: 401-424.

Masson, J. F., P. Collins, G. Robertson, J. R. Woods, and J. Margeson, 2003, Thermodynamics, phase diagrams, and stability of bitumen–polymer blends. *Energy Fuels*, 17: 714-724.

Mehta, R., W Keawwattana, and T. Kyu, 2004a, Growth Dynamics of Isotactic Polypropylene Single Crystals During Isothermal Crystallization from a Miscible Polymeric Solvent. *J. Chem. Phys.*, 120(8): 4024-4031.

Mehta, R., W Keawwattana, A. L. Guenthner, and T. Kyu, 2004b, Role of Curvature Elasticity in Sectorization and Ripple Formation During Melt Crystallization of Polymer Single Crystals. *Phys. Rev. E.*, 69, 061802.

Pal, R., and E. Rhodes, 1989, Viscosity/Concentration Relationships for Emulsions. *Journal of Rheology*, 33(7): 1021-1045.

Petersen, J. C., R. E. Robertson, J. F. Branthaver, P. M. Harnsberger, J. J. Duvall, S. S. Kim, D. A. Anderson, D. W. Christensen, H. U. Bahia, 1994, SHRP-A-367, *Binder Characterization and Evaluation, Volume 1*. Strategic Highway Research Program, National Research Council, Washington, DC.

Redelius, Per, 2004, Bitumen solubility model using Hansen solubility parameter. *Energy Fuels*, 18: 1087-1092.

Roberts, A. P., and E. J. Garboczi, 2002, Computation of the linear elastic properties of random porous materials with a wide variety of microstructure. *Proc. Royal Soc. London*, A458: 1033-1054.

Robertson, R. E., J. F. Branthaver, P. M. Harnsberger, J. C. Petersen, S. M. Dorrence, J. F. McKay, T. F. Turner, A. T. Pauli, S.-C. Huang, J.-D. Huh, J. E. Tauer, K. P. Thomas, D. A. Netzel, F. P. Miknis, T. Williams, J. J. Duvall, F. A. Barbour, C. Wright, 2001, *Fundamental*

Properties of Asphalts and Modified Asphalts, Volume I: Interpretive Report, FHWA-RD-99-212. U. S. Department of Transportation, Federal Highway Administration, McLean, VA.

Sadd, Martin H., 2005, *Elasticity Theory, Applications, and Numerics*, Burlington, MA: Elsevier.

Sadd, Martin H., Qingli Dai, Venkitanarayanan Parameswaran, and Arun Shukla, 2004, Microstructural simulation of asphalt materials: Modeling and experimental studies. *J. Mater. Civ. E.*, 16: 107–115.

Shenoy, A., 2002, Model-fitting the master curves of the dynamic shear rheometer data to extract a rut controlling term for asphalt pavements. *J. Testing Eval.*, 30, 95-102.

Sims, J. S, and N. Martys, 2004, Simulation of Sheared Suspensions with a Parallel Implementation of QDPD. *Journal of Research of the National Institute of Standards and Technology,* 109: 267.

Ulm, F.-J., 2003, Chemomechanics of concrete at finer scales, *Mater. Struct.*, 36: 426–438.

Wang, X.**,** and L. B. Wang, 2006, Continuous Interface Elements Subject to Large Shear Deformations. *International Journal of Geomechanics*, 6(2): 97-107.

Wang, Y. P**.**, L. B. Wang, Q. B. Li, and T. P. Harman, 2007a, Noninvasive Measurement of 3D Permanent Strains In Asphalt Concrete Using X-Ray Tomography Imaging. *Transportation Research Record (TRR)*, In Press.

Wang, L. B**.,** J. Y. Park, and Y. R. Fu, 2007b, Representation of Real Particles for DEM Simulation using X-ray Tomography. *Journal of Construction and Building Materials,* 21(2): 338-348.

Wang, L. B., B. Zhang, D. Wang, and Z. Q. Yue, 2007c, Fundamental Mechanics of Asphalt Compaction Through FEM and DEM Modeling**.** *ASCE GSP 176*, pp. 45-63.

Wiehe, I. A., and K. S. Liang, 1996, Asphaltenes, resins, and other petroleum macromolecules. *Fluid Phase Equil.*, 117: 201-210.

Wolverton, C., 2000, First-principles theory of 250,000-atom coherent alloy microstructure. *Modelling Simul. Mater. Sci. Eng.*, 8: 323-333.

Zhang, B., and L. B. Wang, 2007, Digital Simple Performance Test of Asphalt Concrete. *Proc.*, 7th International Conference of Chinese Transportation Professionals, May 20-21, 2007, Shanghai, China, pp. 98-107.

Zhang, Liqun, and Michael L. Greenfield, 2007a, Molecular orientation in model asphalts using molecular simulation. *Energy Fuels*, 26: 5461-5472.

Zhang, Liqun, and Michael L. Greenfield, 2007b, Relaxation time, diffusion, and viscosity analysis of model asphalt systems using molecular simulation. *J. Chem. Phys.*, 127: 194502.

Work Element F3b: Micromechanics Model

<u>Subtask F3b-1: Model Development</u>

Micromechanical models are powerful in accounting for the interactions among the mixture constituents. They are capable of explicitly modeling the mixture microstructure geometry and the properties of each of the constituents. In this task, the researchers will pursue the development of several micromechanical modeling approaches.

The first approach will develop the analytical micromechanics models that yield effective mastic and mixture properties given the properties and distribution of the constituents. These analytical micromechanics models will also be able to account for the influence of damage distribution on the effective properties. The analytical models will be developed at Texas A&M University.

The second approach will advance the micromechanics-based computational model that has been developed by researchers at the University of Nebraska (NU). Past work has demonstrated a number of innovative features of the model including (1) bridging the scales between micro-scale (fundamental mixture component properties) and macro-scale (damage-dependent behavior of whole asphalt concrete mixtures), (2) explicit prediction of nonlinear-inelastic material behavior, (3) realistic simulation of rate-dependent microscale fracture damage based on a cohesive zone approach, and (4) microstructure characterization to represent mixture heterogeneity and anisotropy. This modeling approach is directly incorporated into this project in that it employs fundamental materials and mixture properties (outcomes from Category 1) that are obtained from testing methods (Category F2), and will be implemented into other modeling efforts including the unified continuum model (Category F3). The NU model will eventually be calibrated and/or validated through various laboratory performance data and the FHWA-ALF experimental results. More specifically, the NU model will use the thermodynamic/mechanical cohesive-adhesive properties of mixture components, linear-nonlinear viscoelastic properties, and geometric information such as mixture microstructure and aggregate images provided by TAMU and UWM as basic model inputs. Furthermore, the model will be elaborated by taking into account several key fatigue damage-associated factors such as the effects of binder modification, binder aging, additives, damage healing, and moisture to seamlessly explain the complex fatigue damage behavior of asphalt mixtures and pavements. As a subcontractor, NU will take the lead in this particular modeling activity by being closely collaborated with TAMU where would lead the experimental-analytical part.

The third approach will further develop the multi-scale lattice micromechanical model. The research group at NCSU will focus on developing, refining, validating, and calibrating the multi-scale lattice micromechanical model and in linking it to nonlocal models for the purpose of carrying out large scale simulations of pavements.

Lattice Model: The lattice modeling technique was developed at NCSU with the ultimate goal of linking micromechanical constituent properties with macroscopic damage behavior of asphalt concrete. Past work in this area showed significant promise of this approach, but highlighted several issues. The most important of these are the scale-dependency of surface energy, the stiffening effect of asphalt binder in thin-film form and the absence of a viscoelastic fracture framework in the lattice model. The extensive experimental program proposed in various work elements of the FHWA DTFH61-07-H-00009 project would provide rich data that could be used to develop a more robust and reliable lattice model. Specifically, the thermodynamic and mechanical, cohesion and adhesion properties as well as data from the aggregate imaging system would provide valuable input to the model. Similarly, any insight gained into asphalt concrete behavior from other microscopic testing by synchrotron and AFM would greatly help refine the lattice model and enhance its predictive capabilities. On the computational side, algorithms to improve the performance of lattice modeling will be developed. During the first year, fundamentals of the aformentioned properties and methods have been studied with the primary objective of improving the current lattice model. A detailed research approach incorporating experimental, analytical, and computational methods will be developed in the beginning of the second year.

Nonlocal Model: While the lattice model provides a micromechanical approach to damage and fracture modeling, the nonlocal models try to achieve the same using a continuum mechanics approach, which is better suited to large scale simulations of pavements. A constitutive model is called nonlocal when the stress (or strain) at a point depends on state variables in a region around the point. Nonlocal models are necessary when the scale of the microstructural features in the material is comparable to the size of the domain being analyzed. In other words, these models try to include the effect of the underlying microstructure on the average material behavior. In the first year, a detailed literature review has been carried out to understand the different forms of nonlocal models and the applicability of these models to asphalt concrete. Since the nonlocal models would require extensive fracture testing for determining the parameters of the model, it seems ideal that the lattice models be used to provide data from virtual testing. During the second year, a nonlocal modeling framework will be developed based on the existing form of the lattice model.

<u>Subtask F3b-2: Account for Material Microstructure and Fundamental Material Properties</u>

Previous research efforts have shown that most micromechanical computational models, irrespective of the numerical implementation, underestimated the stiffness and strength of asphalt mixtures. This was attributed to the lack of realistic representation of the mixture microstructure and the use of bulk properties of the constituents. This finding motivates us to focus some of the research efforts on the use of detailed representation of the microstructure, which can be achieved by using X-ray CT imaging at multiple resolutions. Also, the research will focus on the use of rigorous upscaling methods that are able to incorporate experimental measurements conducted at a small scale into a micromechanical model at a larger scale. For example, the bond energy per unit area calculated from surface energy measurements should be upscaled prior to its use in a micromechanical model. The upscaling takes into account the fact that the micromechanical model cannot, due to computational limitations, account for the nanostructural details at which the surface energy is acting. In other words, the actual area of the microstructure can be reduced by orders of magnitudes when transferred to the model scale.

In summary, the research efforts will focus on improving the cohesive zone-based computational micromechanics model and the lattice model in order to better account for the microstructure distribution (asphalt film thickness, realistic shape of aggregates, aggregate size distribution) and to incorporate the fundamental properties measured in Category 1 of the work plan.

Major Findings from Year 1 for Work Element F3b

An extensive review of the micromechanics-based computational models to characterize damage-dependent behavior of asphalt materials and mixtures was conducted by ARC researchers at the University of Nebraska. The review efforts mainly focused on (i) investigation of the state of the art of modeling techniques typically based on the micromechanics and computational methods such as the finite element method, (ii) strategy for development of the model that can appropriately account for geometric heterogeneity and nonlinear-inelastic constitutive behavior of the asphalt materials and mixtures, and (iii) strategy for appropriate integration of material properties (as model inputs) obtained from other tasks into the micromechanics-based computational model being developed by the researchers at the University of Nebraska.

The following are some of the findings based on this literature review and revisit to the modeling technique being developed at the University of Nebraska:

i. For more accurate characterization and modeling of fatigue damage in asphaltic materials and mixtures, inelastic fracture and corresponding energy dissipation must be considered in the process. Asphalt demonstrates a significant complexity of rate-dependent and inelastic damage behavior.
ii. In order to model heterogeneity of asphalt mixtures, the concept of micromechanics specifically with the aid of computational techniques such as the finite element method is necessary. In addition, damage and failure of asphalt mixtures are associated with the growth of thousands of cracks in multiple scales. Computational techniques can successfully deal with these complex issues.
iii. The model being developed at the University of Nebraska is based on the cohesive zone concept to simulate initiation and propagation of damage. This appears to be reasonable in that the cohesive zone modeling is a well-established fracture mechanics tool, which removes stress singularities ahead of crack tips and takes into account both brittle and ductile fracture behavior within the same theoretical framework. The cohesive zone modeling concept has been receiving increasing attention from the asphalt mechanics community due to its useful and powerful modeling capability.
iv. This micromechanical modeling approach is expected to provide a number of meaningful findings at the final stage of this project, because this effort is directly and strongly incorporated with other key testing-modeling-validation tasks in this project.

Year 2 Milestones for Work Element F3b

i. Continue the review of literature related to the micromechanics-based computational modeling techniques.

ii. Modify and/or elaborate the current cohesive zone model to predict fracture and damage characteristics in asphalt mixtures so that the model can be better fit with material and damage properties that will be measured and provided by the TAMU and UWM.
iii. Determine the representative volume elements (RVE) of various asphalt mixtures to facilitate the computational modeling within the micromechanics concept. This particular milestone will be related to the Work Element F2d: Tomography and Microstructural Characterization led by the TAMU.

In the area of lattice modeling work will primarily focus on:

i. incorporating new computational methods that can increase the computational efficiency by an order of magnitude,
ii. streamlining the analysis procedure that facilitates automated analysis of a large number of lattice mesh realizations, and
iii. investigation of modeling time-dependent fracture in lattice modeling framework.

Work Element F3c: Development of Unified Continuum Model

Subtask F3c-1: Analytical Fatigue Model for Mixture Design

In this task, a fracture model for predicting the resistance of asphalt mixtures to fatigue loading will be finalized. This model is founded based on the principles of the fatigue model developed during the Strategic Highway Research Program (SHRP) at Texas A&M University. The model accounts for the energy dissipated in fracture, energy dissipated in permanent deformation, physio-chemical properties of mixture (adhesive and cohesive bonds), and viscoelastic properties (Masad et al. 2007). This model is capable of unifying the results from stress-controlled and strain-controlled tests. This model can also be used to analyze experimental measurements conducted on the mastic and fine portions of the mix using the dynamic mechanical analysis and on full mixtures using repeated loading.

The model has been used so far to analyze experimental measurements conducted at a limited range of temperatures and loading frequencies. The research will focus on expanding the use of the model to analyze master curves constructed from comprehensive measurements over wide ranges of temperatures, loading rates, stress levels and strain levels. This is necessary to verify the unified nature of the model for stress controlled and strain controlled tests at all temperatures and loading rates representing different pavement structures.

Subtask F3c-2 Unified Continuum Model

This item constitutes significant part of the research as it will lead to the development of comprehensive viscoelastoplastic continuum damage (VEPCD) model that is applicable for wide ranges of temperatures, different loading rates and complex and realistic mechanical and thermal stresses.

The modeling efforts are based on the following theoretical pillars: (1) the elastic-viscoelastic correspondence principle based on pseudo strain for modeling the viscoelastic behavior of the material; (2) the continuum damage mechanics-based work potential theory for modeling the effects of microcracks on global constitutive behavior; (3) the time-temperature superposition principle with growing damage; (4) the strain hardening viscoplastic model for modeling plastic and viscoplastic behavior; (5) the strain decomposition theory for integrating the nonlinear viscoelastic strain and the viscoplastic strain to describe the total strain; and (6) the anisotropic nature of the aggregates structure.

The VEPCD model's ability to predict the material behavior under complex, realistic mechanical and thermal loading conditions has been demonstrated in previous research at NCSU. The only current limitation is that VEPCD model is robust only till the onset of *macro*crack formation. Typically, fracture mechanics models are necessary for modeling the propagation of macrocracks. Thus, in order to get a unified model for accurate prediction of fatigue life, it is crucial to bridge the gap between the continuum damage mechanics and fracture mechanics.

The hybrid VEPCD model combining damage mechanics and fracture mechanics will be developed in this research using the four major components of material modeling research, i.e., experimental, analytical, computational, and optical methods. Experimental and optical research will involve continuum damage and fracture mechanics testing with the aid of Digital Image Correlation (DIC) technique. For theoretical robustness and computational stability, it is important to ensure a smooth transition between the distributed damage characteristic of the VEPCD model and the localized damage characteristic of fracture mechanics. Considering the existence of length scales associated with fracture mechanics (i.e., crack length), and the lack of length scales in the current continuum damage models for asphalt concrete, the NCSU research team proposes to generalize the VEPCD model to include the concept of damage length scales. This theoretical study would aid the development of a constitutive framework; experimental studies described in the previous paragraph would facilitate parameter estimation using direct and detailed measurements; and computational modeling would be used to verify the stability and accuracy of the developed models. It is expected that such a synergistic approach would result in a robust material model integrating distributed damage with fracture mechanics.

The hybrid VEPCD model will be implemented to the finite element program FEP++ developed by the NCSU research team. This pavement structural model is currently being expanded to incorporate three-dimensional analysis with multiaxial VEPCD models. The VEPCD-FEP++ has been successfully used to predict the fatigue cracking performance of standard and polymer-modified asphalt mixtures in the FHWA ALF pavements. The modified FEP++ is expected to perform analysis of pavement structures starting from microcracking, and leading to macrocrack-induced failure in the asphalt pavement under realistic loading conditions with rest periods.

The fundamentals that govern the model's development have already been established by work at NCSU and TAMU. However, there is still significant work that needs to be done as part of this project in order to:

a. integrate all these components in a comprehensive model,

b. verify the model predictions under various loading, environmental and boundary conditions,

c. relate the model's parameters to fundamental material properties as discussed in section F3c-3, and

d. implement the material model in the a public domain finite element structural model developed at NCSU.

Subtask F3c-3: Multi-Scale Modeling

A draw back of conventional continuum damage models is that the parameters are determined based on fitting the model to experimental macroscopic parameters. Therefore, these parameters could lose to a certain extent their link to the fundamental properties and their values could become dependent on the tests used in fitting the model. A major contribution of the research will be to focus on linking the parameters of the continuum model to the fundamental materials properties measured in Category F1. This will be achieved through developing a multi-scale approach in which the micromechanical models described in work element F3b will be used to calculate effective mixture properties based on properties of the mixture constituents. These effective material properties are used as inputs for the continuum model. The multi-scale approach will assist in formulating damage in the continuum model based on the principles of fracture and healing established in work element F1d.

Development of the multi-scale modeling approach has many benefits, including: (1) a more realistic simulation of pavement cracking phenomena by covering the propagation of both microcracks and macrocracks; (2) simpler testing requirements for state highway agencies; (3) a more accurate prediction of performance of asphalt pavements; and (4) a direct relationship between mixture design, material properties and mixture performance.

As part of the multi-scale modeling approach, the results of the computational micromechanical models will be compared to the continuum model results in order to ensure that the macroscopic predictions by the continuum models are explained by the interactions among the mixture constituents in the micromechanical models.

Major Findings from Year 1 for Work Element F3c

Most of the components of the continuum model have been implemented in finite element. The model includes a nonlinear viscoelastic component and a viscoplastic component.

Year 2 Milestones for Work Element F3c

The model will be fully implemented in finite element during the second year. It will be evaluated using based on its ability to predict experimental measurements conducted at TAMU and NC-State on various mixtures during the past three years. It addition, the researchers will utilize the comprehensive testing database available at the University of Nottingham to validate and calibrate the model. The model verification during the second year will focus on the tests conducted on dry mixtures.

Work Element F3d: Calibration and Validation

Calibration and validation will be conducted using materials selected specifically for each task or work element based on its individual hypothesis. The calibration and validation efforts from different work areas will be optimized by:

i. ensuring that core materials described at the beginning of this work plan are included in various tasks as applicable
ii. maximizing the use of materials and mixture designs that are being used in various test sections

RELATIONSHIP TO FHWA FOCUS AREAS

The fatigue work elements support the FHWA Focus Area of Optimizing Pavement Performance by providing a relationship between material property and pavement performance.

BUDGET

		Year 1	Year 2	Year 3	Year 4	Year 5
Category F1: Material and Mixture Properties						
F1a	Cohesive and Adhesive Properties (TAMU)	60,000	100,000	90,000		
F1b	Viscoelastic Properties (TAMU)	70,000	75,000	30,000	25,000	
F1c	Aging (TAMU)	70,000	100,000	110,000	110,000	75,000
F1d	Healing (TAMU)	60,000	105,000	100,000	100,000	75,000
	Healing (UWM)	75,000	75,000	100,000	100,000	50,000
Category F2: Test Method Development						
F2a	Binder Tests and Effect of Composition (UWM)	75,000	100,000	100,000	100,000	50,000
F2b	Mastic Testing Protocol (TAMU)	20,000				20,000
F2c	Mixture Testing Protocol (TAMU)				20,000	20,000
F2d	Tomography and microstructure characterization (TAMU)		70,000	50,000	50,000	
F2e	Verification: DSR fatigue & Mixture performance (UWM)	75,000	100,000	100,000	100,000	100,000
Category F3: Modeling						
F3a	Asphalt Microstructure Model (WRI)		316,000	321,000	321,000	319,000
F3b	Micromechanics Model (TAMU)	60,000	125,000	125,000	125,000	110,000
F3c	Unified Continuum Fatigue Model (TAMU)	60,000	125,000	125,000	125,000	110,000
F3d	Calibration and Validation*			90,000	95,000	140,000
TOTAL		625,000	1,291,000	1,341,000	1,271,000	1,069,000
		5,597,000				

Note* Tentatively only budget from TAMU is reflected here but this element will involve coordination from all agencies.

CITED AND RELATED REFERENCES

Baglieri, O., 2007, Preliminary investigation on healing of bituminous binders, *Internal Report*, *UW-Madison*.

Bahia, H. U., D. I. Hanson, M. Zeng, C. Zhai, M. A. Khatri, and M. Anderson, 2001, Characterization of Modified Asphalt Binders in Superpave Mix Design. NCHRP Report 459, Transportation Research Board, National Research Council, Washington DC, 2001.

Bhasin, A., and D. N. Little, 2006, Characterization of aggregate surface energy using the universal sorption device. *Journal of Materials in Civil Engineering (ASCE)*, Accepted for publication.

Bhasin, A., D. N. Little, R. Bommavaram, and K. L. Vasconcelos, 2008, A Framework to Quantify the Effect of Healing in Bituminous Materials Using Material Properties. *International Journal of Road Materials and Pavement Design*, in review.

Carpenter, S. H., and S. Shen (2006). A Dissipated Energy Approach to Study HMA Healing in Fatigue. 85th Annual Meeting of the Transportation Research Board, Washington D.C.

Della Volpe, C., and S. Siboni, 2000, Acid base surface free energies of solids and the definition of scales in the Good van Oss Chaudhury theory. *Journal of Adhesion Science and Technology*, 14(2): 235-272.

Hefer, A. W., A. Bhasin, and D. L. Little, 2006, Bitumen surface energy characterization using a contact angle approach. *Journal of Materials in Civil Engineering (ASCE)*, 18(6): 759-767.

Huang, C. W., E. Masad, A. Muliana, and H. Bahia, 2007, Development and Numerical Implementation of a Nonlinear Viscoelastic Model for Hot Mix Asphalt. *Mechanics of Time Dependent Materials*, in review.

Kim, B., and R. Roque, 2006, Evaluation of Healing Property of Asphalt Mixture. 85th Annual Meeting of the Transportation Research Board, Washington, D.C.

Kim, Y. R., D. N. Little, and R. L. Lytton, 2003, Fatigue and Healing Characterization of Asphalt Mixes. *Journal of Materials in Civil Engineering (ASCE)*, 15: 75-83.

Kim, Y. R., H. J. Lee, and D. N. Little, 1997, Fatigue Characterization of Asphalt Concrete Using Viscoelasticity and Continuum Damage Theory. *J. Assn. of Asphalt Paving Technologists*, 66: 520-569.

Little, D. N., and A. Bhasin, 2006, Using Surface Energy Measurements to Select Materials for Asphalt Pavement. *Final Report for Project 9-37*, Texas Transportation Institute.

Little, D. N., and A. Bhasin, 2007, Exploring Mechanisms of Healing in Asphalt Mixtures and Quantifying its Impact, in *Self Healing Materials*, S. van der Zwaag, ed., Springer, Dordrecht, The Netherlands, 205-218.

Little, D. N., A. Letton, S. Prapnnachari, and Y. R. Kim, 1994, Rheological and Rheo-Optical Characterization of Asphalt Cement and Evaluation of Relaxation Properties. *Transportation Research Record: Journal of the Transportation Research Board*, 1436: 71-82.

Masad, E., 2004, X-ray Computed Tomography of Aggregates and Asphalt Mixes. *Materials Evaluation Journal, American Society for Nondestructive Testing*, 62(7): 775-783.

Masad, E., V. Castelo Branco, D. Little, and R. Lytton, 2007, A Unified Method for the Analysis of Controlled-Strain and Controlled-Stress Fatigue Testing. *International Journal of Pavement Engineering* (accepted for publication).

Sharon, E., S. P. Gross, and J. Fineberg, 1996, Energy Dissipation in Dynamic Fracture. *Physical Review Letters*, 76(12): 2117-2120.

Song I., D. N. Little, E. Masad, and R. L. Lytton, 2005, Comprehensive Evaluation of Damage in Asphalt Mastics Using X-ray CT, Continuum Mechanics, and Micromechanics. *Journal of the Association of Asphalt Paving Technologists*, 74: 885-920.

Wool, R. P., and K. M. O'Connor, 1981, A Theory of Crack Healing in Polymers. *Journal of Applied Physics*, 52(10): 5923-5963.

	Fatigue Year 2	Year 2 (4/08-3/09)											
		4	5	6	7	8	9	10	11	12	1	2	3
Material Properties													
F1a	**Cohesive and Adhesive Properties**												
F1a-1	Critical review of literature					JP							
F1a-2	Develop experiment design												
F1a-3	Thermodynamic work of adhesion and cohesion												
F1a-4	Mechanical work of adhesion and cohesion												
F1a-5	Evaluate acid-base scale for surface energy calculations												
F1b	**Viscoelastic Properties**												
F1b-1	Separation of nonlinear viscoelastic deformation from fracture energy under cyclic loading							JP		D			F
F1b-2	Separation of nonlinear viscoelastic deformation from fracture energy under monotonic loading							JP		D			F
F1c	**Aging**												
F1c-1	Critical review of binder oxidative aging and its impact on mixtures												
F1c-2	Develop experiment design					D	F						
F1c-3	Develop transport model for binder oxidation in pavements				P						P		JP
F1c-4	Effect of binder aging on properties and performance						JP						P
F1c-5	Polymer modified asphalt materials												
F1d	**Healing**												
F1d-1	Critical review of literature												
F1d-2	Select materials with targeted properties												
F1d-3	Develop experiment design												
F1d-4	Test methods to determine properties relevant to healing							JP					
F1d-5	Testing of materials												
F1d-6	Evaluate relationship between healing and endurance limit of asphalt binders			DP							P		
F1d-7	Coordinate with AFM analysis												
F1d-8	Coordinate form of healing parameter with micromechanics and continuum damage models												
Test Methods													
F2a	**Binder tests and effect of composition**												
F2a-1	Analyze Existing Fatigue Data on PMA						DP						
F2a-2	Select Virgin Binders and Modifiers and Prepare Modified Binder						DP						
F2a-3	Laboratory Aging Procedures												
F2a-4	Collect Fatigue Test Data				P						JP		
F2a-5	Analyze data and propose mechanisms												P
F2b	**Mastic testing protocol**												
F2b-1	Develop specimen preparation procedures						D						
F2b-2	Document test and analysis procedures in AASHTO format						D						
F2c	**Mixture testing protocol**					D, JP	F						
F2d	**Tomography and microstructural characterization**												
F2d-1	Micro scale physicochemical and morphological changes in asphalt binders												
F2e	**Verify relationship between DSR binder fatigue tests and mixture fatigue performance**												
F2e-1	Evaluate Binder Fatigue Correlation to Mixture Fatigue Data												
F2e-2	Selection of Testing Protocols				D, JP		DP,F						
F2e-3	Binder and Mixture Fatigue Testing												
F2e-4	Verification of Surrogate Fatigue Test				JP						P		
F2e-5	Interpretation and Modeling of Data				JP						P		
F2e-6	Recommendations for Use in Unified Fatigue Damage Model												
Models													
F3a	**Asphalt microstructural model**												
F3b	**Micromechanics model**												
F3b-1	Model development									JP			
F3b-2	Account for material microstructure and fundamental material properties												
F3c	**Develop unified continuum model**												
F3c-1	Analytical fatigue model for mixture design												
F3c-2	Unified continuum model						JP						
F3c-3	Multi-scale modeling												

LEGEND

Deliverable codes	**Deliverable Description**
D: Draft Report	Report delivered to FHWA for 3 week review period.
F: Final Report	Final report delivered in compliance with FHWA publication standards
M&A: Model and algorithm	Mathematical model and sample code
SW: Software	Executable software, code and user manual
JP: Journal paper	Paper submitted to conference or journal
P: Presentation	Presentation for symposium, conference or other
DP: Decision Point	Time to make a decision on two parallel paths as to which is most promising to follow througjh
[x]	Indicates completion of deliverable x

Work planned

Work completed

Parallel topic

	Fatigue Year 2 - 5	Year 2 (4/08-3/09)				Year 3 (4/09-3/10)				Year 4 (04/10-03/11)				Year 5 (04/11-03/12)			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Material Properties																	
F1a	**Cohesive and Adhesive Properties**																
F1a-1	Critical review of literature			JP													
F1a-2	Develop experiment design																
F1a-3	Thermodynamic work of adhesion and cohesion																
F1a-4	Mechanical work of adhesion and cohesion						JP	D	F								
F1a-5	Evaluate acid-base scale for surface energy calculations														JP		
F1b	**Viscoelastic Properties**																
F1b-1	Separation of nonlinear viscoelastic deformation from fracture energy under cyclic loading			D,JP	M&A, F				JP		JP		P		JP,M&A,D		F
F1b-2	Separation of nonlinear viscoelastic deformation from fracture energy under monotonic loading			D,JP	M&A, F				JP		JP		P		JP,M&A,D		F
F1c	**Aging**																
F1c-1	Critical review of binder oxidative aging and its impact on mixtures																
F1c-2	Develop experiment design		D, F														
F1c-3	Develop transport model for binder oxidation in pavements		P		P, JP		P		P, JP		P		P, JP			D, M&A	F
F1c-4	Effect of binder aging on properties and performance			JP	P		JP	D	F						JP	D	F
F1c-5	Polymer modified asphalt materials						P				P					D	F
F1d	**Healing**																
F1d-1	Critical review of literature																
F1d-2	Select materials with targeted properties																
F1d-3	Develop experiment design																
F1d-4	Test methods to determine properties relevant to healing			JP					JP	D	F						
F1d-5	Testing of materials						JP				JP			M&A,D	JP, F		
F1d-6	Evaluate relationship between healing and endurance limit of asphalt binders	DP			P	D,JP,F	P		D,F		P		DP,JP		P	D	F
F1d-7	Coordinate with AFM analysis																
F1d-8	Coordinate form of healing parameter with micromechanics and continuum damage models											JP				JP,D	F
Test Methods																	
F2a	**Binder tests and effect of composition**																
F2a-1	Analyze Existing Fatigue Data on PMA		DP														
F2a-2	Select Virgin Binders and Modifiers and Prepare Modified Binder		DP														
F2a-3	Laboratory Aging Procedures																
F2a-4	Collect Fatigue Test Data		P		JP		P		P				JP, D,F				
F2a-5	Analyze data and propose mechanisms				P			P				P			P	D	F
F2b	**Mastic testing protocol**																
F2b-1	Develop specimen preparation procedures		D														
F2b-2	Document test and analysis procedures in AASHTO format		D														
F2c	**Mixture testing protocol**		D, JP	F													
F2d	**Tomography and microstructural characterization**																
F2d-1	Micro scale physicochemical and morphological changes in asphalt binders						JP				JP	M&A,D	F				
F2e	**Verify relationship between DSR binder fatigue tests and mixture fatigue performance**																
F2e-1	Evaluate Binder Fatigue Correlation to Mixture Fatigue Data																
F2e-2	Selection of Testing Protocols	D, JP	F,DP														
F2e-3	Binder and Mixture Fatigue Testing																
F2e-4	Verification of Surrogate Fatigue Test		JP		P	JP				P	JP	D	F, DP				
F2e-5	Interpretation and Modeling of Data		JP		P	JP			DP	P	JP		M&A				
F2e-6	Recommendations for Use in Unified Fatigue Damage Model															D	F
Models																	
F3a	**Asphalt microstructural model**							JP					JP			M&A	F
F3b	**Micromechanics model**																
F3b-1	Model development				JP				JP				M&A	D	DP	F, SW	
F3b-2	Account for material microstructure and fundamental material properties										JP			D		F	
F3c	**Develop unified continuum model**																
F3c-1	Analytical fatigue model for mixture design														M&A,D		F
F3c-2	Unified continuum model			JP				JP					M&A	D	DP	F, SW	
F3c-3	Multi-scale modeling											JP	M&A	D		F	

LEGEND

Deliverable codes	Deliverable Description
D: Draft Report	Report delivered to FHWA for 3 week review period.
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JP: Journal paper	Paper submitted to conference or journal
P: Presentation	Presentation for symposium, conference or other
DP: Decision Point	Time to make a decision on two parallel paths as to which is most promising to follow througjh
[x]	Indicates completion of deliverable x

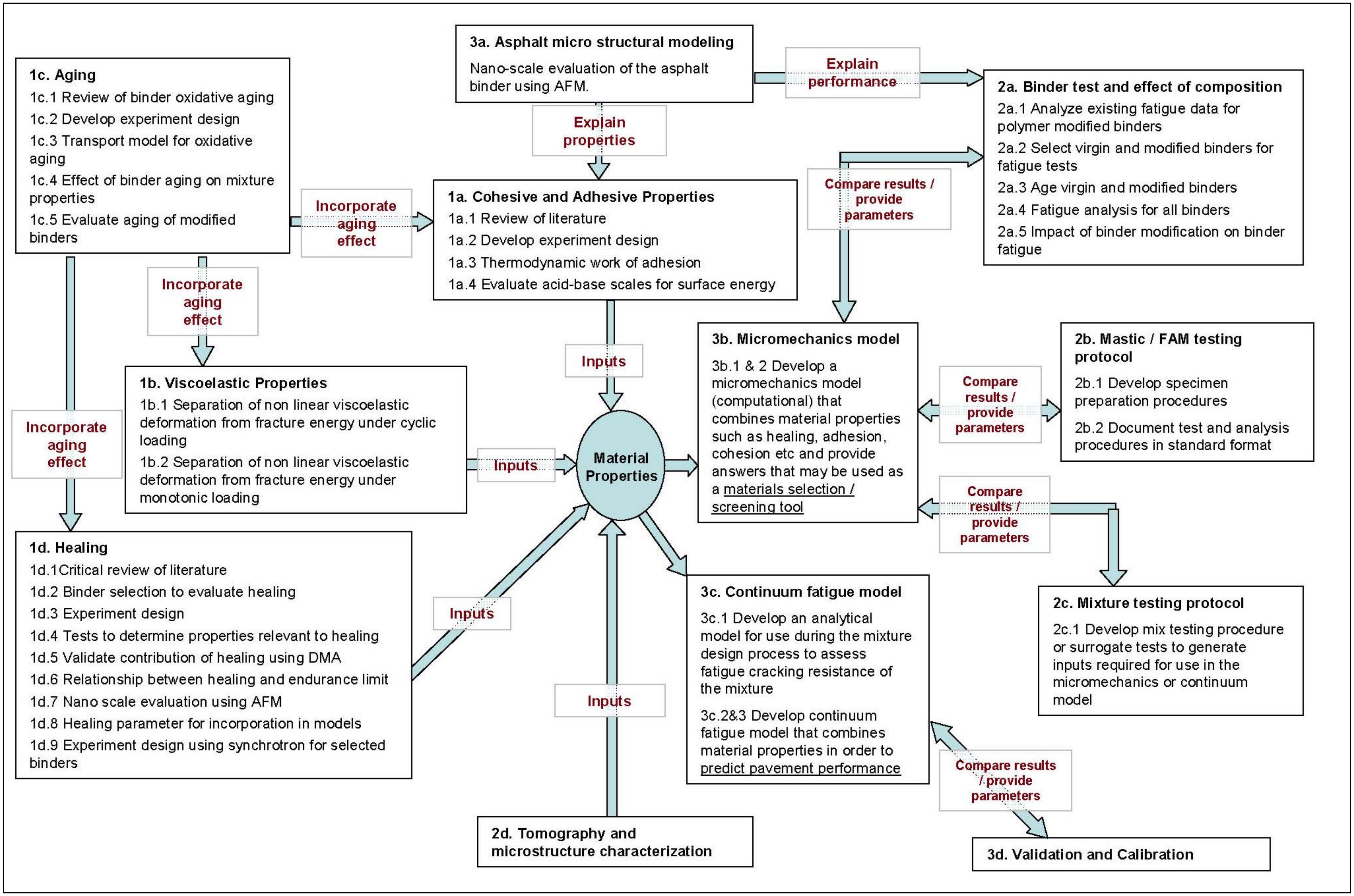
Work planned

Work completed

Parallel topic

Appendix F1

Flow Chart Illustrating Integration of Elements for Fatigue Work Area


3a. Asphalt micro structural modeling
Nano-scale evaluation of the asphalt binder using AFM.
Explain performance
Explain properties
1c. Aging
1c.1 Review of binder oxidative aging
1c.2 Develop experiment design
1c.3 Transport model for oxidative aging
1c.4 Effect of binder aging on mixture properties
1c.5 Evaluate aging of modified binders
Incorporate aging effect
1a. Cohesive and Adhesive Properties
1a.1 Review of literature
1a.2 Develop experiment design
1a.3 Thermodynamic work of adhesion
1a.4 Evaluate acid-base scales for surface energy
2a. Binder test and effect of composition
2a.1 Analyze existing fatigue data for polymer modified binders
2a.2 Select virgin and modified binders for fatigue tests
2a.3 Age virgin and modified binders
2a.4 Fatigue analysis for all binders
2a.5 Impact of binder modification on binder fatigue
Compare results / provide parameters
Incorporate aging effect
Inputs
3b. Micromechanics model
3b.1 & 2 Develop a micromechanics model (computational) that combines material properties such as healing, adhesion, cohesion etc and provide answers that may be used as a materials selection / screening tool
2b. Mastic / FAM testing protocol
2b.1 Develop specimen preparation procedures
2b.2 Document test and analysis procedures in standard format
Compare results / provide parameters
1b. Viscoelastic Properties
1b.1 Separation of non linear viscoelastic deformation from fracture energy under cyclic loading
1b.2 Separation of non linear viscoelastic deformation from fracture energy under monotonic loading
Incorporate aging effect
Inputs
Material Properties
Compare results / provide parameters
1d. Healing
1d.1Critical review of literature
1d.2 Binder selection to evaluate healing
1d.3 Experiment design
1d.4 Tests to determine properties relevant to healing
1d.5 Validate contribution of healing using DMA
1d.6 Relationship between healing and endurance limit
1d.7 Nano scale evaluation using AFM
1d.8 Healing parameter for incorporation in models
1d.9 Experiment design using synchrotron for selected binders
Inputs
3c. Continuum fatigue model
3c.1 Develop an analytical model for use during the mixture design process to assess fatigue cracking resistance of the mixture
3c.2&3 Develop continuum fatigue model that combines material properties in order to predict pavement performance
2c. Mixture testing protocol
2c.1 Develop mix testing procedure or surrogate tests to generate inputs required for use in the micromechanics or continuum model
Inputs
Compare results / provide parameters
2d. Tomography and microstructure characterization
3d. Validation and Calibration

Appendix F2

Working Table of Model Input Data

Working Table of Model Input Data

July 25, 2008

This table provides the current status of the plans for the test methods that will be used in obtaining model parameters. In some cases, ARC research has progressed sufficiently and developed to the point to which specific test methods can be selected to provide model parameters. In other cases, however, ARC research must continue in order to provide more specific data and development of the test methods and/or the models themselves. In fact, the selection of the test method will be an outcome of the research effort and can not be chosen apriori. For example, most of the parameters for the continuum damage model will be obtained from conducing triaxial compression and extension tests. However, the specific conditions of the tests (confinement levels, strain levels, strain rates, stress paths) have not been selected. The selection of such specific parameters will be the result of testing various trial mixtures in order to make sure that certain combinations of these testing parameters can identify the various model's functions (yield surface, flow function, damage function).

The table below is considered a working document that will be updated as more knowledge is gained in the ARC research.

Work Element / Subtask	Examples of models	Examples of test methods to obtain input parameters	Examples of parameters obtained	Examples of application	Validation
F1c. Aging[1]	Models to describe • rate of oxygen diffusion and binder oxidation as a function of temperature / binder viscosity / binder reaction rate constants • oxidation within an asphalt mixture as dictated by its internal microstructure • mixture fatigue as a function of binder oxidation and mixture parameters	• FTIR • DSR • X-Ray CT imaging • mixture: tensile strength; relaxation modulus; repeated direct tension	• Diffusion rate constants • Binder oxidation reaction rate constants • mixture pore size and spacing • mixture fatigue resistance decline with oxidation	Determine degree of oxidation at different depths in an asphalt mixture and its influence on mechanical properties of the binder and mixture	• Compare predictions from these models to the performance and aging in full asphalt mixtures subjected to different aging conditions in the lab • Evaluate the prediction of these models using cores aged in the field for different durations of time
F1a, M1a, M1b, M2a, and M2c. Cohesive and Adhesive properties[1]	Models to describe • total surface energy • work of adhesion (wet and dry conditions) • work of cohesion • Bond strength as a function of temperature, moisture at interface, and pressure applied	• Wilhelmy plate device • USD • Sessile drop method • Micro calorimeter • DSR • PATTI	• Work of cohesion • Work of adhesion • Thermodynamic potential for moisture damage • Tackiness factor as a function of environment		Compare results based on work of adhesion and cohesion to results from • mechanical tests (wet and dry) • transverse tension tests on thin films (wet and dry) and • T-peel tests on thin films (wet and dry)
F1b, F2a, F2e Viscoelastic properties[1]	Models to describe non linear and damage response for bituminous materials subjected to monotonic and dynamic loading. Examples: • Schapery's model with g0, g1, and g2 parameters • Viscoelastic continuum damage model	Monotonic (creep and relaxation) and cyclic load tests performed on binders, mastics, fine aggregate matrix, and full asphalt mixtures in different configurations	Parameters that describe non linear and damage evolution characteristics of different asphalt mixtures	• Use the parameters and the model for materials selection • Use the model as an input (sub model) for the micromechanics and continuum modeling approaches (F3b and M4a)	• Self consistent tests: Use the same test method as used to determine the material characteristic but subject it to different magnitudes of loading, types of loading (e.g., monotonic, cyclic at different frequencies), and material scales (e.g., binder or FAM tests to predict mixture response) • Test materials and mixtures from test sections and compare with available performance data where appropriate • Incorporating these models as sub models in micromechanics and continuum damage models and then evaluating the prediction of these models with available performance data
F1d. Healing[1]	Models to describe • the overall healing of micro cracks during rest periods • the rate of intrinsic healing in asphalt materials as a function of other material properties such as surface energy • the rate of wetting in asphalt materials as a function of other material properties such as viscoelastic properties and surface energy	• DSR • FTIR • MRI or NMR	Parameters required for the • intrinsic healing function and • wetting function		

M2b. Moisture diffusion[1]	Models to describe • diffusion of moisture through different types of binders and mastics • rate of debonding at the binder-aggregate interface • moisture transport through full asphalt mixtures	• FTIR • X-Ray CT Imaging • Moisture suction measurements	• Binder diffusion coefficient • Fracture strength and bond energy • Mixture diffusion coefficient	Use material properties as inputs to the micromechanics and continuum modeling approaches (F3b and M4a)	
F3b. and M4a. Micromechanics models for fatigue and moisture damage	Modeling approaches: • cohesive zone models • Lattice model	Parameters and material characterization models described above (F1a,b,c, d, M1a,b, M2a,b,c)		Predict asphalt mixture behavior under various laboratory and field conditions	• Compare the prediction based on these models utilizing material characteristics as inputs to the laboratory performance of asphalt mixtures. The micromechanics models will focus on validation against laboratory measurements. • Evaluate the prediction of these models with available performance data. Available ALF and LTPP data will be used for the continuum model
		• Mixture fracture test	• Mixture fracture strength		
		• Dynamic mechanical analyzer	• Mastic viscoelastic properties and strength		
		• Aggregate Imaging System	• Aggregate shape characteristics		
F3c, F2e and M4c. Continuum models for fatigue and moisture damage	Viscoelastoplatic continuum damage model	• Triaxial extension and compression	• Mixture hardening • Plastic damage evolution • Yield surface parameters		
		• Mixture fracture test	• Mixture fracture strength		
		• DSR	• Binder rheological properties		
		• Aggregate Imaging System	• Aggregate shape characteristics		
F3a-1.1-8	<u>Computational methods:</u> ab initio Hartree-Fock self-consistent field theory, Møller-Plesset Perturbation Theory, Density Functional Theory, Molecular Mechanics, Atomistic Finite Element Method, Virtual Internal Bond method <u>Input parameters:</u> Molecular structures, volume/mass fractions of chemical class type (e.g., asphaltenes/maltenes, SARA mass fractions, wax mass fraction), Molecular masses, H/C ratios, functional group type, aggregate mineralogy, crystallography.	SARA fraction, molecular spectroscopy, NMR, elemental analysis, structures reported in literature. Computational analyses/simulations	Surface and bulk phase free energies, chemical potentials of phases and phase transition temperature, enthalpy and entropy, activation energies of viscosity/interaction, melting/solidification, molecular motion (vibration-rotational) relaxation times		Task F3a-5. Validation of models will be conducted by comparing simulated distresses with ALF, MINROAD, and ARC validation site materials and mixes, and lab materials and mix structures constructed from materials that are representative of both simulated and tested systems.
F3a-2	<u>Computational methods:</u> Phase field simulation based on finite element method, differential effective medium theory, and dissipative particle dynamics. <u>Input parameters:</u> Phase-field parameters (concentrations, densities, crystal and lattice order) derived from, surface and bulk phase free energies, chemical potentials of phases and phase transition temperature, enthalpy and entropy, activation energies of viscosity/interaction, melting/solidification, molecular motion (vibration-rotational) relaxation times. Mobilities/diffusion constants, scaling parameters	Computational analyses/simulations	Bulk and interfacial stress/strain relationships, fracture and cohesive zone energies and rates, viscosities, 2-D and 3-D renderings of stress/strain regions, wax and microstructural phases and grain boundaries, thermal, chemical potential, surface free energy and stress/strain field gradients. Asphalt molecular distribution gradients relative to aggregate surfaces and in confined thin film states.		

F3a-3	Computational methods: Atomistic and Bulk Finite Element Methods Input parameters: Bulk and interfacial stress/strain relationships, fracture and cohesive zone energies and rates, viscosities, 2-D and 3-D renderings of stress/strain regions, wax and microstructural phases and grain boundaries, thermal, chemical potential, surface free energy and stress/strain field gradients. Aggregate particle distributions, angularity, surface morphology. Composition changes due to chemical and water oxidation kinetics	Computational analyses/simulations	Asphalt/Aggregate composite structure stress/strain fields. 2-D and 3-D renderings of asphalt aggregate debonding sones, cohesive strain energy zones, Potential for observing cracks forming and healing under simulated load and thermal cycles.		
F3a-4	Computational methods: VATCL Input parameters: Bulk and interfacial stress/strain relationships, fracture and cohesive zone energies and rates, viscosities, 2-D and 3-D renderings of stress/strain regions, wax and microstructural phases and grain boundaries, chemical potentials, surface free energy and stress/strain field gradients. Aggregate particle distributions, angularity, surface morphology.	Computational analyses/simulations	2-D and 3-D renderings (energies and energy gradients) of cracks forming and healing under simulated load and thermal cycles. Permanent deformation zones,Moisture build-up zones		

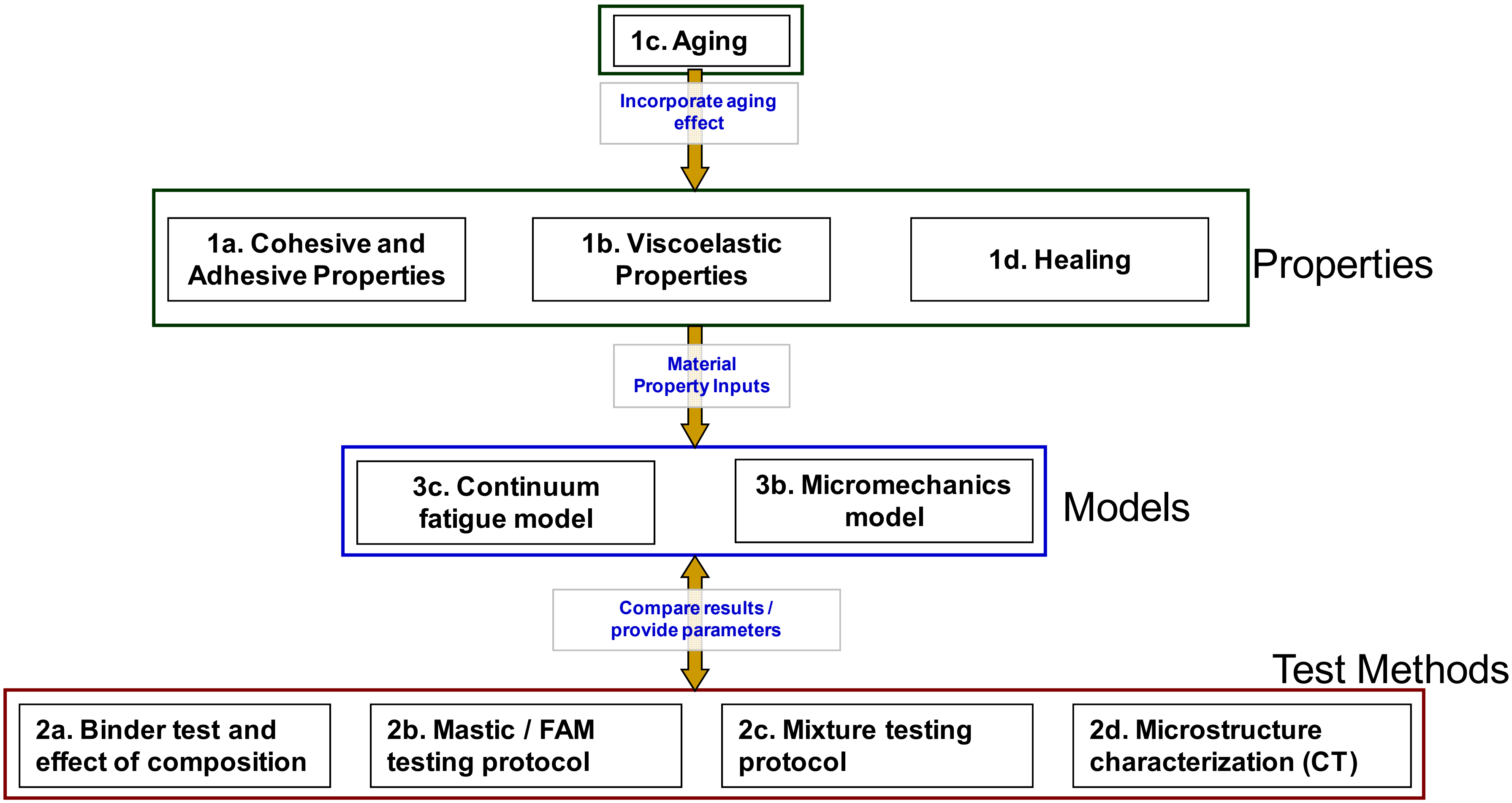
[1] Classified as a material characterization modeling area

(UW-Madison Modeling Efforts)

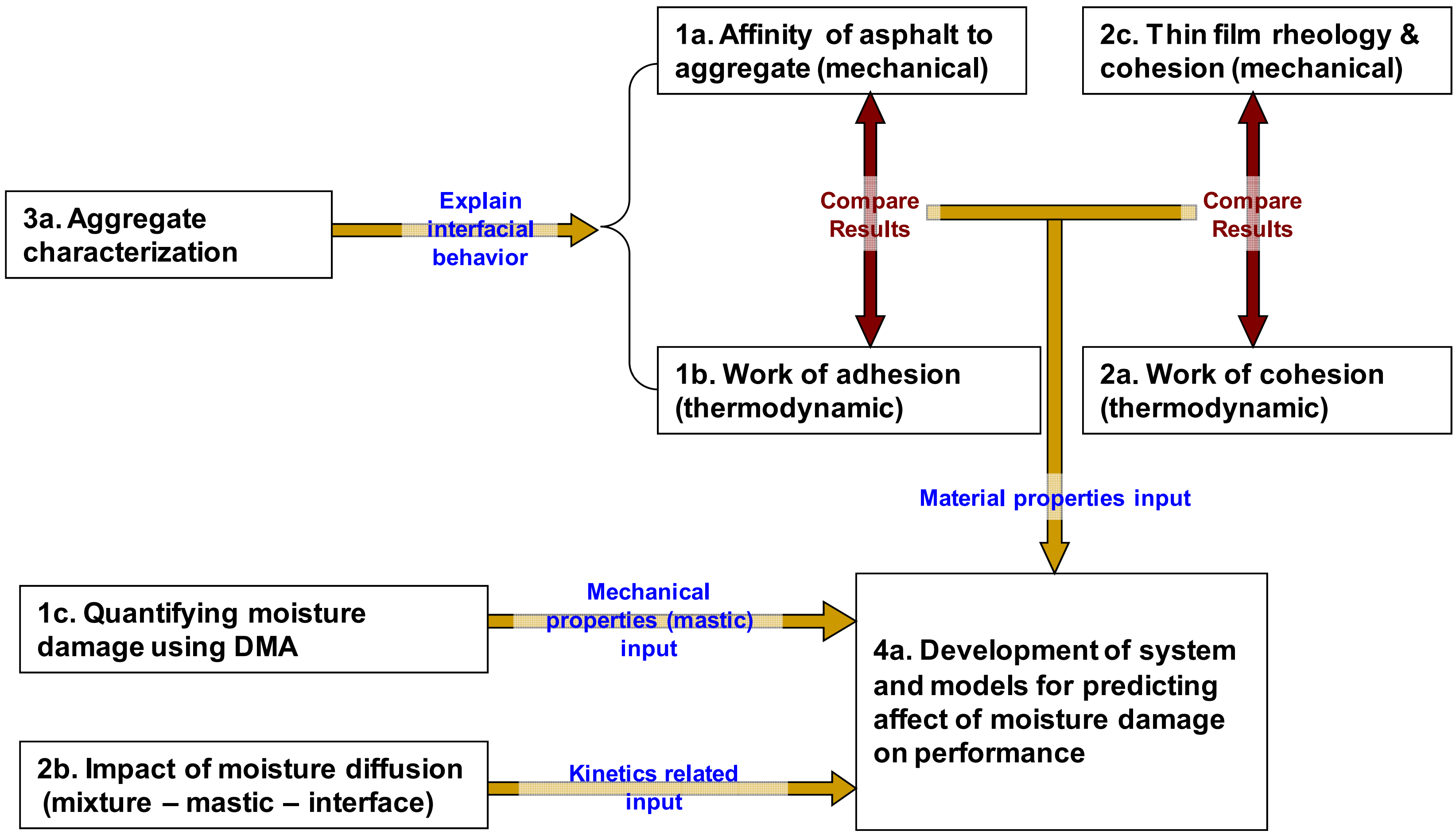
Work Element / Subtask	Examples of models	Examples of test methods to obtain input parameters	Examples of parameters obtained	Examples of application	Validation
E1b-1. Binder permanent deformation	Models to describe • creep compliance of binder as a function of stress level, temperature and loading time • recoverable deformation of binders subjected to repeated creep testing	• DSR creep and recovery testing	• creep compliance • recoverable deformation as a function of time	Determine the stress sensitivity of binders to aid in materials selection criteria	Comparison of modeled output to mixture rutting tests and/or accelerated pavement loading tests
E1c-1. Warm mixtures	Models to describe • binder viscosity characteristics • Binder lubricity • energy of construction effort • energy of traffic resistance • Viscosity of foamed asphalt and rate of recovery as a function of temperature	• Rotational viscometry • DSR for viscosity and rheological properties at various film thiclknesses • Gyratory compaction using Pressure Distribution Analyzer • Workability using a mixing device	• Zero shear viscosity and phase angle leading to recommended mixing and compaction temperatures • Energy to obtain initial construction density as a function of temperature • Energy to reach ultimate density at end of functional pavement life as a function of temperature	• Determine the effectiveness and relative benefit of warm mix procedures • Use models to aid in development of specifications or guidelines for warm mix asphalt pavements	Compare model outputs derived from laboratory testing to: • Plant-produced mix characteristics at reduced temperatures • Construction effort in field sections • Long-term performance of field sections produced at lower temperatures

E1c-2. Development and evaluation of volumetric mix design process and surface treatments design for cold asphalt applications	• Model to describe breaking rate and setting of emulsions • Estimation of adhesion bond of residue to aggregates and prediction of raveling • Models to estimate reduction in enrgy achieved by using cold mix applications	• DSR • Positester • Oven evaporation method • Energy requirements for heating aggregates and asphalts	• Parameters such as $\|G^*\|$, sin δ, and compliance to characterize the extent of asphalt curing • Strain tolerance to measure raveling potential • Pull-off pressure as a function of time and age Energy requirements per unit weight of materials	• Use models to aid in development of specifications for cold asphalt applications including surface treatments and cold mixes • Use models to compare savings in energy achieved by using cold asphalt applications with warm or hot applications	Comparison of mixtures evaluated at various intervals of curing time for mechanical properties as well as resistance to failures such as raveling and bleeding
E2b. Design system for HMA containing a high percentage of RAP material	Models to describe the effect of increasing RAP content on: • the rheological properties of the total asphalt content of the mix • the fracture properties of the asphalt mix via RAP mortar or other methods	• Modified BBR • Single edge notched beam test	• Creep stiffness and m-value • fracture parameters such as ultimate strength and toughness	Determine the effect of increasing RAP content on the selection of virgin materials	Evaluation of test sections for resistance to cracking as predicted by modeling the composite performance of virgin and recycled materials.
E2d. Thermal Cracking Resistant Mixtures for Intermountain States	Models to describe: • Thermovolumetric properties of binders and mixtures • Rate of heat transfer in specimens subjected to thermovolumetric evaluation • Effect of thermovolumetric properties on thermal cracking resistance of mixtures	• Environmental chamber equipped to measure volumetric changes to specimens due to temperature • TSRST	• Glass transition temperature • Coefficients of expansion / contraction • Restrained thermal fracture strength	Determine critical low-temperature properties of asphalt mixtures to better assess resistance to thermal cracking	Evaluation of test sections for resistance to thermal cracking as predicted by performance of mixtures under laboratory conditions
VP2a. Mixture design to enhance safety and reduce noise of HMA	Models to describe: • the effect of mix gradation on friction and noise generation characteristics • the effect of traffic wear or polishing on friction and noise characteristics	• Volumetric mix design procedures • Surface texture characterization (profilometry, direct friction measures) • Impedance tube for noise absorption	• Mixture gradation • Macro- and microtexture • Noise absorption	Use models to identify critical mix design parameters to control for applications where high skid friction or noise reduction are desired	Field sections subjected to current evaluation practices such as skid trailer and close-proximity noise measurement

Overview – Integration of Models and Tests in the Fatigue Work Area



Overview – Integration of Models and Tests in the Moisture Damage Work Area



PROGRAM AREA: ENGINEERED MATERIALS

INTRODUCTION

The Need for Engineered Paving Materials

Demands on flexible pavements in terms of traffic loadings and service life are rapidly increasing. Recent published transportation statistics indicate that between 1993-2002 truck traffic has increased by more than 33 percent while lane miles have increased by only 2 percent. The total vehicle mile travel in the United States is expected to increase by 50 percent in the next 20 years and, more importantly, freight movement is expected to double by 2025. Figure 1 shows the estimated growth in truck traffic on various sections of the National Highway System between 2000 and 2020.

In addition to increased traffic demands, the escalating increase in crude oil prices as well as cost of energy in general, are expected to result in increased production costs of asphalts. The use of recycled asphalt pavements (RAP) is known to reduce the quantity of required asphalt, resulting in a reduction of the energy required for asphalt production. Currently, the use of RAP is limited by state agencies due to risks involved in using it at higher levels in the mix. It is well recognized that more knowledge is needed to allow for effective use of higher percentage of RAP in HMA mix designs.

Engineered Paving Materials (EPMs) are developed for specific performance-related purposes such as extended fatigue lives, moisture or rut-resistance, or durability against thermal and fatigue cracking, and aging. These materials can be designed for ease of construction, quality control/quality assurance, or of maintenance and rehabilitation activities. They can also be designed for many of the other functional and structural objectives that all pavements must satisfy. The process of engineering of materials requires an understanding of the engineering properties of the constituent materials of HMA and how they contribute to the composite properties of asphalt concrete. The performance of HMA is dependent on the response of the properties of this composite under the varying conditions imposed by traffic and weather including the stiffness under rapidly applied loads and slowly applied thermal stresses, thermal expansion and contraction, permeability, thermal conductivity, time-temperature shift, time-aging shift, anisotropy due to the shape of aggregates used, fracture, healing, and plastic properties. Engineering these properties requires the use of materials property models to provide reliable and accurate estimates of the desired properties of the composite. The selection of the precise set of required composite properties is attained as the result of an optimization process in which all of the properties are considered in a prediction of the pavement performance given specific traffic, weather, drainage and subgrade support conditions at the project site. Thus, the engineering design of the pavement structure is not considered as a separate process from the engineering design of the composite material to be used as its surface.

Materials property models have been developed and used successfully in other engineering disciplines such as mechanical engineering, plastics and polymers, and aerospace composites. Admittedly, the materials used in pavements are recognized as being more difficult to model and inherently more variable largely because of the huge volumes of materials that are constructed annually. However, recent successful developments in micromechanics and analytical modeling in these other fields and recent success in FHWA-sponsored research in pavement construction materials have demonstrated that it is now possible to engineer materials that are better able to satisfy the multiple performance requirements that are placed on pavement surfacing.

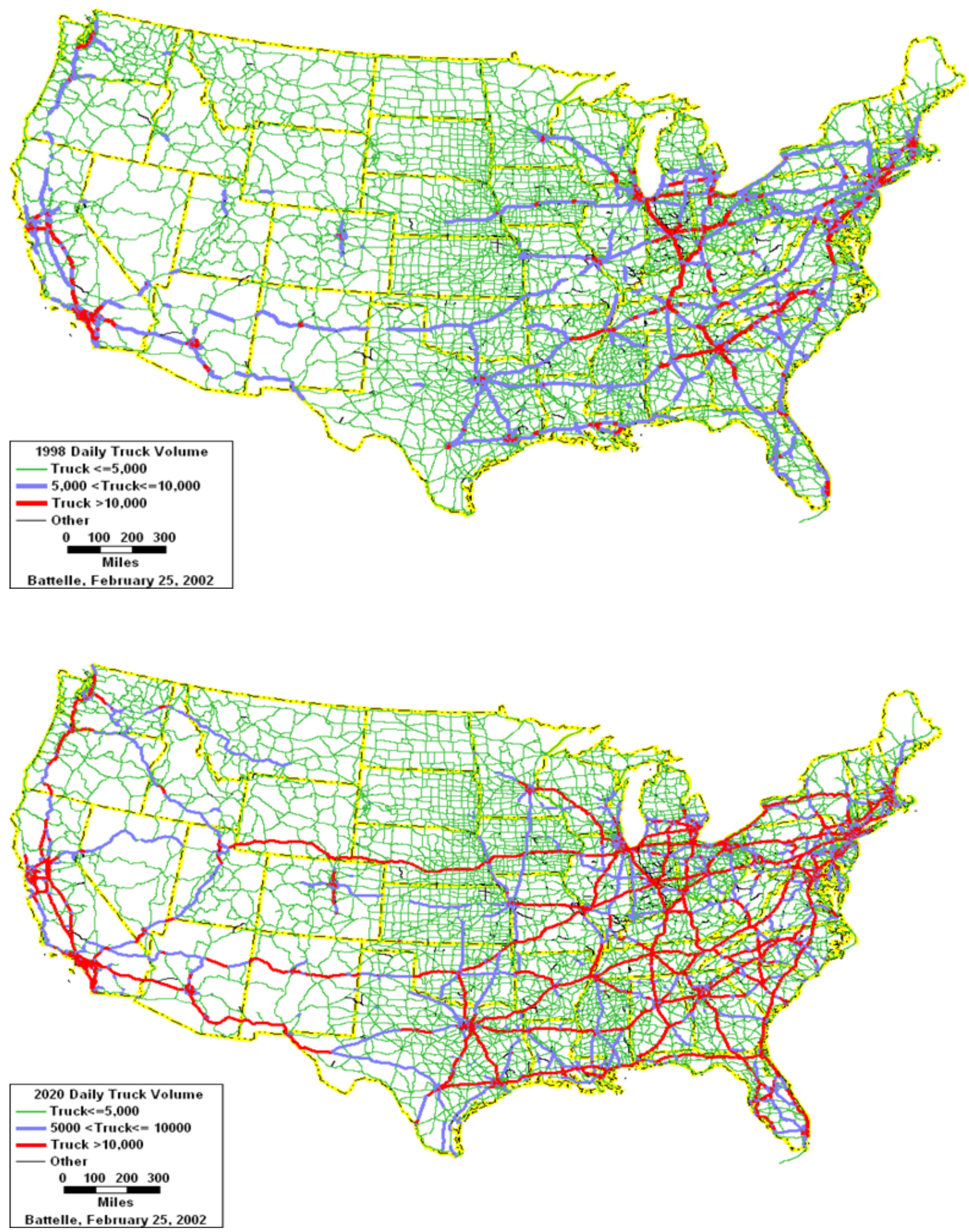


Figure 1. Expected growth of truck traffic on the national highway system.
Source: FHWA office of asset management.

Functional Requirements of Engineered Paving Materials

Since the introduction of Superpave, the types of materials that can satisfy the Superpave performance criteria have changed. The use of modified asphalt, as an example, has increased from 5 percent of the market to more than 15 percent today. The aggregate gradation and characteristics, such as angularity, have also changed significantly. The request for special types of mixtures to deliver specific functions, such as improved friction, less noise, and drainage has increased significantly. All these changes reflect the reaction of the industry to increased traffic and environmental demands. Superpave also introduced more performance-based tests and design systems and enhanced the level of knowledge regarding relationships between material characteristics and pavement performance. These systems have allowed industry to be more effective in choosing materials, have encouraged more innovation in selecting mixtures, and increased the competition on warranted pavements.

Utilizing Engineered Paving Materials (EPMs) is an essential requirement for resistance of damage from increased demands and for reducing cost or increasing reuse of resources. Design and modeling of EPMs for flexible pavements is one of the main focus areas for the research of the Consortium. EPMs for the purpose of this project can be classified into two groups based on their function.

I. High performance to resist damage from the following critical conditions:
   - High Traffic Volume
   - Extreme Heavy Loads and Slow Traffic Speed
   - Extreme Climate
   - Increased friction and reduced noise
   - Perpetual service life

II. Reduce cost, energy, and use of natural resources by increase use of:
   - Recycled Asphalt Pavement (RAP)
   - Warm mixture additives
   - Emulsions for Cold Mixtures Asphalt (CMA)

What Is Needed to Improve the Process of Engineered Paving Materials?

The engineering of pavement surface materials requires the use of analytical computer models that are both fast and accurate while requiring input data that are generated by simple, rapid, and accurate test methods. The approach that is most amenable to these requirements makes use of the measured response of the input materials and models the behavior using the disciplines of mechanics. The demand for accuracy in the input and the predictions is not academic; instead it is imposed by the need for high degrees of reliability in the predicted service life of the pavement material. The accuracy is determined by proper sampling and monitoring of delivered properties at the time of construction. Thus development of simple, rapid, and accurate methods to measure as constructed materials inputs is essential for improved engineering of pavement materials. Accurate predictions and high reliability are requirements of performance-based specifications and the use of warranties, as well as for the subsequent management of the maintenance, rehabilitation, and re-construction operations to be conducted by the operating agency. Engineering of materials should include models that can define the end result of this engineering process, which is reliable prediction of materials performance. It is a simple truth that reliability can be assured by almost any method; however, by reducing the variance of the predictions, the risk of spiraling life-cycle costs to the operating agency is reduced, as are the time-delay costs to the traveling public. Reducing the variance requires methods of measuring materials properties that have low coefficients of variation. The goal should be to have methods with measured coefficients of variation of approximately 5-10 percent rather than 35-40 percent. With this level of accuracy, it will be possible to reliably engineer materials for pavement surfaces that will meet all of the site-specific demands for performance.

Required Material Inputs–Components and Scaling

The material properties to be determined must take into account all of the physical, chemical, and thermodynamic processes that are known to have a significant effect on the performance of pavements. The deterioration processes include fracture and plastic deformation, both of which are scale-dependent phenomenon. Therefore, the materials properties that are measured and modeled must be consistent with the scale of the deterioration process. For example, the cracks and plastic zones that eventually coalesce into macroscale distress begin as micro-cracks and micro-plastic zones.

Asphalt concrete is a composite material that begins with the binder that may be altered by a modifier and/or a filler, and further altered by the addition of fine aggregate particles as well as coarse aggregate particles. Each alteration changes the material properties of the composite and the final composite properties are the result of the accumulation and interactions of all of the materials at smaller scales. The disciplines of micromechanics have developed energy-based methods of combining the properties of the constituent materials to produce composite properties that partition, store, release, and dissipate energy in the same manner as the actual composite material.

Research Needed to Better Engineer Paving Materials

While the list of properties needed for ideal mechanics based modeling seems to be impossibly long, this project will focus on finding the importance of these properties and identifying those that play a prominent role in enhancing the reliability of the engineering process. Major progress has been made by the Consortium partners and others in identifying the most critical properties that are needed for modeling of performance. Also progress has been made to reduce testing requirements. For example, it has been found in recent moisture damage work at Texas A&M that when dealing with material properties, it is possible to catalog these fundamental properties and eliminate the need to repeat the measurements. The tests to assure that the materials have not changed or to determine the degree to which they have changed are simple and rapid to perform. Recent efforts at UW-Madison and FHWA have also introduced simple tests that can more accurately model the damage accumulation in asphalt binders. The MSCR test and the fatigue surrogate tests are such examples.

Cataloguing material properties simplifies the task of engineering materials and is one of the major benefits of focusing on analytical methods to model material properties. It is then possible to make use of mechanics-related computer models of pavements and use these catalogued properties and materials models to optimize the materials selection process for a give set of site conditions based on expected performance and resistance to distress. The principle objective of the Engineered Materials work plan is to define tools that allow reliable and cost effective methods (tests and models) to select materials to meet required and specific functional performance.

Engineered Paving Materials (EPMs) are modified mixtures which are designed to deliver specific functions related to increased traffic or environmental demands, to re-use of pavement materials, and to allow less energy intensive and more practical construction methods. EPMs include mixtures with binders of specific modification, aggregates with special characteristics, and void distributions that provide a high level of resistance to damage caused by traffic or environment. Furthermore, they include mixtures with high levels of RAP that is well characterized and introduced by specific production methods. Finally, EPMs include warm mixtures, cold mixtures, or other types of mixtures that are produced and constructed to optimize performance, production, and construction. Such mixtures will be designed using fundamental understanding of mechanisms of interactions between asphalt, mineral surface, and air voids; using micromechanics of viscoelastic materials and granular materials; and the use of damage resistance characterization.

RESEARCH HYPOTHESES

The Consortium working hypotheses for EPMs are:

i. All materials of which asphalt concrete is composed have mechanical and geometric properties which may be combined, using the energy principles of micromechanics, to obtain the net properties of the composite materials.
ii. Using additives and or new production processes, modified asphalt binders and mixtures can be designed to deliver superior performance that can tolerate extreme traffic and climatic conditions.
iii. Using fundamental engineering principles in design of mixtures superior performance can be achieved with using high concentration of recycled asphalt mixtures, emulsions, or warm mixture additives.
iv. Practical and effective protocols for testing and modeling of such superior materials could be developed. Such protocols would provide guidance for selecting high performance materials with predictable (less risky) performance.

GENERAL RESEARCH OBJECTIVES

1. Develop analytical models of the properties of binders, mastic, and mixtures using the principles of mechanics.

2. Develop guidelines for producing and selecting engineered pavement materials focused on limiting risks of pavement failures.
3. Develop guidelines for high level use of recycled pavement mixtures, warm mixtures, and cold mixtures.
4. Use laboratory damage testing and coordinate with validation activities of the Consortium to verify that these guidelines are useful and implementable.

EXPERIMENTAL DESIGN - WORK ELEMENTS PLANNED

Eight major work elements, organized in two categories are planned. Modeling is considered a basic tool to improve prediction of material performance and thus reduce risk of failures. Design guidelines are the tools to make the best use of modeling in practice. The work elements compose an integrated solution linking materials' mechanics to traffic, climate, and age conditions.

Category E1: Modeling

Work element E1a: Analytical and Micro-mechanics Models for Mechanical behavior of mixtures (Year 1 start)

The FHWA Pavement Distress Manual recognizes 17 different types of distress in asphalt pavements. The materials properties that are realistically needed to predict the appearance of distress include the viscoelastic, viscoplastic, and fracture properties, thermal conductivity and heat capacity, thermal expansion and contraction, time-temperature, and time-aging shift properties, diffusivity of the material to air and water in liquid and vapor form and several electrical properties that are important to non-destructive testing such as conductivity and permittivity. While this seems to be an impossibly long list of properties, it has been found in recent moisture damage work at Texas A&M that when dealing with material properties, it is possible to catalog these fundamental properties and eliminate the need to repeat the measurements. The tests to assure that the materials have not changed or to determine the degree to which they have changed are simple and rapid to perform. Cataloguing material properties makes the task of engineering materials much simpler and is one of the major benefits of focusing on analytical materials models of materials properties. It is then possible to make use of mechanics-related computer models of pavements to use these catalogued properties and materials models to devise the best materials from available components for a given site based upon the expected performance and resistance to distress. This is the principle objective of Engineered Materials.

Hypothesis

The properties of full asphalt mixes can be developed by applying the same broad principles and approaches of micro-mechanics to combine the properties of the mastic with the mechanics and geometric properties of the coarse aggregate portion of the mix. These properties include the relaxation modulus of the mixture including isotropy and anisotropy and non-linearity in both the response and damage properties, time-temperature-aging shift, viscoplasticity, permeability to both air and water in liquid and vapor form, thermal conductivity, thermal expansion and contraction coefficients, thermal heat capacity, both adhesive and cohesive fracture and healing characteristics, as they are affected by moisture and aging, and dielectric permittivity.

It is these properties of the full mixture that are needed as input to a pavement performance prediction model to anticipate what the expected performance and resistance to the various forms of distress will be. These properties can be estimated using the mechanics principles noted above and the accuracy that can be achieved with these measurements will be verified by the planned testing in this project. The performance prediction must be capable to translate the variance of the input values into the variance of the predicted result and the resulting reliability.

Objectives

1. Develop analytical models of the properties of binder, mastics and mixtures using the principles of mechanics. Relate the properties of the binders to the molecular composition, structure, and energy potentials.
2. Verify with laboratory tests the predicted materials properties of the models from Item 1.
3. Implement the models into a mechanics-based pavement performance prediction model which is capable of taking into account the effect of the traffic, weather, drainage, and subgrade support on the candidate asphalt mixture using the estimated mechanics properties. The model should be capable of predicting fatigue cracking, moisture damage, aging, and permanent deformation.
4. Calibrate the pavement performance model to actual known pavements in the LTPP data base with sufficient materials data to permit the estimation of the mixture properties using the analytical models of Item 1 and verify the predicted distress with pavements that were not used in the calibration process.
5. Incorporate into the model of Item 4 the ability to calculate the variance of the estimated life and the reliability of the designed pavement structure for each of the predicted types of distress.
6. Design and initiate materials properties catalogues including all of the materials properties which are needed for the models of Item 1 and which do not change or have predictable changes.
7. Design and initiate a selection engine which will calculate the best combinations of available materials which will provide acceptable mixture properties or resistance to distress.

Attaining these objectives will make it possible to provide the pavement designer with a rapid method of considering all available component materials, and using the materials property catalogues to select the combinations that will provide the greatest likelihood of successful construction and performance. The engineer will also be able to evaluate the likely service lives, variances and reliabilities of each type of distress. With these efficient computerized tools available, it will be possible to engineer pavement surface materials properties as part of the engineering design of an engineered pavement structure.

The properties of the materials to be modeled and used in the models of the binder, mastic, and full mixture will be those for which laboratory characterization protocols will be developed in this research project in coordination with the other team members of the Coalition and with the ongoing binder characterization work in the FHWA.

Experimental Design

The development of the materials property models of the binder, mastic, and mixture will not require an experiment design but will require that the other work elements and subtasks in this project will conduct the necessary tests to provide an evaluation of the accuracy of the models that are developed. This will require coordination with every work element within this project in which characterization work is being accomplished. To the extent that no other work element in this project is focused on developing a needed property, such as thermal coefficient of expansion or contraction, it will be necessary to design a limited experiment within this part of the project to provide the experimental data to verify the model that is developed. In these experiments, the design will be reviewed or developed by the project statistician, Dr. E. S. Park of the Department of Statistics at Texas A&M University.

Subtask E1a-1: Analytical Micro-mechanical Models of Binder Properties
Subtask E1a-2: Analytical Micro-mechanical Models of Modified Mastic Systems
Subtask E1a-3: Analytical Models of Mechanical Properties of Asphalt Mixtures
Subtask E1a-4: Analytical Model of Asphalt Mixture Response and Damage

This work element will be coordinated with the modeling efforts discussed in the fatigue and moisture damage plans. As discussed in the fatigue plan, multi-scale modeling approach will be followed in order to relate the fundamental material properties to the models' parameters. This will be achieved by developing subroutines that use the micro-mechanical models of binders, mastic and mixture to determine the parameters of the continuum models that will be used for predicting mixture performance.

Major Findings from Year 1

The focus in this first year were twofold: (a) to develop micromechanics methods to determine the mechanical properties of the components of mixes from tests that were made on those mixes and (b) to determine the properties of the mixes from the properties of the constituents, namely, aggregates, bitumen, and air. In part (a), a program has been developed to compute the bulk and shear moduli of aggregates from resilient modulus tests made on mixes using a self-consistent micromechanics model and systems identification to determine the two properties of the aggregates. In part (b), a program has been developed to compute the bulk and shear moduli of mixes from the same properties and volumetric composition of the constituents of the mixes, again using the systems identification approach. The method in part (a) works well and quickly and the computations of the bulk and shear moduli of different types of aggregates from mixture tests is under way.

Year 2 Milestones

The reverse analysis of a variety of mixes and aggregates will be completed and a catalog will be initiated of the properties of a wide range of aggregates will be developed concentrating on gaining knowledge of the characteristic values of aggregates from different geologic origins and mineralogy. It is expected that most of the variability of the results within a given aggregate type will be attributable to the form, angularity, and texture of the aggregate surfaces.

The forward analysis of a variety mixes will be conducted starting with the properties of the aggregates determined in the reverse analysis and determining the bulk, shear and resilient moduli of mixes with a variety of bitumen binders. The results will be compared with measured values.

The forward analysis of a variety of mixes with the properties of the bitumen tested at different temperatures will be used to determine the bulk and shear compliances and relaxation moduli of the mixes at different temperatures.

The forward analysis of a variety of mixes with the properties of bitumen tested at different ages will be used to determine the properties of mixes at different ages. An aging shift function due to Grasley and Lange (2007) will be used with varieties of bitumen to determine the accuracy and robustness of the shift. If successful, the forward analysis of shifted bitumen properties will be used to determine the age-shifted properties of the mixes. Overall, this micromechanics approach will greatly accelerate and simplify the task of making accurate estimates of mixture properties in the field.

Formulation of reverse and forward micromechanics analysis methods will be developed for the following mixture properties: thermal contraction coefficient; adhesive and cohesive bond surface strength; short-term and long-term healing bond surface strength; moisture diffusivity; anisotropic compliance and relaxation moduli; viscoplasticity parameters; dielectrical permittivity and tensile strength.

Reference:

Grasley, Zachary C., and David A. Lange, 2007, "Constitutive Modeling of the Aging Viscoelastic Properties of Portland Cement Paste." Mechanics of time-Dependent Materials, Springer Science, accepted for publication.

Work element E1b: Binder Damage Resistance Characterization (DRC)

Subtask E1b-1: Rutting of Asphalt Binders

Subtask Lead: Haifang Wen

Introduction

While linear viscoelastic rheology is considered a major step forward in binder performance modeling, damage resistance characterization is found necessary for low risk selection of high performance materials. Modified binders can be best differentiated and effectively qualified for high performance by using damage resistance testing principles. Binder rutting tests have been performed generally using low stresses. However, it is not clear that testing at a low stress level is the best way to characterize the rutting resistance of an asphalt binder. The stresses and strains in the binder can be very high – much higher than the linear limit for the material. Estimates of the strain in the binder of a typical mixture can vary between 0 and 500 times the overall mixture strain. Due to this fact, when the asphalt mixture is subjected to loading, some of the binder performs in the linear viscoelastic region and some of the binder reaches the region of nonlinear behavior. Current research is being performed at FHWA and also at UW Madison on this topic. A limited number of binders and mixtures are currently being used to find a relationship between the binder nonlinear behavior and the mixture permanent deformation. FHWA results reported at the Binder ETG meetings indicates that stress levels that mimic binder conditions in typical mixtures are not known and are difficult to estimate. The stress levels that are used in the current version of the MSCR test (AASHTO TP 76) are intended to measure stress sensitivity but are not clearly related to mixture behavior. Recent results collected at UW-Madison, as part of a study for the Airfield Asphalt Pavement Technology Program (Project 04-02), indicate that a stress of 3200 Pa, which is recommended in the MSCR AASHTO standard, could be too low and a much higher stress is needed to correlate binder and mixture rutting. The recent results also indicate that the stress level is not the only important parameter in rutting testing, but the accumulated loading time is one as well. It is found that asphalt binders reach a yield point similar to the tertiary flow in mixtures, and thus loading time in a binder rutting test needs to be considered as an important parameter. The results of these recent works will be extended in this study to confirm the validity of the current MSCR procedure or to propose modification to it based on testing a wider number of asphalt binders and mixtures. This work will be coordinated with FHWA staff.

Relationship to FHWA Focus Areas

This work element is related to the following focus areas:

- Optimum Pavement Performance: Introducing methods for better characterization of modified asphalts.
- Advanced Quality Systems: Further development of test methods that are more related to actual pavement performance.

Hypothesis

The stress level at which the binder performs and the time of total loading are two parameters that highly influence the permanent deformation of mixtures. Binder needs to be characterized at different stresses and loading times in order to accurately predict the rutting performance of mixtures.

Objectives

The objective of this subtask is to quantify the relationship between binder creep and recovery testing results using the newly proposed procedures and the rutting performance of asphalt mixtures. The binder testing will be done at various stress levels and for various loading times to mimic stress conditions in typical pavements. Based on these relationships, recommendations for binder specification limits will be proposed.

Experimental Design

The objective of this subtask will be addressed as follows:

vii. Literature Review. A detailed search of existing data and published papers on the subject will be compiled. The review will include worldwide publications and will cover the binder rutting evaluation and also most recent development in mixture rutting evaluation. An attempt will be made to focus on studies in which relationship between binder and mixture behavior is documented. A critical review will be conducted and documented in a report. In addition, a database will be established for available data.

viii. Selection of Materials and Development of Testing Plan. Based on the findings of the literature review, an experimental plan will be developed. The plan will include testing a set of binders and aggregates to represent the different modification types currently used in the United States. The binder and mixture variables under consideration are as follows:

High temperature PG grades: PG 64-XX, PG 70-XX, and PG76-XX

Modification types: SBS, Elvaloy, SB, EVA, PPA, oxidized

Mixture Gradation: Fine, Coarse, and OGFC

Aggregate shape: Angular and Rounded

Asphalt Content: Design and Design+ 0.5 percent

The plan will also consider the testing methods that are needed. It will include the following binder and mixture tests.

- The binder tests should include creep and recovery testing using the dynamic shear rheometer. Extended creep testing can also be included as a complement.
- Two geometries should be considered: parallel plate and cone and plate. Parallel plate should be included because is the most widely used geometry for testing binders. Cone and plate should be used because it provides a homogeneous

distribution of shear rates which are needed for non linear characterization. The stresses should consider from 100 Pa (linear range) up to 50000 Pa (maximum range for commercial DSR).

- The time of loading (or number of cycles) should be enough to reach the tertiary creep region.
- The temperature of testing should be the same used in the mixture testing.
- Mixture rutting test should be performed on samples prepared with the selected binders. Two temperatures would be recommendable: 46 °C and 58 °C.
- Mixture rutting test using the creep and recovery should be used. At least two stress levels should be considered: 22 psi (standard stress for Flow Number test) and 100 psi (representing high tire pressures).

ix. Conduct Testing of Binders and Mixtures. Testing of binders and mixtures will be carried out. The data will be organized in a database to allow for statistical correlations and for modeling of behavior using various models found in the literature.

x. Analysis and Interpretation. The concept will be to explore a few approaches to characterize the non-linearity of asphalt binder and fundamentally evaluate the effects of asphalt binder on asphaltic mixtures. The hypothesis is that the permanent deformation in asphaltic mixture is a function of permanent deformation of asphalt binder, as well as interaction with other components of asphaltic mixtures. The team will employ the mechanistic approaches currently available for either asphalt binders or asphaltic mixtures and identify the most effective approach for the rutting of asphalt binder.

The approaches which the team is evaluating are introduced, as follows:

- Viscoelastoplasticity. This approach has been used to characterize the fatigue of asphaltic mixture. However, in other fields, it is also used for plastic deformation of materials. In addition, the theory of viscoelasticity has been used for rutting study of asphalt binder. The strain consists of linear viscoelastic (including instantaneous elastic), and viscoplastic (including instantaneous plastic) strains. Saadeh et al. (2007) used this concept for repeated creep tests on asphaltic mixtures and characterized the viscoplastic response of materials. The nonlinear viscoelastic response was subtracted from the total strain during loading to calculate the viscoplastic strain as a function of loading time.
- Viscoplastic Damage. This approach has been used in other fields to characterize the creep damage of materials, such as metal (Bellenger and Bussy 2001). The macroscopic modeling of the creep curves with its three stages was based on the irreversible thermodynamics theory with internal variables. A unified viscoplastic model is used to describe primary and secondary creep behaviors, and the tertiary creep description is based on the introduction of a scalar damage variable and the nonlinear effects of changes in geometry. Viscoplastic damage models in nonlinear geometry are defined in order to describe different modes of creep damage development. The numerical properties of the models allow obtainment of a different crack growth development, providing information on the post-critical behavior and the damage development until failure.

- Power Law Model. For asphaltic mixture, flow number is defined as the cycle number when the deformation slope starts increasing, which means that tertiary flow is starting. For some mixtures, however, this increase in slope is very gradual and they can resist many cycles of loading after Fn without considerable increases in deformation. To further analyze the influence of the binder characteristics in the rutting performance of mixtures, the deformation results can also be studied using a power law model to include the primary, secondary, and tertiary flow of asphalt binder.

The data collected will be analyzed to identify the relationship between binder rutting and mixture rutting as a function of stress level, aggregate properties, and mixture volumetric properties. The data will also be used to verify the analytical models developed for mechanical behavior of asphalt mixtures. The focus will be on defining the importance of testing variables including stress level (no-linearity), temperature, total time of loading, RTFO aging, and number of cycles used to allow prediction of traffic volume effects. The interpretation will be conducted using statistical correlations and fitting as well as mechanics based phenomenological models.

xi. Standard testing Procedure and Recommendations for Specifications. The results of analysis will be used to evaluate the current MSCR standard protocol and suggest modification if needed. Also, a recommendation for inclusion of the procedure and limits for acceptance in the PG binder specification will be developed. The limits will be based on the correlations to mixture response and on LTPP data of rutting performance.

Major Findings from Year 1

During Year 1, the materials and testing conditions for the plan were selected and are shown in table E1b-1.1. A testing plan was also developed and the proposed tests are shown in table E1b-1.2. Since the start of Year 1 work plan, the team has extensively evaluated two aspects of rutting for asphalt binder: tertiary flow for asphalt binder, and power law modeling of asphalt binders and asphaltic mixtures. The major findings are briefed here.

Table E1b-1.1. Matrix of materials and conditions.

Neat Binders	PG64-22	Aggregates	Limestone
	PG70-22		Granite
	PG76-22		
Modifiers	SBS	Mix Designs	E-10
	Elvaloy		
	PPA		
	Sasobit		
	EVA		
	Oxidized		
Mineral Fillers	Limestone	Testing Temp	46 C
	Granite		58 C
	Ottawa sand		70 C

Table E1b-1.2. Proposed tests on asphalt binders and mixes.

Asphalt Binder	Extended Creep	Stress Level	100Pa
			1000Pa
			10kPa
			20kpa
			30kPa
	MSCR	Stress Level	100Pa
			1000Pa
			10kPa
			20kpa
			30kPa
		Loading/unloading	0.1s/0.9s
			0.2s/0.8s
Mix	Extended Creep	Stress Level	0.69Mpa
			1.035Mpa
			1.38Mpa
	MSCR	Stress Level	0.69Mpa
			1.035Mpa
			1.38Mpa
		Loading/unloading	0.1s/0.9s
			0.2s/0.8s

Tertiary flow of asphalt binder. Repeated creep and recovered tests were conducted on asphalt binders, using parallel plate in Dynamic Shear Rheometer (DSR). Tertiary flow was clearly observed. However, when the parallel plate was replaced with the cone plate, the tertiary flow disappeared. Figure E1b-1.1 shows the tests results on the same binder when parallel plate and cone plate were used, respectively. It can be seen that the creep strains from parallel plate test exhibited tertiary flow and diverted from the strains of cone plate tests in which no tertiary flow occurred. Digital pictures were taken for both parallel plate and cone plate tests, as shown in figure E1b-1.2. It was found that material loss was severe when the parallel plate was used. The opposite was true for cone plate tests. For parallel tests, the cross section of asphalt binder specimens reduced as the material flows away from the plate. It seems that the tertiary flow is partially a result of the change of geometry.

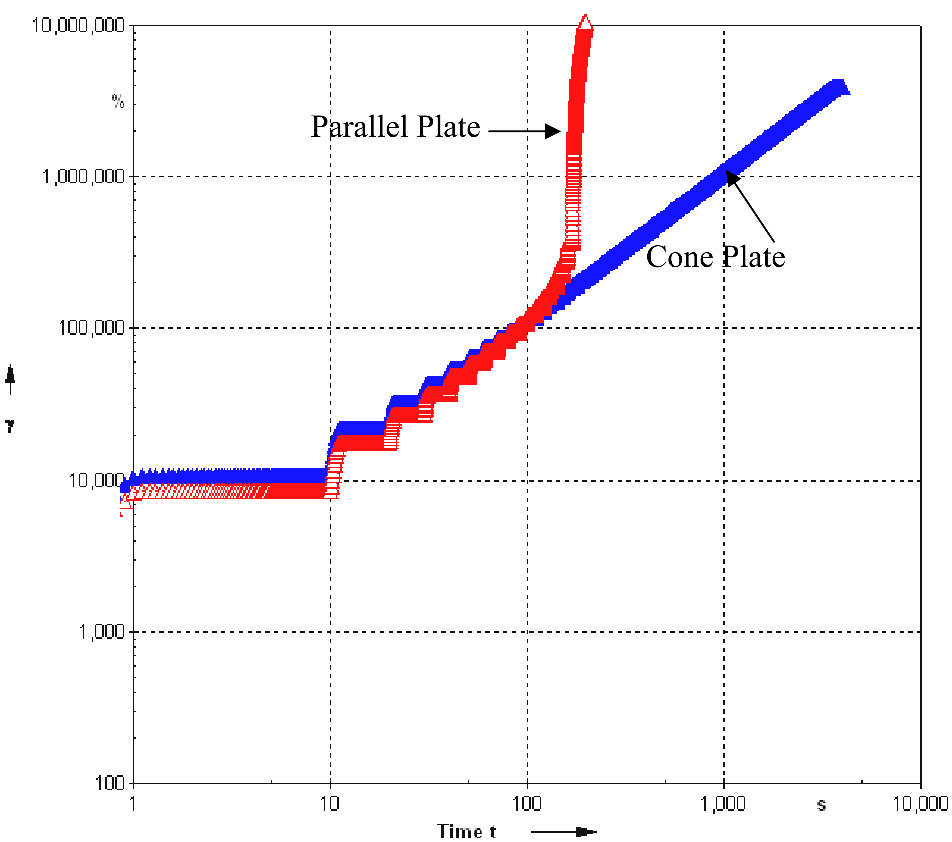


Figure E1b-1.1. Chart. Discrepancy of shear strains between parallel and cone plate under creep test.

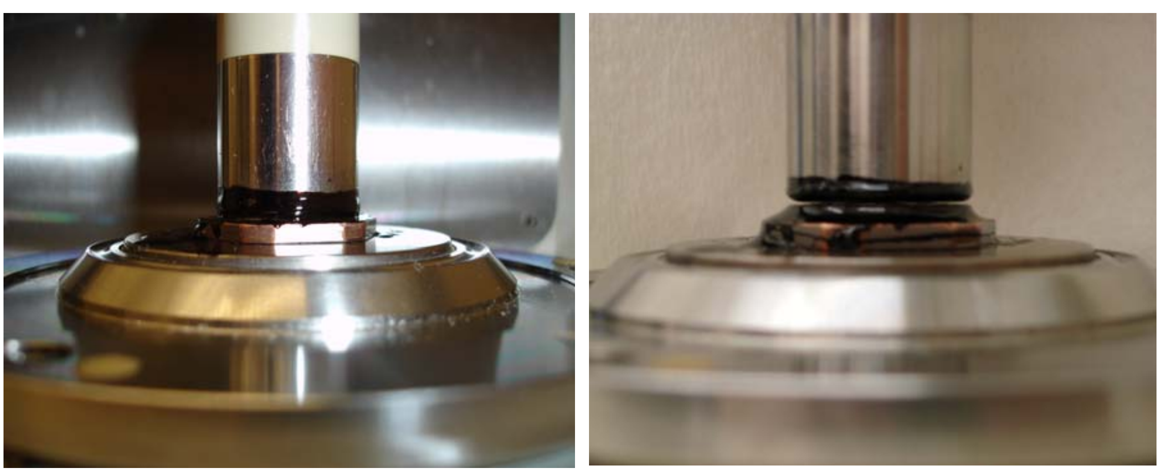


Figure E1b-1.2. Photo. Specimen before and after parallel plate tests.

<u>Power Law Modeling of Rutting of Asphalt Binder.</u> Considering the linear shape of the curves in the log-log scale, the nonlinear power representation seems to be the best fit for the behavior of the material. Nonlinear power representation is given by the following equation:

$$\gamma(t,\tau) = \sum_{i=1}^{m} k_i \cdot t^{n_i} \cdot \tau^{p_i}$$

Where:	γ	=	shear strain
	t	=	time
	τ	=	shear stress
	k_i, n_i, p_i	=	constants

The number of arguments, m, to be used depends on the material. For the polymer modified binder, a value of m equals to two was found to be enough to describe the shape of the curves. This is logical considering that the curves show a linear shape with two different slopes.

Nonlinear fitting using was used to determine the parameters of the model. In order to give the same importance to the low strain/time range than to the high strain/time range, the fitting was weighed using the strain as the weighing variable. The fitting showed to be very good, with an R value of 0.998. The following equation shows the results of the nonlinear power law fitting.

$$\gamma = 2.3668 \cdot 10^{-4} \cdot t^{0.58717} \cdot \tau^{0.99412} + 1.8484 \cdot 10^{-19} \cdot t^{2.0019} \cdot \tau^{4.0265}$$

The first argument on the right side of the equation represents the behavior at low stress levels and shorter times. The power parameter on the stress variable is almost equal to one, which confirms the linear behavior on this region. The second argument on the right side of the equation represents the nonlinear behavior at higher stresses and longer loading times. Figure E1b-1.3 shows the results of the fitting of the shear strain using the power law model.

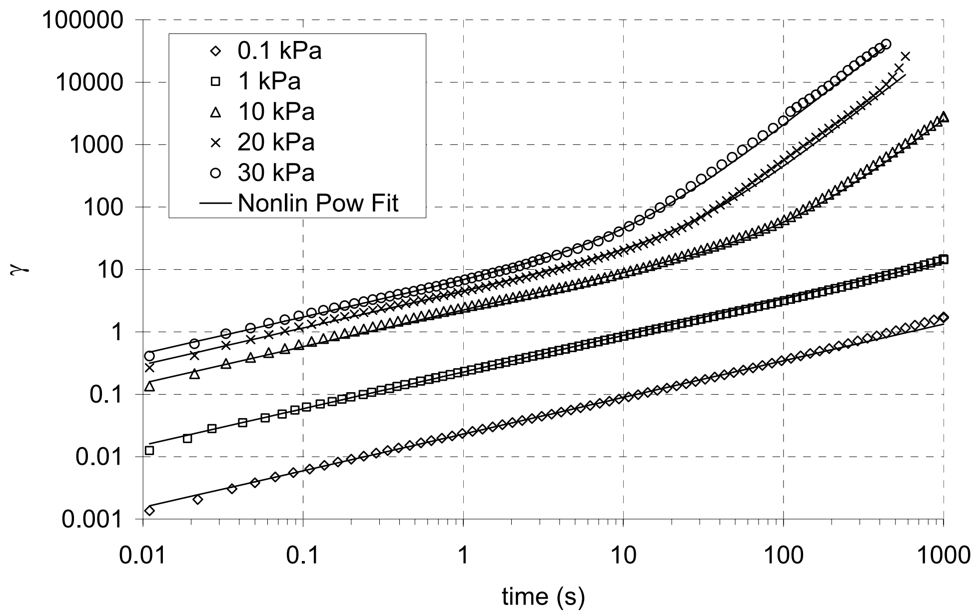


Figure E1b-1.3. Chart. Nonlinear power fitting, creep phase, PG64-34 binder, 1000 seconds loading.

The creep compliance of the material can be obtained by dividing the shear strain by the shear stress, as follows:

$$J(t) = 2.3668{\cdot}10^{-4}{\cdot}t^{0.58717}{\cdot}\tau^{0.00588} + 1.8484{\cdot}10^{-19}{\cdot}t^{2.0019}{\cdot}\tau^{3.0265}$$

$$J(t) \approx 2.3668{\cdot}10^{-4}{\cdot}t^{0.58717} + 1.8484{\cdot}10^{-19}{\cdot}t^{2.0019}{\cdot}\tau^{3.0265}$$

Year 2 Work Plan

During Year 2, the team will continue to evaluate different approaches for rutting performance of asphalt binder and evaluate the effectiveness of different analytical approaches, based on the experimental results. The experimental plan was designed to evaluate the factors that have potential to influence the rutting performance of asphalt binders, as well as asphaltic mixtures.

The test results will be analyzed using different analytical approaches. These analyses will determine the fundamental properties of asphalt binder that govern the resistance to rutting. In addition, the team will strive to quantify the relationship between the rutting properties of asphalt binders and those of asphaltic mixes.

Figure E1b-1.4 depicts the research approach defined for this work element.

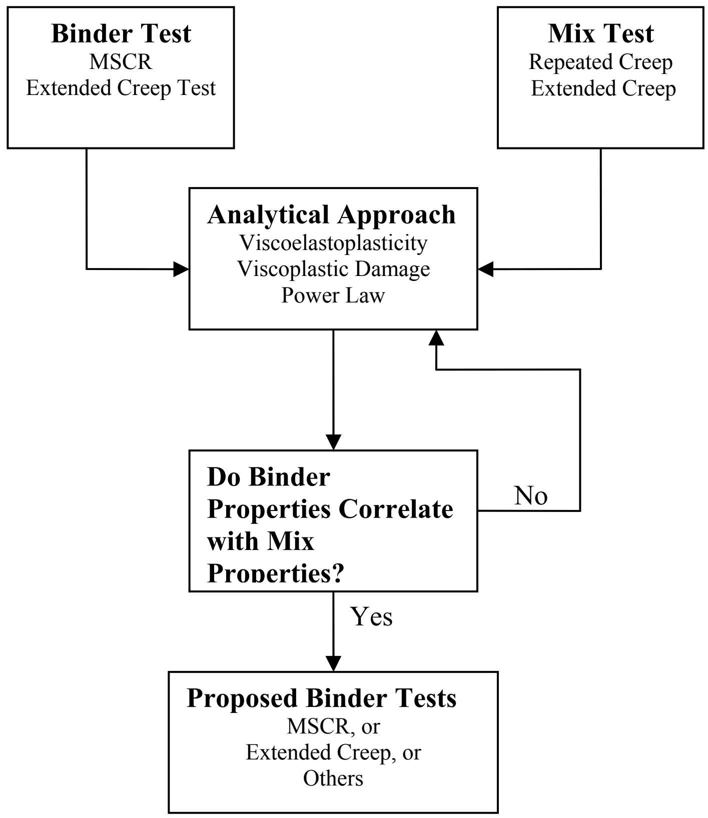


Figure E1b-1.4. Chart. Flow chart for research approach.

Year 2 Milestones

- Complete report on review of literature for rutting of asphalt binders and asphaltic mixtures
- Finalize material selection and experimental plan
- Conduct the proposed tests on asphalt binders and prepare for mix tests
- Develop framework for emulsion selection and design of surface treatments

Budget

The estimated budget for this subtask is $350,000 over the four years. The work will be conducted by the University of Wisconsin-Madison.

Cited and Related References

Bellenger E., and P. Bussy, 2001, Phenomenological Modeling and Numerical Simulation of Different Modes of Creep Damage Evolution. *International Journal of Solids and Structures*, 38: 577-604.

Delgadillo R., D. W. Cho and H. U. Bahia, 2006, Non Linearity of Repeated Creep and Recovery Binder Test and the Relationship with Mixture Permanent Deformation. In *Transportation Research Record: Journal of the Transportation Research Board*, No.1962, TRB, National Research Council, Washington, DC, 2006, pp. 3-11.

Hudson, S. W., and S. B. Seeds, 1988, Evaluation of Increased Pavement Loading and Tire Pressures. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1207, TRB, Washington DC, pp. 197-206.

Kose, S., 2001, Development of a Virtual Test Procedure for Asphalt Concrete, PhD Thesis, UW Madison.

Lakes, R., 1999, *Viscoelastic Solids*. CRC Press.

Masad, E., N. Somevadan, H. U. Bahia, and S. Kose, 2001, Modeling and Experimental Measurements of Strain Distribution in Asphalt Mixes. *Journal of Transportation Engineering*, 127(6): 477-485.

Saadeh, S., E. Masad, and D. Little, 2007, Characterization of Asphalt Mix Response under Repeated Loading Using Anisotropic Nonlinear Viscoelastic-Viscoplastic Model. *Journal of Materials in Civil Engineering*, ASCE, October 1, 2007, 19(10): 912-924.

Subtask E1b-2: Feasibility of determining rheological and fracture properties of thin films of asphalt binders and mastics using nanoindentation

Subtask Lead: Dante Fratta

Introduction

The effort in this subtask will be closely coordinated with similar work at WRI in the "Fundamental Properties of Asphalts and Modified Asphalts III" contract with FHWA. If any research is identified here, it will be complementary research. The behavior of asphalt mixtures is highly affected by the rheological and fracture properties of the asphalt mastic, the glue that holds together the aggregate skeleton in the composite asphalt mixture. The current asphalt binder specifications are based on mechanical tests performed on specimens with dimensions that are not representative of the scale of asphalt films found in a typical asphalt mixture, which is in the range of 13.5 μm to 600 μm, with 30 to 50 percent in the range of 13.5 to 17 μm. Currently, there are not any documented research studies that address nondestructive determination of mechanical properties of asphalt thin films in an asphalt mixture. If such technology were developed it could revolutionize the methods of accepting pavement materials after construction is complete. It would greatly simplify the task of monitoring changes in materials due to aging or repeated loading in the field, eliminate the need for the expensive and destructive methods used today, and, perhaps most importantly, allow for rapid and simple quality control for contractors. The purpose of this study is to evaluate the usefulness of nanoindentation devices to measure asphalt binder or mastic properties.

The work will be conducted in collaboration with the University of Minnesota and will focus on utilizing nanoindentation equipment available at the University of Minnesota or other research establishments for exploratory measurements. These measurements will be compared to measurements collected with conventional methods used today in the PG grading such as the DSR, BBR and the Direct Tension.

Relationship to FHWA Focus Areas

This work element is related to the following focus areas:

- Optimum Pavement Performance: Introducing methods for better characterization of modified asphalts.
- Advanced Quality Systems: Further development of test methods that are more related to actual pavement performance.

Hypothesis

In-situ properties of asphalt binders in asphalt mixtures can be determined using nanoindentation equipment with or without minor modifications.

Objectives

The proposed study has the following objectives:

i. Determine the rheological and fracture properties of asphalt binders and mastics using nanoindentation equipment.
ii. Compare the rheological and fracture properties of asphalt mastics determined with the current PG grading test methods to the similar properties determined using nanoindentation.

Experimental Design

The objectives of this subtask will be addressed as follows:

i. Literature Review and Identification of Equipment
ii. Exploratory Use of Nanoindentation Devices
iii. Conduct of Exploratory Tests on Binder Specimens
iv. Compare the Binders Responses with the Dynamic Shear Rheometer (DSR) device

v. Develop & Design Testing Setup for Exploratory Testing on Mixtures
vi. Conduct Exploratory Tests on Mixture Samples
vii. Test Binders and Mastics Using PG Grading Test Methods
viii. Analysis and Report: Develop Recommendation for Possible Implementation

Major Findings from Year 1

During year one, the materials and testing conditions for the plan were selected and are shown in table E1b-2.1. The University of Wisconsin-Madison research team contacted the University of Minnesota to evaluate the potential of nanoindentation measurements to evaluate the rheological and fracture properties of binders. In a set of exploratory tests at 5 and 10 μm indentation, the results show a great amount of creep and stress relaxation (figures E1b-2.1 and E1b-2.2). During testing, the technicians faced the issue of large adhesion between the binder sample and the indenter probe. To reduce/control the effect of adhesion on the probe, a drop of water was added to the surface of the binder sample.

These results seem to show some potential for the use of the technique to evaluate rheological properties of asphalt binder. Several more tests, including a small parametric study, will be run to further the potential of the nanoindentation technique for the evaluation of the viscoelastic and fracture properties of asphalt binders.

Table E1b-2.1. Matrix of materials and conditions.

Neat binder	PG 58-28
	PG 64-22
Modified binders with	SBS
	Elvaloy
	PPA
Mineral fillers	Limestone
	Sandstone
	Ottawa Sand

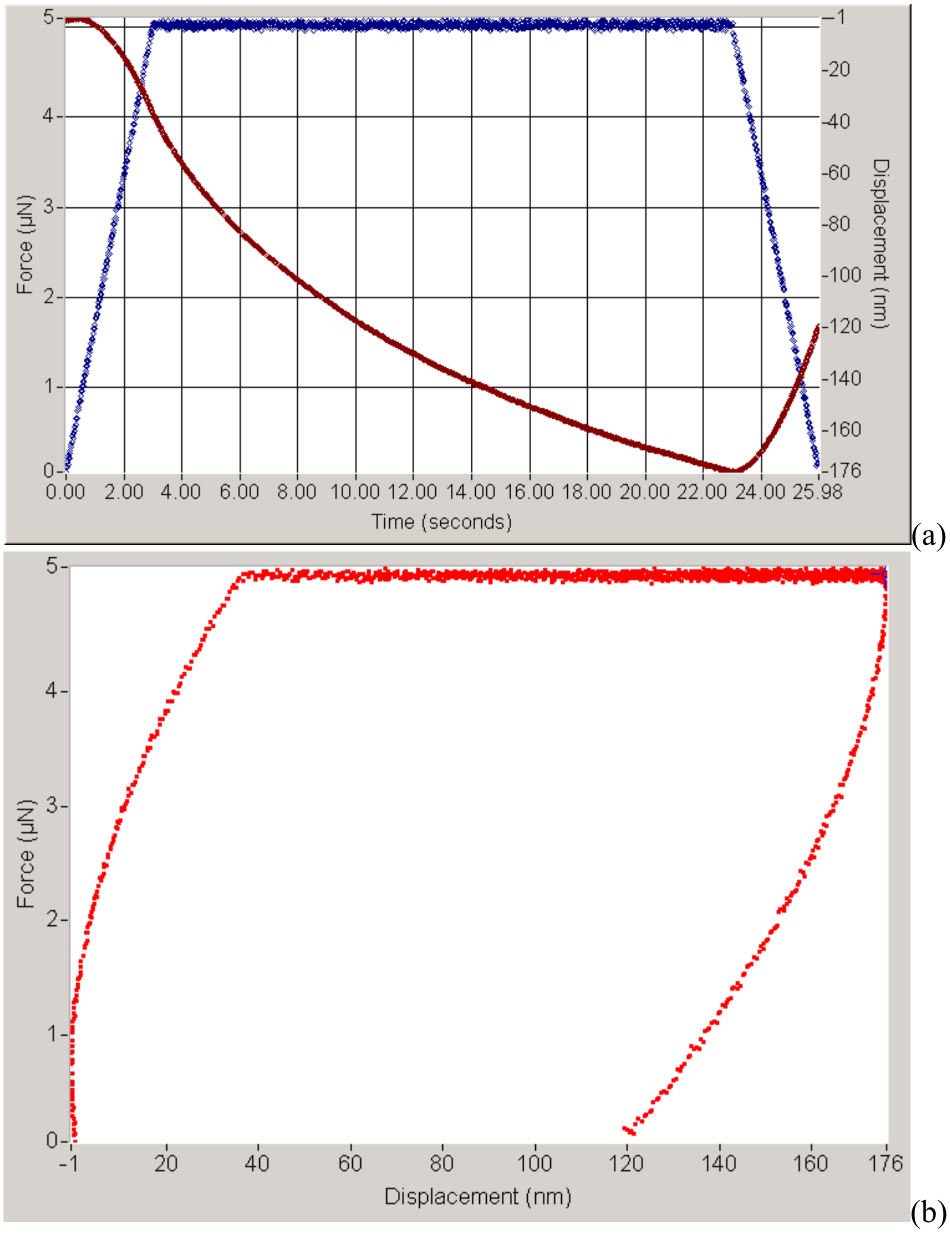
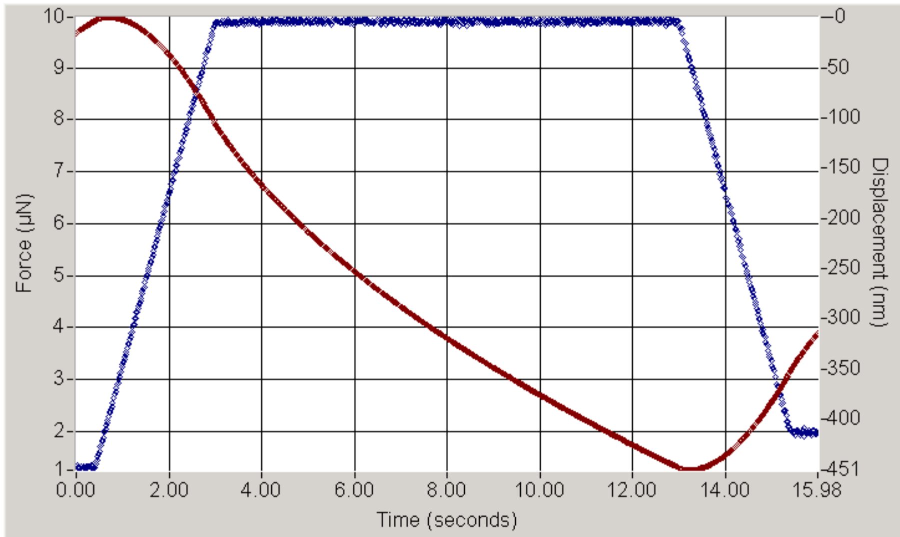
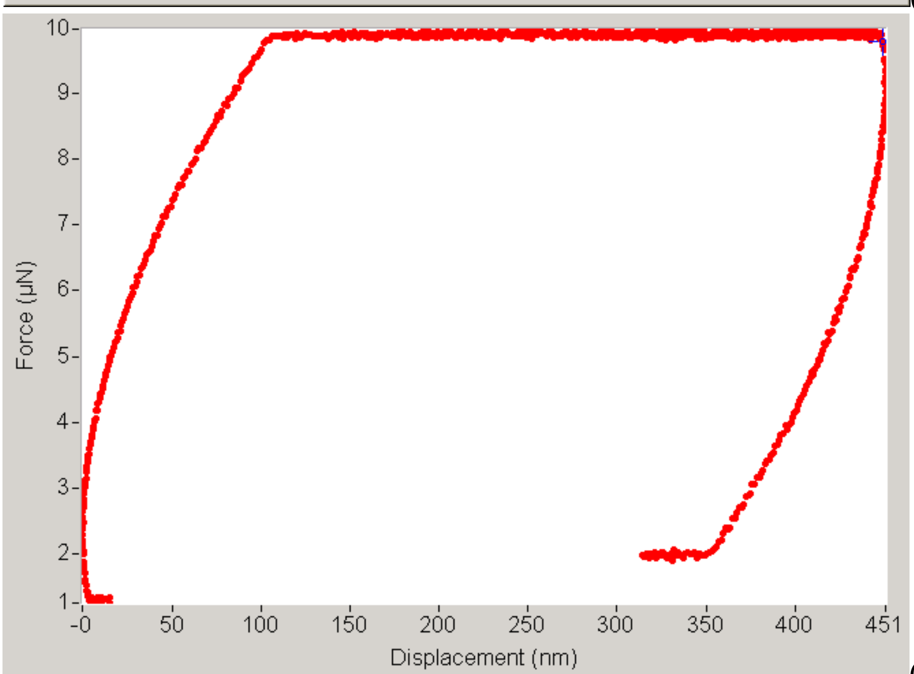


Figure E1b-2.1. Chart. 5 µN indentation results on BAY+filler with a 500 µm flat punch probe. (a) Force and displacement versus time and (b) force versus displacement.



(a)



(b)

Figure E1b-2.2. Chart. 10 µN indentation results on BAY+filler with a 500 µN flat punch probe. (a) Force and displacement versus time and (b) force versus displacement.

Year 2 Work Plan

The binders presented will be tested at 10 and 25ºC to evaluate how well the nanoindentation technique can be use to systematically and rapidly evaluate the rheological and fracture behavior of binders. The binders will be tested both with the nanoindenter and the DSR to provide an independent verification of the material response. Once the research team evaluates the response of the materials, and it establishes meaningful correlations between nanoindentation and DSR results, the methodology for the evaluation of the rheological and fracture behavior of asphalt mixtures will be proposed.

Because the nanoindenter and DSR do not measure the exact same material parameters (e.g., different size scales, different deformation modes, etc.), the research team will evaluate the differences in boundary condition, loading rates, and scales (McGennis et al. 1994; Lin et al. 2006). The Kelvin-Voigt model will be used to evaluate the rheological properties (Ashby and Jones 1996; Roberts et al.1996; Pichler et al. 2005). Figure E1b-2.3 depicts the research approach defined for this work element.

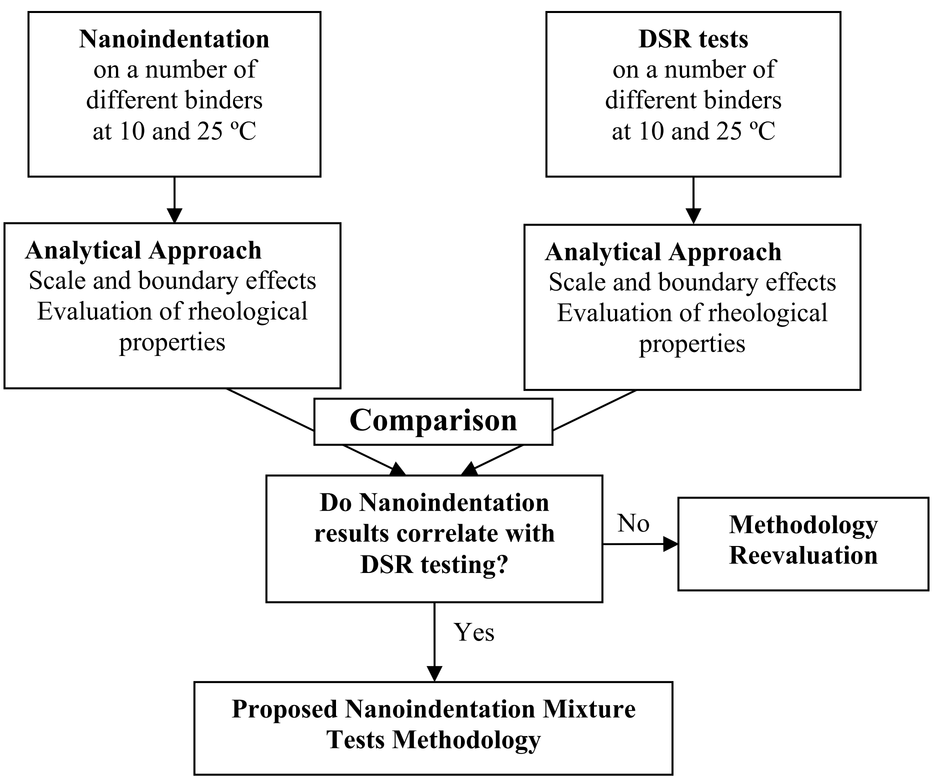


Figure E1b-2.3. Chart. Flow chart for research approach.

Year 2 Milestones

- Complete report on review of literature
- Finalize material selection and experimental plan
- Conduct the proposed tests on asphalt binders and mastics
- Evaluate the boundary conditions, loading rates, and scales
- Compare nanoindentation results with those of DSR

Budget

The estimated budget for this subtask is $150,000 over the four years. The work will be conducted by the University of Wisconsin-Madison and University of Minnesota.

Cited and Related References

Ashby, M. F., and D. R. H. Jones, 1995, *Engineering Materials 1*. Butterworth-Heinemann, 306 pp.

Lin, D. C., E. K. Dimitriadis, and F. Horkay, 2006, Advances in the mechanical characterization of soft materials by nanoindentation. *Recent Res. Devel. Biophys.*, 5: ISBN: 81-7895-215-7.

McGennis, R. B., S. Shuler, and H. U. Bahia, 1994, *Background of SUPERPAVE Asphalt Binder Test Methods*. Federal Highway Administration Report No. FHWA-SA-94-069.

Pichler, C., A. Jager, R. Lackner, and J. Eberhardsteiner, 2005, "Identification of Material Properties from Nanoindentation: Application to Bitumen and Cement Paste." 22nd Danubia Adria Symposium on Experimental Methods in Solid Mechanics, Sept. 28-Oct. 1, 2005, Moniticellu Terme. Parma, Italy.

Roberts, F. L., P. S. Kandhal, E. R. Brown, D.-T. Lee, and T. W. Kennedy, 1996, *Hot Mix Asphalt Materials, Mixtures, and Construction*. National Asphalt Pavement Association – Research and Education Foundation, Lanham, MD, 585 pp.

Work element E1c: Warm and Cold Mixes

Subtask E1c-1: Warm Mixes

Subtask Lead: Codrin Daranga

Introduction

Rising energy prices and more stringent environmental regulations have resulted in significant interest in warm mix asphalt additives. These additives are means to decrease the energy consumption and emissions associated with conventional hot mix asphalt production by allowing asphalt mixes to be produced at lower mixing and compaction temperatures, addressing the prominent environmental and economic factors currently faced by industry. Lower production temperatures reduce plant emissions and energy consumption. There is also great technical benefit to the use of warm mixes, namely, extension of the construction season and reduced aging of the asphalt binder. The ability to achieve a suitable in-place density at lower temperatures allows for extension of the construction season. Reduction of the short term aging (oxidation and volatilization) of the asphalt binder during conventional construction would also lead to enhanced pavement performance through reduced thermal and fatigue cracking, thus improving the life cycle cost of the pavement.

The concept behind warm mix technologies is reduction in asphalt binder viscosity, allowing for the asphalt to attain suitable viscosity for coating of the aggregate and compaction of the mix at lower temperatures. Currently there are two commonly used types of warm mix additives in the market: wax-based additives that are added to the asphalt binder through low shear mixing and hydrated mineral compounds that are added to the pugmill during normal batching operations. Each of these additives achieves reduced binder viscosity by different mechanisms.

One of the most widely used wax-based additives currently on the market is Sasobit®. This additive is a "long chain aliphatic hydrocarbon produced by Fischer-Tropsch synthesis of coal or natural gas." The wax has been engineered such that it is completely soluble at 115 ºC, allowing it to be incorporated into the asphalt binder homogenously. This wax-based additive has been classified as an "asphalt flow improver" due to its ability to reduce viscosity above the previously defined temperature threshold. Below this temperature threshold the wax additive crystallizes, forming a lattice structure in the binder that leads to enhanced binder stiffness at high temperatures while minimizing low temperature performance.

The hydrated mineral compounds reduce asphalt binder viscosity by foaming of the asphalt at mixing and compaction temperatures. Currently there are aluminum-silica and phosphorous based mineral additives available. These additives contain 18-21 percent water by mass and it is expected that the entrapped water is released in the asphalt at temperatures between 85-180 ºC. At these temperatures the water is released in the form of vapor, creating a volume expansion of the binder which results in foaming of the asphalt. The foamed asphalt enhances lubrication, allowing for workability and aggregate coating at lower temperatures. In theory, once the asphalt mixture is placed and cooled, the water vapor evaporates from the mix. Therefore, the performance of the mixture is not enhanced.

The implementation of warm mix technology as a viable option for paving operations is a promising concept. However, further investigation of the effects of the aforementioned additives on the constituent materials of asphalt mixtures and pavement performance must first be investigated. Specifically, the effects of the additives on fundamental binder and mixture properties must be defined, the impact of the additives on mixture workability quantified, and the field performance of pavements placed using warm mix technologies evaluated and compared to conventional HMA mixes. Past research has defined rutting, moisture damage, and mix design as key issues that have yet to be fully resolved. Recent work at UW-Madison has shown that Sasobit additives increases the S(60) and decreases m(60) and thus low temperature cracking could be affected negatively. It is imperative that the effects of these additives be fully understood and evaluated to facilitate development of specifications and construction guidance to allow for wide spread application of this technology.

Relationship to FHWA Focus Areas

This work element is related to the following focus areas:

- Promotion of environmental stewardship.
- Development of the use of the gyratory plate as an improved measure of mix workability.
- Clear definition of mix design and construction procedures to provide a basis for modeling of energy savings associated with the use of warm mixes.
- Field investigation quantifying the risk of compromising performance at the expense of energy savings.

Hypothesis

- Detailed investigation of the effects of wax and mineral-based warm-mix asphalt additives on the performance of asphalt binders and mixtures will provide a basis for best practices of incorporating this technology into current practice.
- Laboratory testing of materials during field trials and subsequent monitoring of pavement performance will verify laboratory findings, identify deficiencies in current procedures, and allow for development of best practices for mix design and construction of warm mix asphalt.

Objectives

The overall objective of this research effort is to gain an understanding of the effects of commercially available warm mix additives on the performance of the asphalt binder and mixture and mixture workability. This understanding will allow for optimization of mixture design and construction practices for application of warm mix technology to the field. Optimized practices will be applied in field trials and evaluated/refined through monitoring of pavement performance.

Experimental Design

The following activities will be completed in order to achieve the objectives of this research effort.

i. Evaluation of the Effects of Warm Mix Additives on the Rheological Properties of Asphalt Binders

   Understanding of how the warm mix additives affect binder properties is imperative for further comprehension of mixture and field performance. The current state of industry requires that both polymer modified and neat binders be investigated.

ii. Evaluation of the Effects of Warm Mix Additive on Mixture Workability and Stability

The Gyratory Load Plate developed by UW Madison will be used to measure the resistance of the asphalt mixture to compactive effort. Previous research has used air voids to define increased workability due to reduction in viscosity caused by warm mix additives. The use of the gyratory load plate will provide a more fundamental measure of these effects. Previous work at UW-Madison has defined two indices, the Construction Energy Index (from 88 to 92 percent Gmm) to quantify mix workability and the Traffic Energy Index (92 percent - 98 percent Gmm) to evaluate the stability of the mixture. All mixes will be compacted past Nmax to allow for measurement of both these parameters.

Nine parameters at two to four levels have been defined above, making a full factorial experimental design infeasible. A partial factorial design will be used to design an experiment that will identify significant effects while reducing the number of mixtures required for testing.

iii. Mixture Performance Testing

Effects deemed to be significant through binder and compaction testing will be varied to evaluate the performance of asphalt mixtures.

- Moisture Damage: Previous research has found moisture damage to be a significant mode of distress in warm mixes. The following tests will be used in conjunction with binder cohesion testing to investigate moisture damage in warm mixes and its causes.
    - Mastic: The fine materials (R30 and below) will be used to create torsion cylinders to quantify the effects of moisture on the mastic in aggregate blends tested.
    - Mixture testing: Moisture damage will be defined using TSR testing. If moisture damage is found to be a problem, investigate the use of liquid anti-stripping additives and hydrated lime.
- Simple Performance Tests (E* and FN).
    - Dynamic Modulus (E*) and Flow Number tests will be used to characterize the stiffness and rutting resistance of mixtures using warm mix additives and to compare the results to conventional HMA mixes. Tests will be performed on short and long term aged mixtures.
- Resistance to Fatigue and Thermal Cracking (IDT):
    - Fracture Energy: Literature review has shown that the fracture energy parameter at different testing temperatures is able to predict resistance to fatigue and thermal cracking (Wen and Kim 2002).

iv. Refine Mix Design Procedure with Consideration of the Phase I NCHRP 9-43 Report; Develop Performance Recommendations

Results of binder and compaction testing will be used to identify any necessary revisions to current Superpave mix design procedures. Possible revisions include:

- Binder grade: Define appropriate binder grade adjustments to account for contribution of wax lattice structure or to compensate for reduced rutting resistance.
- Aggregate Moisture Content: The appropriate moisture content of the aggregate blend must be defined to provide consistency between laboratory tests and field application.
- Optimum Asphalt Content: Guidance on whether optimum asphalt content should be based on warm mix compactions or conventional HMA compaction.
- Additive Concentration: Define concentrations of additive that will provide optimum performance.
- Mixing and Compaction Temperatures: Define optimum and mixing and compaction temperatures based on warm mix additive concentration.
- Anti-stripping additives: Specify additives and concentrations to prevent moisture damage.

v. Field Evaluation of Mix Design Procedures and Performance Recommendations

The results of the binder and mixture testing previously discussed will be used to identify key variables for field investigation and define parameters for the design of test sections for field investigation. Furthermore, guidance developed in part iv (above) will be used in the construction of warm mix test sections to evaluate the mix design procedures. The following parameters should be measured in the field during construction:

- Mixing temperature
- Compaction temperature
- In-place density (Nuclear Gauge)
- Number of Passes to Achieve Target density
- Thickness
- Thickness-NMAS ratio

Field mix will also be obtained from each site and evaluated using the test procedures defined in the previous parts of this subtask that indicated potential effects caused by using warm mixes.

Field performance will be monitored through pavement distress surveys and pavement coring and correlated to laboratory testing results. This field evaluation will lead to refined mixture design and construction guidance. (Work will be done with UW Platteville.)

The team will coordinate with other research activities in this area, such as NCAT, NCHRP 9-43 and 9-47.

Major Findings from Year 1

During Year 1, the materials and testing conditions for the plan were selected and are shown in table E1c-1.1. In addition, the preliminary test plan is shown in table E1c-1.2. Activities in Year 1 focused on the effects of both wax-based (Sasobit) and a proprietary mineral based warm mix additives on asphalt binder properties. The preliminary study focused on the effects of both additives on mixing and compaction temperatures as measured in the Brookfield Viscometer. Furthermore, the effects of Sasobit on physical hardening and mineral based additives on binder rutting performance were investigated. The following is summary of the findings of each of these efforts.

Table E1c-1.1. Matrix of materials.

Binder		Mineral Aggregate			Warm Mix Additive		
Neat	Polymer Modified	Granite	Limestone	Gravel	Zeolite (Aspha-min)	Wax (Sasobit)	Emulsion (Evotherm)

Table E1c-1.2. Proposed tests.

Viscosity	Adhesion/Cohesion		Rutting		Fatigue	Low Temperature	
Brookfield RV	Thin Film Rheology	UW-Madison Tack Test	DSR G*/sinδ	MSCR	Monotonic Test	BBR	SENB

1. *Effects of Sasobit on Binder Viscosity and Mixing and Compaction Temperatures*

The effects of Sasobit on binder viscosity were evaluated through assessment of the binder viscosity profiles for two different binder grades (PG 70-22) and concentrations (1 percent and 3 percent). Viscosity profiles were created for three temperatures: 105 ºC, 135 ºC, and 165 ºC. Figures E1c-1.1 and E1c-1.2 provide the viscosity profiles at the aforementioned testing temperatures for PG 70-22 and PG 70-28, respectively.

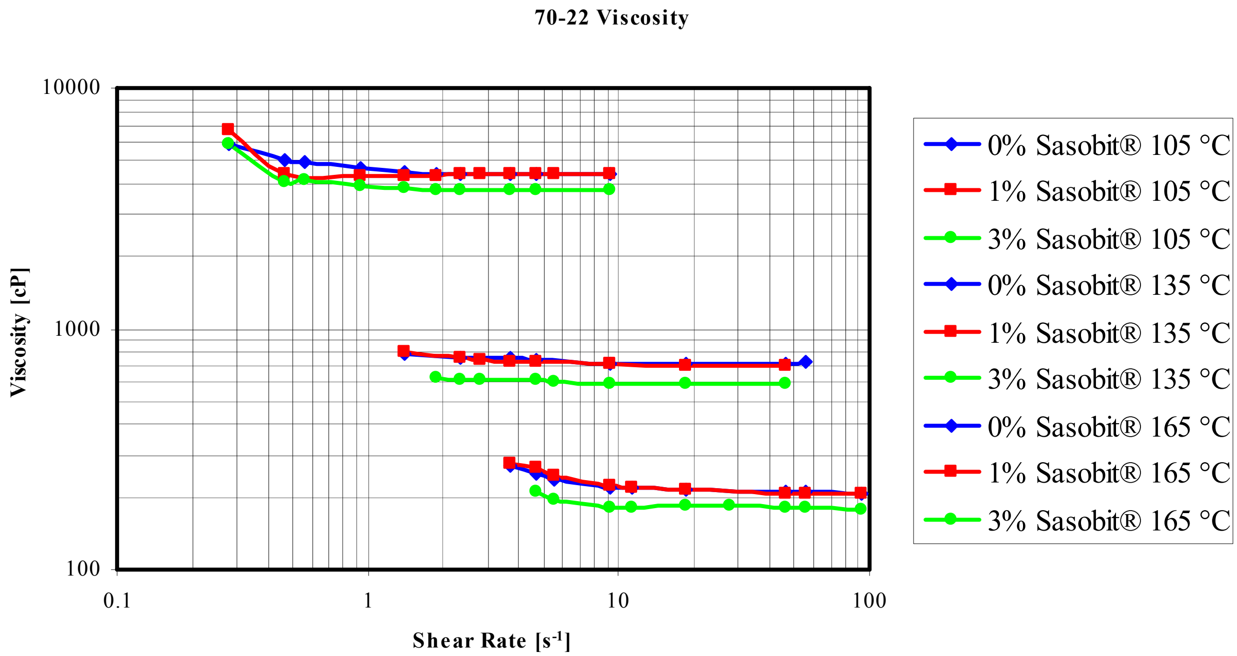


Figure E1c-1.1. Chart. Viscosity profile for PG 70-22.

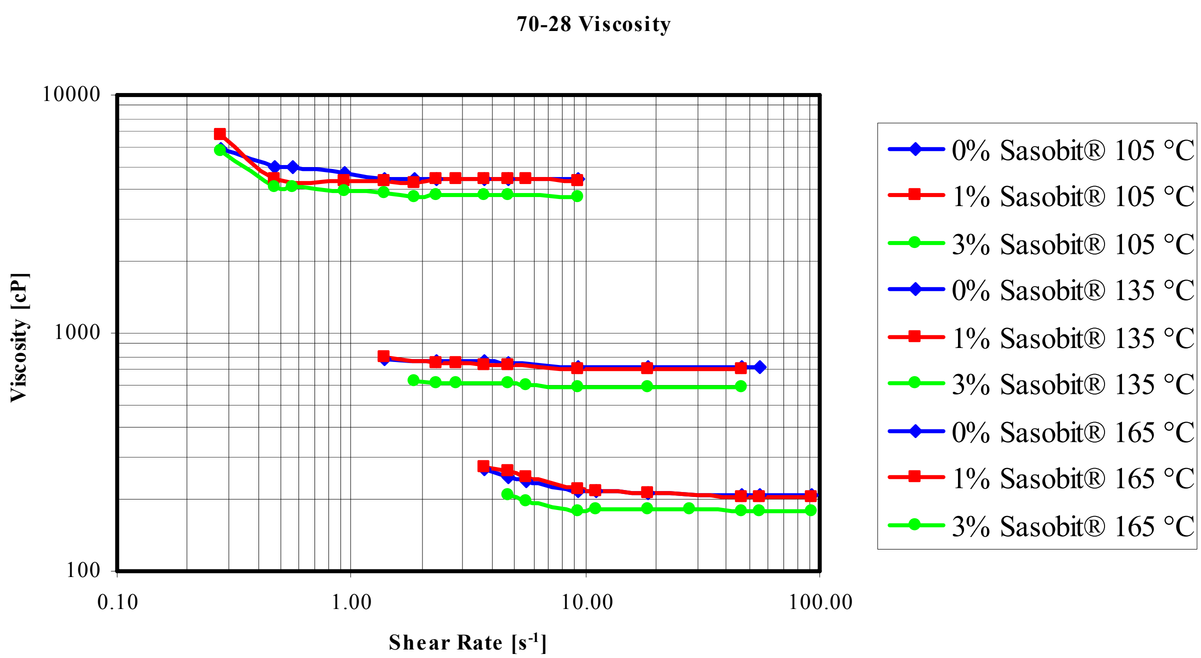


Figure E1c-1.2. Chart. Viscosity profile for PG 70-28 binder.

The viscosity profiles for both binder grades show virtually no effect of the addition of Sasobit on binder viscosity for all shear rates at concentrations lower than 3 percent. To investigate the relationship between the measured viscosity profiles and mixing and compaction temperatures, the methodology developed in NCHRP 9-10, which uses measurements of zero shear viscosity and curve fitting using the Cross Williamson Model, was applied. Table E1c-1.3 provides a summary of the mixing and compaction temperatures determined for a given Sasobit concentration and binder type.

Table E1c-1.3. Summary of estimated mixing and compaction temperatures for Sasobit.

		Sasobit Concentration		
Binder	**Temperature (C)**	**0%**	**1%**	**3%**
PG 70-22	Mixing	144.3	---	140.4
	Compaction	132	---	128.7
PG 70-28	Mixing	152.3	152.9	145.9
	Compaction	137	137.3	132.4

The data provided in table E1c-1.3 shows only and approximately 4 ºC reduction in mixing and compaction temperatures for 3 percent Sasobit. Based on the extra cost of the additive and the potential reduction in low temperature binder performance, this reduction is not significant enough to justify the use of Sasobit. However, further work needs to be done to verify these results and investigate the effect of binder grade on the ability of Sasobit to reduce mixing and compaction temperatures.

Effects of Sasobit on Physical Hardening

The same binders and concentrations of Sasobit previously discussed were used to examine the effects of Sasobit on the physical hardening of asphalts. The conclusions of the study are as follows:

- The addition of Sasobit to the binder produces a significant increase of the stiffness, and a reduction of the m-value. The magnitude of this effect is almost identical for both RTFO and PAV aged samples, thus indicating a minor susceptibility of Sasobit to aging.
- BBR and glass transition tests show that Sasobit has a negligible influence on rate and magnitude of physical hardening. Specifically, the phenomenon is slightly intensified for PAV aged binders, while it is vaguely weaker for RTFO aged ones. This tendency is somehow more marked for the PG 70-22 asphalt.
- For the PG 70-28, the T_g of the Sasobit-modified binder is higher than the one of the original binder. The explanation could be that the addition of the FT-wax (a glasslike

material) the glassy region of the material is extended. On the other hand, the PG 70-22 shows an opposite behavior, proving – besides the non-optimal dispersion of the experimental data – the strong dependency on asphalt.

- Both asphalts exhibit clearly the occurrence of physical hardening through the different T_g measured during cooling and heating processes. Furthermore, the free volume estimated during heating is always bigger than the one during cooling, revealing the free volume fraction which is lost in the isothermal conditioning period of 10 minutes.
- Future research should be focused on the dependency of physical hardening on the PG grade of the binder, the possible interference of Sasobit with previous modifying agents and the occurrence of physical hardening in WMA mixtures.

2. *Mineral Based Additives Effects on Binder Viscosity*

The effect of a proprietary mineral additive on binder mixing temperatures and the duration for which the effect is realized in the binder was measured through evaluation of binder viscosity at a three prescribed shear rates (0.68, 2.04, and 6.80 /s) at mixing times of 1 and 6 hours. Temperature was also varied (150 ºC, 115 ºC, and 90 ºC) to capture the temperature dependence on the rate of release of the water from the hydrated compound and its effects on reduction in binder viscosity. All tests were conducted using a PG 64-22 binder. Furthermore, anhydrous molecules of the mineral additives investigated were acquired to provide a control. The effect of the WAM additives on binder viscosity is shown in figure E1c-1.3 as a plot of the ratio of viscosity of additive to that of neat binder for a given shear rate.

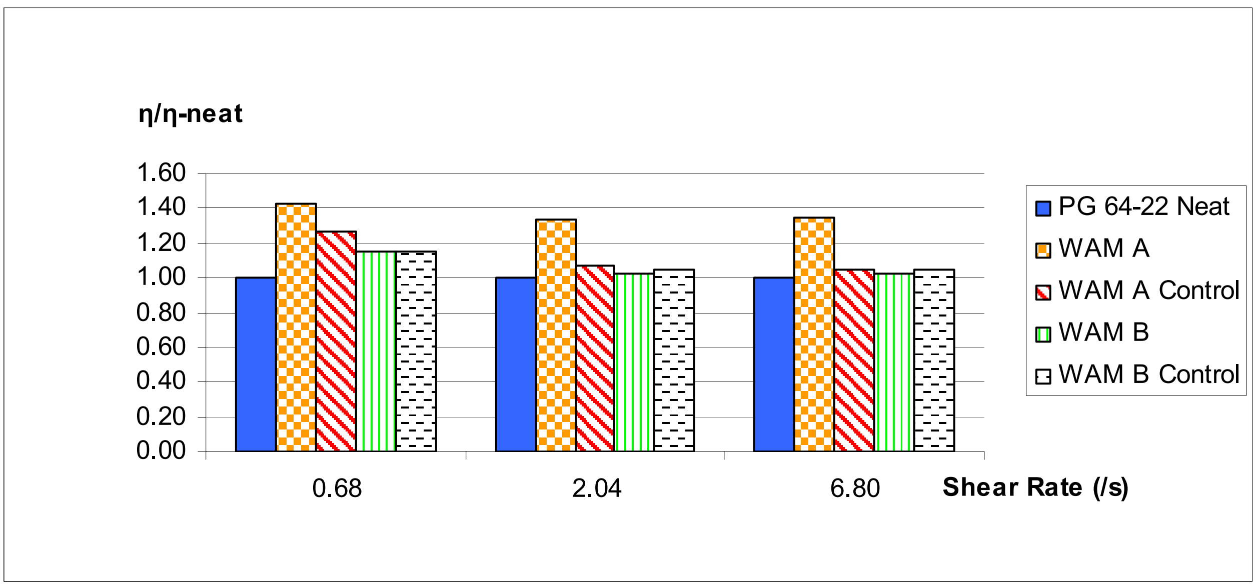


Figure E1c-1.3. Chart. Plot of viscosity ratio for 115 ºC mixing temperature and 1 hour conditioning time.

For all shear rates, addition of the warm mix additive did not result in a reduction in viscosity. In fact, in most cases viscosity increased, possibly due to the effect of the mineral filler used as a delivery system for the hydrated compound. As expected, reduction in viscosity was also not realized after 6 hours of conditioning time. The main finding from this investigation is that other test methods for quantifying the effect of water based warm mix additives on mixing and compaction temperatures must be researched as part of this work plan. New potential methods are being developed in NCHRP 9-39; the applicability of these methods to water-based warm mix additives will be developed upon delivery of the final report, which is due June 30, 2008.

3. *Mineral Based Additives – Effect on Binder Rutting Performance*

The effect of mineral based warm mix additives on binder performance was evaluated through a frequency sweep (0.5-20 Hz) at testing temperatures of 40 ºC, 52 ºC, 64 ºC, and 76 ºC using 40 mm parallel plate geometry in the Dynamic Shear Rheometer. The frequency sweep was chosen as an evaluation tool for binder performance over the conventional rutting parameter of G*/sinδ because it allows for more comprehensive characterization of binder performance through development of master curves using time temperature superposition while still allowing for determination of the Superpave rutting parameter. An example of master curves generated using this testing procedure is provided in figure E1c-1.4.

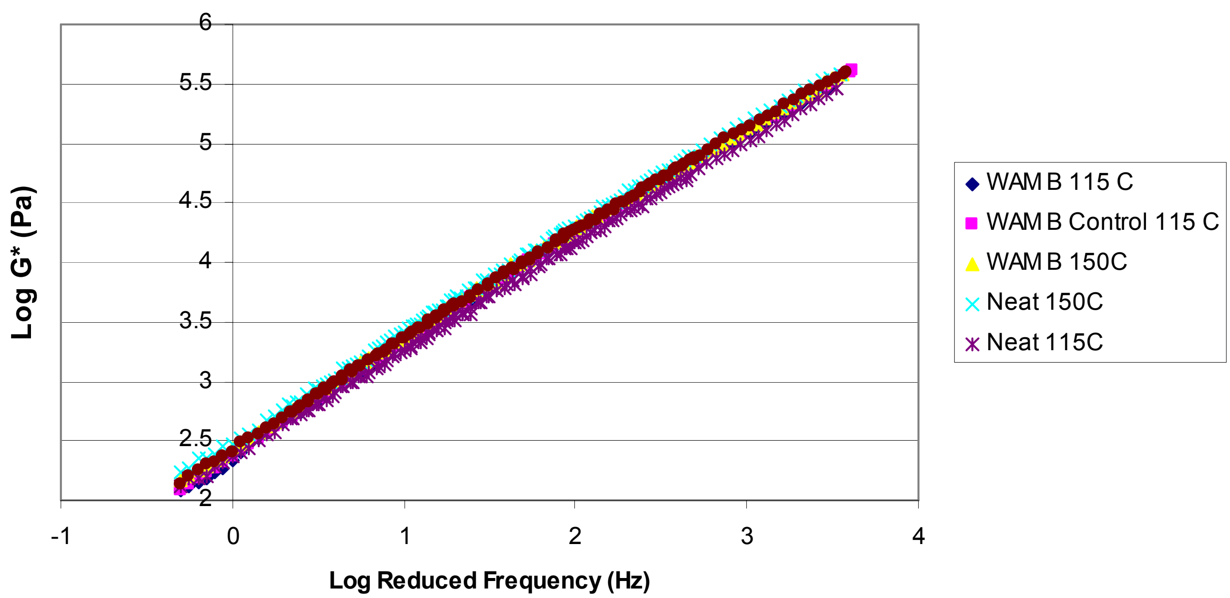


Figure E1c-1.4. Chart. Master curve comparison of neat binder and WAM B at 115 ºC and 150 ºC mixing temperatures.

Master curve data generated in figure E1c-1.4 shows that the warm mix additive has no significant effect on binder performance. The significant finding from this aspect of the research is the development of a test method that has the ability to characterize binder performance that can be used to for both wax based and water based warm mix additives as the study moves forward.

Year 2 Work Plan

This work plan will focus on the following items:

1. *Wrap up the evaluation of the warm mix additives effect on rheological properties of binders*
   - Viscosity (Brookfield RV): The reduction in viscosity due to the addition of warm mix additives must be further quantified over a wide range of additive concentration and binder temperatures. Year one work has indicated that reduction of binder may be binder specific. Specifically, the benefit of warm mix additives will not be realized in neat binders, which have inherently low viscosity. Furthermore, the time effect associated with creation and evaporation of the water vapor produced with the mineral additives must be understood.
   - Thin Film Rheology Measurements Using the DSR: Effect of film thickness on warm mix behavior will be studied by running DSR measurements at gaps around 25 μm.
   - Adhesion and Cohesion Testing (Tack Test developed by University of Wisconsin-Madison): Moisture damage has been identified as a critical distress found in warm mix pavements. TSR testing with the mineral based additives found a premature cohesive mixture failure possibly due to the emulsification of the asphalt in the foaming process. The effects of the release of water vapor over time on cohesion must be investigated further. The wax additive must also be evaluated to understand the contribution of the wax lattice structure to binder cohesion.
   - Rutting ($G^*/\sin\delta$ and MSCR)
     - Superpave Rutting Parameter: $G^*/\sin\delta$ will be measured for all binders to evaluate the rutting resistance of warm mix and unmodified binders as defined by Superpave. The use of this parameter will provide a direct link to how warm mix additives affect rutting resistance in terms of a widely accepted specification.
     - Multiple Stress Creep and Recovery: A fundamental understanding of binder rutting will be obtained through evaluation of accumulated strain using the MSCR test. This will further quantify the any contribution to rutting resistance by the crystalline lattice associated with the wax additives or any increase in accumulated strain caused by the inability of the water vapor to completely evaporate from the asphalt binder.
   - Fatigue (Monotonic Test): The monotonic test in performed in the DSR using the 8-mm geometry. The binder specimen is prepared the same as for traditional Superpave binder fatigue evaluation. Instead of oscillation, though, the specimen is subjected to a constant shear-rate (twist) loading until the maximum amount of stress is developed in the specimen. Parameters such as strain at maximum stress, yield energy, and the characteristic C(S) curve from viscoelastic continuum damage mechanics can be used to evaluate fatigue performance. Fatigue performance will be measured to identify any effects caused by the wax lattice structure or entrapped water from the mineral additives.

- Low Temperature Properties (BBR): What is the effect of the lattice structure from the wax or any entrapped water from the mineral additive on low temperature properties?
- Single Edge Notched Beam Test (SENB): This test will provide useful information on the brittleness of the binders before and after warm mix additive addition.
- Aging (RTFO and PAV): The reduction in short term aging due to lower mixing and compaction temperatures and its effect on the previously mentioned binder properties must be understood in order to predict mixture and field performance.

2. *Continue work on evaluation of the effects of warm mix additives on workability and stability of mixes*
   - Compactive Effort: Mixes will be compacted at 600 kPa and 300 kPa. Previous research has found the SGC to be insensitive in terms of mix densification to temperature changes. Measurement of the forces related to compaction will bring resolution to this issue.
   - Temperature: Temperature will be varied to define mixture workability and stability as a function of temperature for the warm mix additives and unmodified mixtures. Variation of temperature will also identify the tender zone for warm mixes.
   - Aggregate Type: Different aggregate types have different properties in terms of aggregate shape and strength, necessitating the investigation on how these properties affect the performance of the warm mix additives. Granite, limestone, and gravel aggregate types will be used.
   - Gradation: Fine and Coarse or S-Shaped aggregate blends will be used.
   - Binder Grade: If viscosity testing reveals an effect on unmodified and modified binders, both neat and polymer modified binders will be evaluated to establish a relationship between binder viscosity and mixture compaction.
   - Asphalt Content: Investigate the effects of asphalt content. Literature review identified a need to investigate if the asphalt content for warm mixes should be defined through normal mix design procedures or volumetrics obtained from warm mix compaction.
   - Additive Type: Three types of warm mix additives will be used; a zeolite (Aspha-Min®), a wax (Sasobit®), and a non-zeolite water bearing additive (Evotherm®) in order to evaluate three different mechanisms. Possible other additives considered are Redi-set Warm Mix Additive by Azko Nobel and Waterless Warm Mix by Gerald Reinke.
   - Additive Concentration: Define high and low levels of warm mix additive concentration.
3. *Start work on mixture performance testing*
   - Simple Performance Tests (E* and FN)
     - Dynamic Modulus (E*) and Flow Number tests will be used to characterize the stiffness and rutting resistance of mixtures using warm mix additives and to compare the results to conventional HMA mixes. Tests will be performed on short and long term aged mixtures.

4. *Begin field evaluation of current mix design and construction procedures*

- Dr. Robert Schmitt of UW-Platteville will perform research services in this area, including:
    - Coordinate with WisDOT and contractors to conduct field evaluation of warm mix construction projects in the State of Wisconsin.
    - Arrange traffic control as necessary with county highway departments.
    - Perform nuclear density testing.
    - Obtain loose mix samples and pavement cores for laboratory testing.
    - Perform pavement field distress surveys.

Figure E1c-1.5 depicts the research approach defined for this work element.

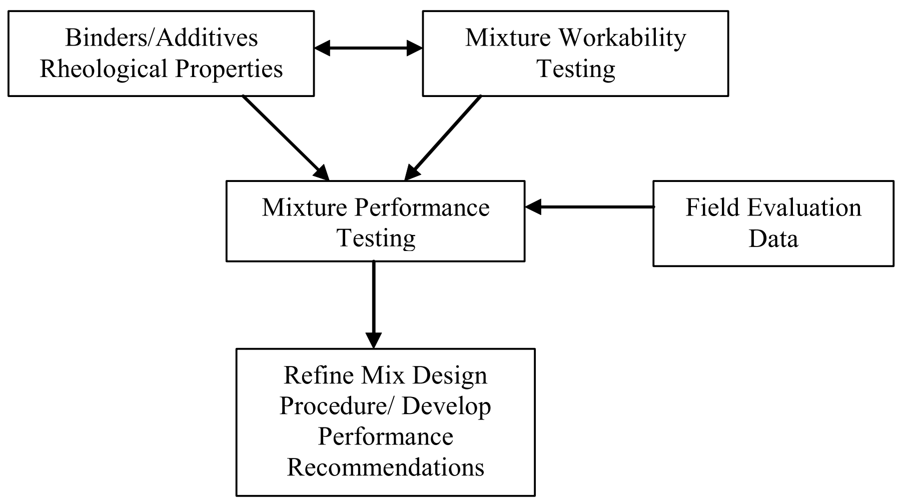


Figure E1c-1.5. Chart. Flow chart for research approach.

<u>Year 2 Milestones</u>

- Complete the evaluation of the effects of warm mix additives on rheological properties of asphalt binders
- Complete the effects of warm mix additives on mixture workability and stability
- Start conducting the proposed tests on asphaltic mix tests
- Start field evaluation and validation of laboratory test results

Budget

The estimated budget for this subtask is $475,000 over the five years. The work will be conducted by the University of Wisconsin-Madison.

Cited and Related References

Kanitpong, K., S. Sonthong, K. Nam, W. Martono, and H. Bahia, 2007, Laboratory Study on Warm Mix Asphalt Additives. Transportation Research Record, Journal of the Transportation Research Board. Transportation Research Board 2007. Taken from the Annual Meeting CD ROM.

Hurley, G., and B. Prowell, 2005, "Evaluation of Aspha-min Zeolite for use in Warm Mix Asphalt." National Center for Asphalt Technology, Auburn University, 277 Technology Parkway, Auburn, AL, June 2005.

Hurley, G., and B. Prowell, 2006, Evaluation of Potential Processes for Warm Mix Asphalt. *Journal of the Association of Asphalt Paving Technologists*, Vol. 75. Association of Asphalt Paving Technologists, Savannah, GA. 2006.

Hurley, G., and B. Prowell, 2005, "Evaluation of Sasobit for use in Warm Mix Asphalt." National Center for Asphalt Technology, Auburn University, 277 Technology Parkway, Auburn, AL, June 2005.

NCHRP Report 530, "Evaluation of Indirect Tensile Test (IDT) Procedures for Low Temperature Performance of Hot Mix Asphalt," Transportation Research Board, National Research Council, Washington, DC, 2004.

Wen, H., and R. Y. Kim, 2002, Simple Performance Test for Fatigue Cracking and Validation with WesTrack Mixtures. *Transportation Research Record 1789*, Paper No. 02-2924, Transportation Research Board.

Subtask E1c-2: Improvement of Emulsions' Characterization and Mixture Design for Cold Bitumen Applications

Subtask Lead: Hussain Bahia and Peter Sebaaly

Introduction

Rising energy costs and increasing environmental awareness have led to an increased interest in the research and development of surface treatments and cold mix asphalt technologies. Cold asphalt applications and cold mixture technologies allow for coating of aggregates and subsequent compaction of the asphalt mixture at ambient temperatures. As a result, energy requirements and emissions are significantly reduced relative to conventional HMA mixtures (Jenkins et al. 2002). The economic and environmental implications of successful implementation of well-designed surface treatments and cold mixtures for flexible pavements have the potential to provide a sustainable alternative to current HMA practice. However, further research is needed to improve evaluation methods of emulsions and to develop a more rigorous mixture design procedure to ensure that performance of pavements is not significantly compromised at the expense of energy saving or environmental sensitivity.

Surface treatments are the prime candidates for pavement preservation activities. Within the last few years, focus on pavement preservation has increased significantly. The concept of preventive maintenance as a more cost effective alternative to corrective maintenance is widely accepted and practiced. Emulsions are the main component of pavement preservation strategies. However, the test methods used to characterize emulsions are some of the most empirical and the most outdated tests methods used in the asphalt industry in North America. While the hot binder application has seen significant change in sophistication of grading and testing, emulsion technology has lagged behind.

The use of Cold Asphalt Mix (CMA) is a viable option for pavement layer stabilization, particularly for cold in place recycling, and for surface layers under moderate traffic. Although this is widely recognized, a volumetric mixture design procedure consistent, or comparable, to the current HMA practices, such as Superpave specifications, is not yet available. Specifically, CMA design procedures should include guidance on mixing and compaction temperatures, quantify the rate of curing of the mixture, and evaluate test methods to assess the performance of mixtures under traffic, including moisture susceptibility and aging effects. If cold mixes are expected to serve as surface layers, the mechanical properties of the mix and the performance required for different applications must established.

In cold asphalt applications, the workability of the material is derived from reduction of viscosity in the asphalt binder through emulsification. The use of these mechanisms allows the coating of aggregates and compaction of the mix to occur at ambient temperatures. In the emulsification process an emulsifying agent is added to the asphalt resulting in the dispersion of asphalt cement in water (Asphalt Institute, 1989). In this mixture the water serves as the continuous phase with the asphalt suspended in discontinuous droplets throughout the medium. After a certain period of time the emulsion sets or "breaks" and cures, leaving behind an asphalt mixture. The curing time of an emulsion is based on the grade of emulsion used, the ambient conditions, and the physical and chemical characteristics of the surface the emulsion is applied to.

Development of a performance-based emulsion selection system and a mixture design process will improve use of emulsions in surface treatments and define potential uses for cold mixes. The development of these technologies will facilitate development of specifications and construction guidance to allow for widespread application of cold asphalt technologies.

<u>Relationship to FHWA Focus Areas</u>

This subtask is related to the following focus areas;

- Promotion of environmental stewardship.
- Development of the use of the gyratory plate as an improved measure of mix workability.
- Clear definition of mix design and construction procedures to provide a basis for

modeling of energy savings associated with the use of cold mixes.

- Mixture performance testing to provide insight into the risk of compromising performance at the expense of energy savings.

Hypothesis

- Development of test methods and performance thresholds for emulsions, based on type of application, will provide a more consistent scientific tool for classification of emulsified asphalts. A system similar to the performance grading of conventional asphalts, which is climate, traffic, and application based, could significantly improve emulsion use and acceptance.
- An application-based CMA design procedure that considers handling and performance of mixes will allow a more predictable performance for mixtures used for partial depth recycling, full depth recycling, and surface paving applications. Design procedures should include consideration of curing time and allow for recommendations on the timing of opening constructed cold mixes to further construction activities and/or traffic.
- Mixture performance testing compatible with the requirements of the AASHTO MEPDG procedure will provide basis for considering CMAs as viable options for any pavement layer. Further understanding of the mechanical properties of cold mixes will allow for better definition of limitations and opportunities for using these materials.

Objectives

The overall objective of this study is to develop a more scientific characterization system of emulsified asphalts, including the residual binder properties. Such system will lead to development of volumetric mixture design procedures and a mixture performance framework based on the application. The feasibility and practical application of the emulsion characterization, mix design procedures, and performance framework will be evaluated through field trials.

Experimental Design

The objectives of this subtask will be addressed by pursuing nine subjects:

i. Review of National and International Standards for Emulsions, Aggregates, and Performance Evaluation of Cold Asphalt Applications. There are many standard test methods and local specifications that are used all over the world. It is important to collect these standards and analyze similarities and differences in these standards, as a starting point to develop rational methods and standards. Because cold asphalt applications vary in components and intended purpose, the review in this subtask will address three areas:

   a. Review testing methods, standards, and specifications related to asphalt emulsions.

   b. Review testing methods, standards, and specifications related to aggregates used in cold asphalt applications such as surface treatments and CMA.

c. Review testing methods, standards, and specifications related to performance evaluation of cold mix applications including surface treatments and CMA.

ii. Create an International Advisory Group for the Project. A significant part of emulsion testing and applications is based on experience of various individuals, contractors, and suppliers. Very little is documented in publications. It is thus necessary to create an advisory group to identify the critical gaps in the knowledge and guide the research to change some of the tests that are specified today but have no real relationship to performance. The advisory group could help simplify testing and focus specifications on important and relevant properties. The advisory group will meet twice a year at convenient location and in coordination with annual conferences to review progress and provide feedback. The group will also serve as the link to AEMA, ISSA, and other organizations that have a stake in this field.

iii. Identify Potential Performance Related Tests. Based on results of subjects i and ii, a list of tests that show high potential for measuring properties of emulsions, aggregates, and other additives that are related to performance of surface treatments and cold mixtures will be identified. The details of each test including engineering basis, cost, practicality, repeatability, and relevance will be defined. The tests will be ranked and an experimental plan for evaluating the tests and validating their attributes will be developed. The tests will be divided into three types:

    a. Emulsion tests
    b. Aggregate and surface condition tests
    c. Performance test of complete mixture or application

iv. Establish a Materials Reference Library for Cold Asphalt Applications. To validate tests methods and to derive criteria limits, it is necessary to have reference materials that are used in the field and materials that have gone through rigorous testing in the lab. Samples of emulsions, aggregates, additives and mixtures used in various projects will be collected and stored to validate tests and to establish limits for acceptance. It is recognized that lab-prepared materials could be very different from field-prepared materials. Therefore an attempt will be made to store both finished products as well as components used in production. The following list presents the materials to be sampled in this subtask:

    a. Base asphalts used in emulsion production
    b. Emulsifiers
    c. Additives
    d. Aggregates and filers
    e. Polymers
    f. Field-produced samples for emulsions or mixtures

The properties of the sampled materials will be stored in the ARC Materials Reference Library following the ARC's established procedure for sample tracking and data storage.

v. Conduct Laboratory Evaluation Plan Developed in subject iii. The plan for evaluating "promising" testing methods developed in subject iii will be conducted in this subtask. The plan will include materials that are representatives of the range in formulations used in practice today and will cover applications that are widely used. The results collected will be analyzed using statistical methods to relate response measured on emulsions and aggregates with performance of mixtures or surface treatments. The relationship derived will be used to propose limits to be used for quality control.

vi. Develop Performance Guidelines for Emulsion and Aggregates that are Application Specific. Based on the results of subject v, guidelines for material selection and mixture design will be developed. These guidelines will build on the current manuals and design recommendations published by AEMA, Asphalt Institute, ISSA, and other international organizations. The attempt will be to revise and modify existing manuals and guidelines to include new or improved tests and design procedures.

vii. Field Validation of Guidelines and Criteria Limits. Field validation will start in Year 3 of this project. It will include implementation, on an experimental basis, of the test methods and design procedures that are developed in subjects v and vi.

viii. Cold Mix Asphalt Design. The many uses of cold mix technologies necessitate development of mix design procedures based on application and location within the pavement structure. Specifically volumetric mix design procedures will be developed for partial depth recycling, full depth recycling, and cold mix paving applications. Information gathered in parts i and ii of the study regarding the constructability and in-service performance properties of different emulsions and residual asphalts will be used as a baseline for developing mix design procedures. It is understood that the aggregate properties and how they affect the mixture-emulsion interaction play a significant role in the workability, and performance of the mix and must be considered.

Mix design procedures will be evaluated and refined through practical experience and volumetric mixture analysis. As stated previously, different mixture design procedures could be necessary for full depth recycling, partial depth recycling, and paving applications.

The performance of cold mixes for the previously specified applications will be evaluated in terms of rutting, fatigue, and low temperature cracking using existing test methods or those developed through the other work elements in the ARC. The research team will work closely with the other ARC partners to ensure the state of the art testing procedures will be used. The aim of this project is not to directly compare the performance of cold mixes to conventional HMA. Instead the focus will be on quantifying the functional or structural performance of cold mixtures and suggestion of practical applications based on this performance. A summary of the properties and parameters that could be considered in this subtask is shown in table E1c-2.1. It is recognized that the relevance of these properties and their importance could vary by mixture type and application intended.

ix. Develop Cold Mix Asphalt (CMA) Guidelines. In this part of the subtask a mixture design manual will be developed. The manual will include different types of mixtures as follows (n.b., this list is from one of the reviewers of the original work plan):

   a. Micro-surfacing (a mix design method is already being worked on by Caltrans)

b. CIR
c. FDR
d. Stockpile mixes (made with RAP or virgin aggregate)
e. Central plant CMA
f. Paver-produced CMA

The manual will include information for proportioning, testing of components and completed products, and construction guidelines.

Table E1c-2.1. Mix design evaluation parameters to be considered.

Engineering Property	Parameter(s) Measured	Comments
Emulsion Selection	Breaking Rate as measured by the change in tensile strength over time.	Results of Task 2 and consideration of the aggregate components in the mix and how the mix will be applied (base vs. surface course) will be used to define emuslsion selection crtieria.
Optimum Emulsified Asphalt Content	Aggregate Coating Workability Air Voids	Optimum emuslified asphalt content will be estimated based on aggregate gradation, absorption, and RAP content in the blend. Estimates will be verified through analysis of air voids and compactive effort as measured be the PDA.
Mixing and Compaction Conditions	Change in mixture workability/compaction over time and how it is effected by conditions.	Appropriate mixing chambers and evaluation parameters must be developed in order to understand the effects of temperature and humidity on mixture curing and how this can be accounted for in the field.
Establishment of Gradation Thresholds	Air Voids	Typical Superpave gradations may not apply to cold mixes due to the increased amount of space required to accommodate the emulsion. Gradation limits will be set through evaluation of mixing and compaction performance.
Definition of Gyration Levels and Density Thresholds	Air Voids	Discussion with industry indicated the Superpave gyration levels are too high for cold mixes. Application based gyration and density levels need to be developed and defined.
Restistance to Raveling	Raveling Test according to ASTM D7196	Proposed test will provide insight to rate of curing of the mix.
Moisture Damage	TSR as specified by ASTM D4867	TSR testing will be conducted on mixtures and compared to moisture damage results of binder and mastics collected in Task 2.
Aging	Laboratory for aging after specimen is cured	A mixture aging protocol must be established to simulate aging in the field after the CMA has cured. This will be used to evaluate inservice mix performance.

Major Findings from Year 1

During year one, the focus was put on collecting information on emulsions, surface treatments and cold mixtures. The process for information gathering involved a comprehensive literature search and review, visits and interview of experts in the United States and abroad, and attending various workshops or meeting related to the subject. These efforts have resulted in a concept paper in which a system of performance grading of emulsions is proposed. Also, a tentative list for performance measures has been established.

Two applications of cold asphalt technologies have been identified: Spray and mixing. Based on this concept two types of emulsion grades can be introduced as shown in table E1c-2.2. The types of application in which each of these two emulsion grades are used are listed as well.

Table E1c-2.2. Grades and applications of emulsified asphalts.

Grade	Application
Spray	Chip Seals
	Microsurfacing
	Crack Sealing
Mixing	Full Depth Recycling
	Partial Depth Recycling
	Asphalt Stabilized Base Course
	Paving Applications as a Binder or Surface Course

Based on the activities of subject i, the definition of physical properties of emulsions that are important to the design and construction of the various applications were developed and a tentative list is shown in table E1c-2.3. The definition of the parameter to be used and the proposed test methods to measure these properties are also summarized. The properties are divided into two categories: (1) construction properties, which cover emulsion characteristics related to the construction process, and (2) in-service properties, which are related to performance during traffic.

Table E1c-2.3. Summary of pertinent construction and in-service properties for surface treatments.

Engineering Property	Parameter(s) Measured	Comments
Construction Properties		
Storage Stability (ASTM D6930)	%Stability defined as the difference in residue at the top and bottom of the storage vessel after 24 hours.	Emulsions must remain homegenous and fluid during the transport and construction. Unstable emulsions will result in difficulties spraying, breaking, and wetting of aggregates.
Breaking Rate	Change in binder stiffness (G*) at a given temperature and curing time.	Inert, basic (limestone), and acidic (granite) fillers will be used to evaluate the effects of aggregate mineralogy on breaking rate. Temperature sensitivity will also be investigated.
Spray-ability and Drain Out	Viscosity	Binder must have an optimum range of viscosity which is low enough to allow for application and high enough to prevent drain out off the road.
Wetting of Aggregates	Adhesion	PATTI test will be used to evaluate the adhesion of different emulsion/aggregate combinations.
In-Service Properties		
Resistance to Bleeding	Creep Stiffness Early Adhesion	Binder stiffness and adhesion characteristics during emulsion curing may identify potential bleeding problems.
Restistance to Raveling	Residual Binder Cohesion Wet Adhesion of Residual asphalt to aggregate	Raveling is either caused by binder softness (lack of cohesion) or lack of adhesion. Proposed testing addresses both causes.
Fatigue Cracking	Creep Stiffness Estimated Rate of Creep Stiffness Elongation at Break	Excessive cracking will greatly increase the permeability of the surface treatment leading to premature failures.
Aging	Change in rheological properties due to short and long term aging.	The effects of aging on the performance of the residual binder must be understood and applied to design of surface treatments.

Year 2 Work Plan

During Year 2, subjects i, ii, and iii will be completed. The team will continue the literature review and will focus on collecting information on specifications and design practices from various countries for spray seals for cold mixtures. In addition, the international advisory group will be formed in coordination with AEMA. The evaluation of potential performance related tests for emulsions will also start and is expected to result in a short list of tests to be evaluated. Figure E1c-1.1 depicts the research approach defined for this work element.

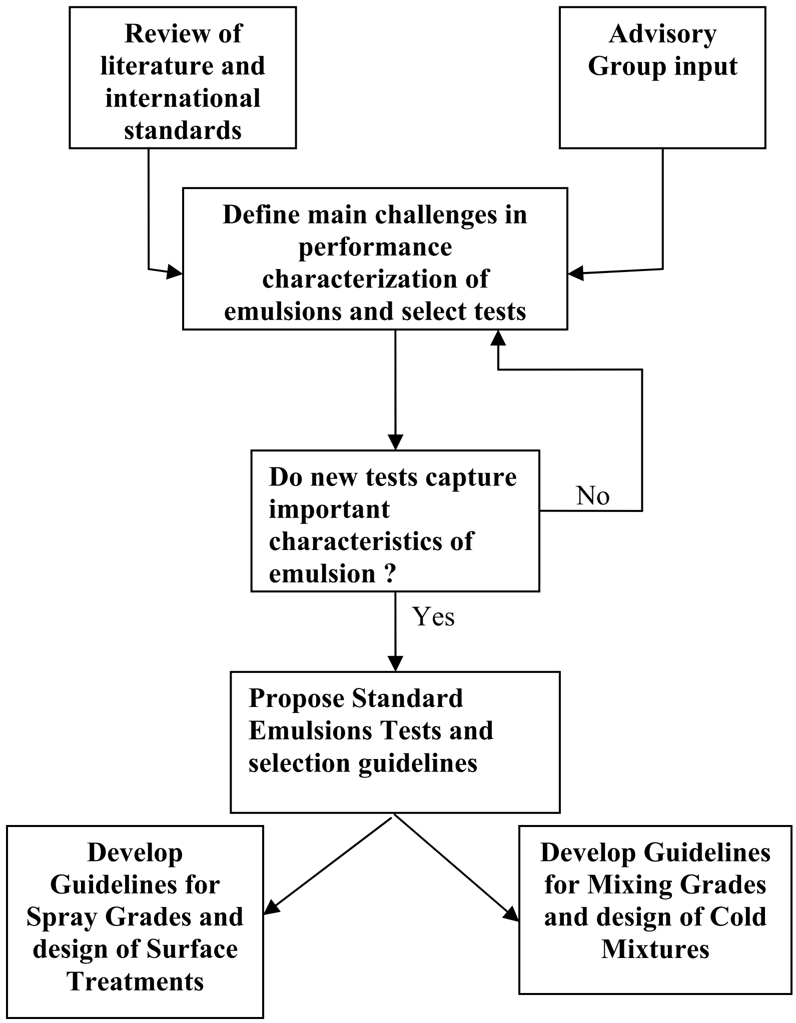


Figure E1c-2.1. Chart. Flow chart for research approach.

The tentative list of variables to be considered for testing of emulsions during year 2 are shown in table E1c-2.4. This list is based on significant discussions with experts in the field and review of many manuals and papers on the subject of emulsions. Initial contacts to secure samples of emulsions already used in the market has already started.

Table E1c-2.4. Variables to be considered in the testing of emulsions for this work plan.

Variables	Ranges
Emulsion - Rate of Setting	Slow
	Medium
	High
Emulsion - Viscosity	High
	Low
Emulsion - Charge	Cationic
	Anionic
	Inert
Asphalt Modification	SBS
	SBR
	Elvaloy
Base Asphalt	Source 1
	Source 2

Year 2 Milestones

- Complete report on review of literature and international practice for cold asphalt applications
- Identify advisory group members and hold the first two meetings
- Develop the short list of best tests for emulsions and generate typical data to evaluate feasibility and practicality of tests
- Develop a framework for emulsion selection and design of surface treatments

Budget

The estimated budget for this subtask is $350,000 (for UWM) and $ 255,000 (for UNR) over the five years. The work will be conducted by the University of Wisconsin-Madison and the University of Nevada-Reno.

Cited and Related References

Asphalt Institute, 1989, "Asphalt Cold Mix Manual," Asphalt Institute, Lexington, KY.

ASTM D3628, 2006, "Selection and Use of Emulsified Asphalts." *Annual Book of ASTM Standards*, American Society for Testing and Materials, Philadelphia, PA.

ASTM D4867, "Standard Test Method for Effect of Moisture on Asphalt Concrete Paving Mixtures." Annual Book of ASTM Standards, Vol. 04.03, American Society for Testing and Materials, Philadelphia, PA.

ASTM D7196, "Standard Test Method for Raveling of Col Mixed Bituminous Emulsion Samples." Annual Book of ASTM Standards, 2006, American Society for Testing and Materials, Philadelphia, PA.

Jenkins, K. J., A. A. A. Molenaar, J. L. A. de Groot, and M. F. C. van de Ven, 2002, Foamed Asphalt Produced Using Warmed Aggregates. Presented at the Association of Asphalt Paving Technologists, March 18-20, 2002, Colorado Springs, Colorado.

Category E2: Design Guidance

Work Element E2a: Comparison of Modification Techniques

Subtask Lead: Codrin Daranga

Introduction

A successful modification of an asphalt binder with a polymer is intended to improve one or more of the basic asphalt properties such as rigidity, elasticity, brittleness, durability, adhesion, and compatibility. Modification can be classified into three types: (1) chemical modification, such as oxidation and acid reaction; (2) additive modification, such as with polymers, crumb rubber, or other materials; and (3) a combination of chemical and additives. In all modification techniques compatibility of additives and base asphalt is very important. An asphalt-polymer blend is considered compatible if the polymer is soluble in the asphalt cement or if it can be swollen by the asphalt oils without causing flocculation of the asphaltenes. Most polymer modifiers are used to enhance the rutting resistance of asphalt binders. When it comes to the influence of modifiers on fatigue resistance and Low Temperature Cracking (LTC) resistance, some have a positive influence, while others can have a negative influence. It is to be expected that by adding more flexibility or strength (increase in toughness) to the binder, fatigue and LTC resistance will increase. If on the other hand the modifiers will stiffen the material at medium and low temperatures, then a decrease in fatigue and LTC resistance is expected. The morphology of the polymers used as modifiers, as well as their chemical structure and affinities play an important role on how the binder will perform in field applications. The flexibility of rubbers will bring toughness to the asphalt binder, possibly increasing its fatigue resistance. The hardness of waxes will improve rutting resistance properties. On the other hand, crystallinity promoted by rigid wax chains can diminish the fatigue life of asphalt binders and decrease their low temperature cracking resistance. Therefore a fine balance needs to be maintained between flexibility and stiffness, between elastic and plastic domains within the asphalt binder, between the affinity towards polar compounds (e.g. mineral aggregate) and moisture damage resistance, etc. In addition to initial properties, aging can have a significant impact on properties of binders. It is however not clear if aging has a negative effect on fatigue and LTC under all conditions of loading. For example, aging is expected to increase stiffness and strength but decrease ductility (flexibility).

In the current market, there is significant (30 – 100%) increase in cost of binders when they are modified. There are also significant implications in terms of handling and storage of modified binders. There are many concerns regarding the quality control methods, the level of improvements achieved and the alternatives available to meet the required performance. These concerns have intensified recently as acid modification is being used by many suppliers as a cost effective and extremely practical approach to meet some of the grades. There are also many suppliers that are using combined modification with polymers and acid and there are many claims regarding the benefits of such modifications. It is therefore necessary to provide realistic picture of what can be expected from modification in terms of better performance, what are the premature failure risks associated with some modifiers, and what are the necessary handling precautions, if any, that need to be considered.

Every modification technique and every modifier has its own set of advantages and disadvantages. Acid and air-blowing modification are less costly and requires very little or no modification to the binder handling installation that supplies the binder. Polymer modification can be more expensive, but the higher modification cost is usually balanced by better performance and longer service life. Non-reactive modifiers tend to be easier to incorporate, while reactive modifiers, especially reactive polymer modifiers, can add a reaction time needed to achieve its full potential. In short, the modification of asphalt binders can be as simple and inexpensive as air-blowing or as complicated as highly engineered reactive polymer modification in the presence of acids that can act as catalysts and/or take active part and change/influence the overall modification process.

This work element will focus on developing guidelines for best practice of selecting and handling modified asphalts. The selection criteria will include models for analysis of modification cost (including handling installation), risks of handling problems, and performance improvements. The cost The handling criteria will be based on short and long term stability of modified asphalts and their effect on the overall construction process.

Hypothesis

The hypothesis is that binder modification has a great impact on damage resistance properties of pavements. They also have significant cost and handling consequences when used. A fundamental understanding of how polymers interact with asphalt, and how aging and chemical modifiers control binder properties, can result in development of analysis models and guidelines to improve modifier selection process and to reduce risk of negatively impacting construction and performance of asphalt pavements.

Objectives

This four year study will focus on the following objectives:

(a) Identify the possible binder modification targets and the additives that could achieve these targets. The processes and methodologies to be used in order to achieve these targets will be left at the manufacturer's discretion.
(b) Test and compare different binders and modifiers in order to gauge and better understand the modifier's impact on binder properties.
(c) Develop models that allow estimation of level of modification and a costing index.

(d) Write an asphalt modification manual that includes possible modifiers and historical information about their use and performance, guidelines that allow conducting a cost-benefit analysis (with risk estimates) based on the additives main effects on binder properties, construction, and pavement performance.

Experimental Design

The work plan for this element includes manufacturer-prepared modified binders. Modifiers will be sought to provide both low and high levels of modification (one and two PG grade bumps). A minimum of three manufacturers will be solicited to provide materials so that three different modifiers at a minimum are included in this work plan.

The research team will recommend a base binder, but the ultimate binder selection will be at the manufacturer's discretion. In the event that a manufacturer decides to use a different base binder than the one recommended, the manufacturer will be asked to provide a sample of its selected base binder along with the modified materials.

Major Findings from Year 1

No work has been performed during year one. This work-plan starts during year 2.

Year 2 Work Plan

During Year 2 this work element was restructured after multiple discussions among consortium partners and experts. Table E2a.1 gives details of the revised experimental matrix. A request for materials letter will be sent out to several manufacturers asking for their participation in this project. Once the participation offers have been collected, the modified and base binder(s) will be collected. The high temperature, low temperature, and intermediate temperature properties will be investigated for all the binders (modified and unmodified) included in this work-plan. This will allow for classification and comparison of the different binder modifiers, the goal being to map the effect of modification on binders.

The modified binders will be subjected to storage stability test like the Cigar Tube Test and the Laboratory Asphalt Stability Test (LAST) in order to evaluate their homogeneity and storage capability.

Based on the feedback from the review group, the experimental plan of this work element was revised and adjusted to reflect recommendations of the group. The revised testing matrix is shown in table E2a.1.

Table E2a.1. Revised experimental matrix.

Binders (modified by suppliers)	SBS Modified	no modification (base binder)	Testing Matrix (In addition to PG grading and PG+ testing)	MSCR
		low level of modification (one PG grade bump over base)		G* and sinδ
		high level of modification (2-3 PG grades bump over base)		Frequency Sweep Master curve
	Elvaloy Modified	no modification (base binder)		SNEB/BBR
		low level of modification (one PG grade bump over base)		Fatigue (BYET)
		high level of modification (2-3 PG grades bump over base)		viscosity and phase angle (@mixing and compaction temp)
	Acid (PPA) Modified	no modification (base binder)	Storage stability and storage separation @ High Temperature	0 hours
		low level of modification (one PG grade bump over base)		24 hours
		high level of modification (2-3 PG grades bump over base)		72 hours
	EVA	no modification (base binder)	Adhesion Dry/wet	DSR – Tackiness with 2 aggregates
		low level of modification (one PG grade bump over base)	Cohesion Dry/wet	DSR- Tackiness with metal plate (full adhesion)
		high level of modification (2-3 PG grades bump over base)		
	Binary Modification (Polymer +PPA)	no modification (base binder)		
		low level of modification (one PG grade bump over base)		
		high level of modification (2-3 PG grades bump over base)		

As indicated earlier this work element will be focused on using materials provided by different manufacturers. Each manufacturer will be asked to provide three binders (unmodified, low level and high level of modification) as proposed in table E2a.1. The binders will be chosen and supplied by the respective manufacturers of the modified binders. The task will include four different modifiers (Elvaloy, SBS, EVA and acid PPA modifier). This will bring the total of different binders to 12 (4 unmodified, 4 with a low level of modification and 4 binders with a high level of modification). In addition suppliers will be asked to provide a set of binders modified with a binary system (polymer and acid). The exact percentages of the modifier to be used and the exact modifier type will be selected by the manufacturers. The suggested targets for the provided binders are:

- Unmodified (base) binder PG58-XX
- Low level of modification PG64-XX
- High Level of modification PG76-XX

Both modified and unmodified binders will be subjected to a battery of tests (see table E2a.1) in order to evaluate the Performance and Damage Resistance Properties of these materials. This will allow us to gain a better understanding of how different modifiers affect the performance of asphalt binders both in the lab and in service.

The data analysis in this project will be focused on three main areas: rheological properties, damage resistance characterization, and storage stability.

The rheological properties investigation serves as a tool to classify and rank starting materials, as well as a monitoring tool during the modification and conditioning process. This is accomplished by measuring parameters like $G^*/\sin\delta$, an indication of the rutting resistance of binders, as well as performing Multiple Stress Creep Recovery tests on the binders. Time sweep tests at different frequencies will provide the necessary information to built Master Curves, highlighting the impact of modification over a broader range of properties. Bending Beam Rheometer testing will shed light over the effect of modification on behavior in low temperature conditions. Important information will be provided this way on how the modification of binders affects their properties.

The damage resistance characterization part of the investigation will focus on classifying and ranking different modifiers and/or modification techniques based on their impact over the binder's ability to resist damage. This is focused on fatigue damage (Monotonic Test), rutting damage (MSCR Test), and low temperature (Single Edge Notched Beam Test) damage control tests to maintain perspective on monitoring the overall binder properties.

The storage stability will focus on handling and high temperature storage during the production of HMA.

Year 2 Milestones

- Complete the list of possible binder modification targets and the additives and processes that can be used to achieve each of the targets based on existing literature and interviews with experts in industry and in the user community.
- Develop a consortium for research and education on modified asphalts and invite suppliers to contribute to a center at the University of Wisconsin-Madison. This will be at no cost to the project and will be presented as a cost-share activity.
- As part of the center develop a user friendly database model for publications and ongoing research on modified asphalts.
- Develop a materials library for modifiers and invite suppliers of additive to add to share materials intended for this market.
- Collect the modified asphalts and start the testing of the most widely used additives in practice.

Overall Schedule

Activity	Year 1	Year 2	Year 3	Year 4	Year 5
i. Literature Review Report		X	X		
ii. Develop a New System for Classification and ranking of Additives		X	X		
iii Conduct Testing and Propose Models		X	X	X	
iv Write an Asphalt Modification Manual			X	X	X
v. Develop Database for Effect of Additives			X	X	X

Year 2 Schedule

Activity	Qtr 1	Qtr 2	Qtr 3	Qtr 4
i. Literature Review Report		X	X	X
ii. Develop a New System for Classification of Additives		X	X	X
iii Conduct Testing and Propose Models		X	X	X

Budget

The estimated budget for this subtask is $450,000 over the four years. The work will be conducted by the University of Wisconsin-Madison.

Cited and Related References

Alexander, S. H., 1973, "Method of Treating Asphalt," U.S. Patent #3,751,278, 1973.

Belgian Road Research Center, 1991, BRRC Experimental Procedure, MF 65/91, Brussels.

Burke R.E., and C. H. Whitacre, 1939, "Manufacture of Improved Asphalts", U.S. Patent, # 2,179,208.

De Filippis, P., C. Giavarini, and M. Scarsella, 1995, Improving the aging resistance of straight-run bitumens by addition of phosphorus compounds. *Fuel*, 74(6): 836-841.

De Filippis, P., C. Giavarini, and M. Scarsella, 1996, An Integrated Process for Stabilization and Upgrading of Residues and Bitumens. *Fuel Science and Technology Int'l*, 14(6): 821-838.

Giavarini, C., D. Mastrofini, and M. Scarsella, 2000, Macrostructure and Rheological Properties of Chemically Modified Residues and Bitumens. *Energy & Fuels*, 14: 495-502.

Orange, G., D. Dupuis, J. V. Martin, F. Farcas, C. Such, and B. Marcant, 2004a, Chemical Modification of Bitumen through Polyphosphoric Acid: Properties – Microstructure Relationship. 3rd Eurasphalt Eurobitume Congress, Book I, Vienna, Austria, pp. 733-745.

Orange, G., J. V. Martin, A. Menapace, M. Hemsley, and G. L. Baumgardner, 2004b, Rutting and Moisture Resistance of Asphalt Mixtures Containing Polymer and Poly-phosphoric Acid Modified Bitumen. *Road Materials and Pavement Design*, 5(3): 323-354.

Work element E2b: Design System for HMA Containing a High Percentage of RAP Material

Work Element Lead: Peter Sebaaly (UNR), Scot Schwandt (UW-M)

Introduction

Reclaimed asphalt pavement (RAP) is produced either by cold planning (CP) or by heating/softening and removal of the existing aged asphalt pavement. Recycling of the aged pavement has become more popular since the late 1970's although it had been practiced as early as 1915. The escalation of crude oil prices as well as cost of energy in general are expected to result in increased prices of asphalts which in turn raises the interest in the use of RAP in pavements. Furthermore, several studies showed that asphalt mixtures containing RAP can have equivalent performance to virgin mixtures. Hence, many agencies and contractors have made extensive use of RAP in constructing highway.

The overall goal of the mix design process of hot mixed asphalt (HMA) is to recommend a mix that can withstand the combined actions of traffic and environment. Therefore, it is critical to assess the impact of the various mix components on the performance of the constructed pavement (i.e. resistance to rutting, fatigue, and thermal cracking). The existence of RAP in the mix presents a challenge to the design engineer due to the complex interaction among the new and recycled components of the mix. The inclusion of RAP materials in the HMA mix can improve its resistance to rutting while it may greatly jeopardize its resistance to fatigue and thermal cracking. The key to successfully include RAP in the HMA mix is to be able to assess its impact on pavement's performance while recognizing the uniqueness of each project with respect to both materials and loading conditions.

One of the main concerns in RAP HMA mixtures is the effect of the RAP material on the mixture durability. Moisture susceptibility is regarded as the main cause of poor mixture durability. Moisture susceptibility can be evaluated by performing laboratory tests on unconditioned and moisture conditioned specimens. However, two recent research studies did not support the concerns over the durability of RAP containing HMA mixtures. Stroup-Gardner and Wagner (1999) showed that the inclusion of coarse RAP decreased the moisture susceptibility of HMA mixtures. In 2000, Sondag used the tensile strength ratio to evaluate the moisture sensitivity of 18 different mix designs incorporating three different asphalt binders, two sources of RAP and varying amounts of RAP. Sondag concluded that the addition of RAP to a mixture had no positive or negative influence on the mixture moisture susceptibility. In 2007, Hajj et al. concluded that if the appropriate virgin binder grade and anti-strip additive are used, the moisture sensitivity of the RAP containing HMA mixtures can be greatly reduced.

The properties of RAP are largely dependent on the properties of the constituent materials (i.e. aggregate type, quality and size, extracted binder grade, etc.). The RAP composition is also affected by the previous maintenance and preservation activities that were applied to the existing pavement. Additionally, sometimes RAPs from several projects are mixed in a single stockpile where deleterious materials or lower quality materials are also present. Consequently, a high variability is introduced in the RAP materials affecting the RAP properties and most likely resulting in a variable HMA mixture. Using low quality and/or highly variable RAP materials will definitely lead to premature failure of the HMA pavement.

The RAP percentage in the mixture significantly affects the properties of the HMA mixture. Several highway agencies have their own specifications on RAP usage in HMA mixtures. Currently, a total of 35 highway agencies allow the use of RAP with the majority allowing in excess of 30 percent RAP in HMA mixes (Sebaaly & Shrestha 2004). Some highway agencies do not specify a maximum limit on the percentage of RAP but leave it up to the mix design process to identify the maximum allowable percentage of RAP. Several highway agencies restrict the use of RAP to the layer underneath the wearing course.

Relationship to FHWA Focus Areas

This research effort fits under the FHWA Focus Areas of Optimize Pavement Performance and Environmental Stewardship.

Hypothesis

The use of RAP materials in HMA can be highly beneficial from both the economical and long-term performance aspects if the appropriate testing and analysis procedures are used to design the final mixtures.

Objectives

The overall objective of this research effort is to develop testing and analysis procedures that can be effectively used to evaluate RAP materials and optimize the performance of HMA mixtures containing RAP materials. The research effort will cover the various aspects of the design process starting with the evaluation of the RAP materials (binders and aggregates) through the mix design process and the performance evaluation of the final HMA mixture containing RAP materials.

Experimental Design

The following subtasks will be completed in order to achieve the objectives of this research effort.

Subtask E2b-1: Develop a System to Evaluate the Properties of RAP Materials

Evaluating the RAP materials consists of measuring the properties of the binder and aggregates of the reclaimed mix. Several research studies have been conducted to identify the best methods for separating and testing the binder and aggregates of the RAP materials but there have not been any standard procedures that agencies can use on a routine basis.

In the case of the binder in the RAP, the two critical properties are: binder content and binder properties. The binder content of the RAP can be easily identified through the extraction process. However, measuring the properties of the binder is still a complex process. Extracting and recovering the asphalt binder from the RAP materials faces the fundamental issues of the impact of the extraction/recovery process on the properties of the recovered binder and the health/environmental impact of the chemicals used in the process. These issues become very difficult to resolve when polymer-modified or crumb rubber modified binders are present in the RAP materials.

This subtask will review the previous research work on the development of an effective system to test the properties of asphalt binders from RAP materials. The review will focus on considering one or more of the following alternatives:

1. If a binder extraction/recovery system that is feasible, environmentally safe, and practical exists, or could be developed, it will be developed and standardized.
2. If such a system does not exist and the potential of developing it is not likely, a separation technique of the mortar from the RAP, without using solvents, will be pursued. A method for estimating RAP binder properties from the mortar deploying the technology currently used in binder testing will be developed.
3. If mortar separation and testing is too complex and not likely to be successful, a RAP mixture testing system will be developed instead.

In the case of the aggregates in the RAP, the two critical properties are: gradation and specific gravity. The gradation of the aggregates in the RAP materials can be easily evaluated through the extraction process. Determining the specific gravity of the RAP aggregates represents a challenge. Several techniques have been used in the past but there is not an accepted standard procedure. This subtask will identify a standard method for measuring the specific gravity of RAP aggregate and develop a standard procedure.

An experimental plan was developed to cover the activities to be conducted under Subtask E2b-1. The objective of this subtask is to develop systems to evaluate the properties of the aggregates and binders in the RAP materials. Two experiments will be conducted: one experiment to recommend a system to evaluate the properties of the RAP aggregates and one experiment to recommend a system to evaluate the properties of the RAP binder.

E2b-1.a: Develop a System to Evaluate the Properties of RAP Aggregates: The objective of this experiment is to recommend a system to evaluate the properties of the RAP aggregates. In order to recommend the most effective system, it is critical to evaluate the impact of the current extraction techniques on the properties of the extracted RAP aggregates. This objective will be achieved by producing RAP mixtures in the laboratory and extracting the aggregates using different extraction techniques. The physical properties of the aggregates before mixing with the asphalt binder and after the extraction process will be evaluated and compared.

Three existing extraction methods will be evaluated under this experiment: centrifuge, reflux, and ignition oven. It is believed that the reflux method had the least impact on the properties of the aggregates after extraction however this was never verified. The proposed experimental plan consists of the following:

- Identify four aggregate sources with different mineralogy (i.e., soft limestone, hard limestone, granite, andesite). Select two sources from the east and two sources from the west of the U.S.
- UNR will identify and evaluate the aggregate sources from the west and NCAT will identify and evaluate the aggregate sources form the east.
- UNR will identify one binder to be used with the two aggregate sources from the west and NCAT will identify one binder to be used with the two aggregate sources from the east. Both binders will be graded following the PG system.
- For each combination of aggregate source and binder, conduct the experiment listed below. UNR will evaluate the two west sources and NCAT will evaluate the two east sources.
    - Develop an intermediate Superpave gradation for each of the aggregate sources.
    - Measure the physical properties of the blend aggregates: gradation, LA abrasion, soundness, absorption, specific gravity, fine aggregate angularity (FAA), coarse aggregate angularity (CAA), fractured faces, sand equivalent, and durability index.
    - Conduct a Superpave mix design for each combination of aggregate source and binder based on 6 millions ESALs for a top lift.
    - For each mixture, subject loose samples to the short-term aging as recommended by Superpave followed by long-term aging as recommended by the Superpave for compacted samples with the exception that the loose samples should be stirred once a day.
    - Extract the aggregates from the aged loose specimens using the centrifuge, reflux, and ignition oven following the most current standard procedures. Use an 85 percentTCE+15 percent Ethanol solution for the reflux and centrifuge methods.
    - Measure the same physical properties of the extracted aggregates that were measured on the virgin aggregates.
    - Evaluate the impact of the extraction method on the physical properties of the aggregates by comparing the measured properties of the aggregates before and after extraction.
    - Conduct the following experiment to evaluate the impact of reflux and centrifuge on the properties of the recovered binder.
        - Prepare two replicate samples from each mix without any aging.
        - Recover the asphalt binder from the centrifuge and the reflux methods using the Rotovap method.

- Grade the recovered asphalt binders according to the Superpave grading system and the guidelines provided by the NCHRP Research Results Digest No. 253.
- Compare the properties of the recovered binders from the two extraction methods to their original properties.

E2b-1.b: Develop a System to Evaluate the Properties of the RAP Binder: The amount and properties of the aged binder in the RAP material determines the amount and grade of the virgin asphalt that needs to be added to the new mixture containing the RAP. The researchers strongly believe that the process of extracting and recovering the RAP binder followed by determining its PG grade and using it in the blending chart to identify the required grade of the virgin binder is not a very reliable/practical method for the design of HMA mixtures containing RAP materials.

The objective of this subtask is to identify an innovative system that can evaluate the impact of the RAP binder on the required properties of the virgin binder without resorting to the extraction-recovery process. The proposed research approach is based on the assumption that evaluating the mortar portion of the RAP material can lead to valuable information on the properties of the RAP binder and on the interaction between the RAP binder and the virgin binder in the final blended mix. Fractionating the RAP material at the #8 sieve and using the passing #8 fraction (i.e. mortar) to evaluate the properties of the RAP binder provides an accurate asphalt blending analysis. It also allows a more accurate representation of the blending that occurs between aged and virgin binders. The amount of virgin asphalt that needs to be added to RAP containing mixes without affecting grade requirements could also be estimated.

The properties of the RAP binder can be evaluated at high and low temperatures using voidless asphalt mortar samples that includes passing #8 RAP and virgin binders. The objective is to develop a testing protocol that evaluates the high and low temperature properties of the RAP mortar by using a modified Bending Beam Rheometer (BBR) test method and/or Dynamic Shear Rheometer (DSR). This testing protocol will be used to determine the affect that the RAP aggregate has on the RAP mortar properties, and will also determine the linear relationship between virgin binder grade and measured property compared to various RAP mortar mixtures and their measured property.

The following experimental plan will be followed:

Materials

- Identify four different RAP sources:

  Modified-Stiff: AAT from the DC area
  Modified-Very Stiff: UNR from Nevada
  Unmodified-Stiff: NCAT from the Southeast
  Unmodified-Very Stiff: UNR from Palm Springs California

- Extract and recover the binders from the RAP mixtures (UNR).
- Grade the recovered RAP binders according to the Superpave grading system and the guidelines provided by the NCHRP Research Results Digest No. 253 (UNR).

- Select three virgin binders grades:

  PG64-22: UNR from Paramount
  PG64-28: NCAT unmodified from CITGO
  PG58-34: UWM from Wisconsin

- Verify the grade of all three selected binders.
- Sieve the RAP mixtures on the #8 sieve. The material passing #8 sieve will be referred to as RAP(-#8) or mortar and will be used for further testing.

Evaluation 1: Evaluate the Mortar with 100 percent Virgin Binders

- For each source, extract the RAP aggregates from the RAP(-#8) mortar according to the procedure identified in E2b-1.a with the least impact on the aggregate properties.
- Determine the RAP(-#8) mortar binder content for each RAP source material.
- Mix the extracted RAP aggregates with each of the three selected virgin binders to produce a virgin mortar material at a10 percent twm binder content.
- Measure the high temperature and low temperature properties of the virgin mortar mixtures in the BBR and/or DSR (actual tests to be recommended by UNR and UWM).

Evaluation 2: Evaluate the Mortar with Blended Binders

- Mix the RAP(-#8) mortar with each of the three selected virgin binders at a 10 percent twm binder content.
- Measure the high temperature and low temperature properties of the virgin mortar mixtures in the BBR and/or DSR (actual tests to be recommended by UNR and UWM).
- Extract and recover the RAP+virgin binders from the mortar materials.
- Grade the recovered asphalt binder according to the Superpave grading system.

Evaluation 3: Evaluate the Binder Grade of the RAP Mixtures

- Compact replicate samples from each of the four RAP sources in the Superpave Gyratory Compactor (SGC) to 4 percent air-voids.
- Measure the volumetric properties of the samples compacted in the SGC.
- Measure the E* Master curves for all mixtures and use the Hirsch model to estimate the properties of the RAP binder.

<u>Subtask E2b-2: Compatibility of RAP and Virgin Binders</u>

The compatibility between the RAP and virgin binders is a significant factor for the long-term performance and durability of the HMA mixture containing the RAP materials. There are chemical as well as rheological tests that can estimate the compatibility of binders. One of the possible simple compatibility tests is the measurement of viscosity of the blended binder. Also evaluation of G* and Phase angle could be used to measure compatibility. The expectation is that G* of blended binders should be in between the values of the virgin and the RAP binders. In most cases a linear relationship between log G* and percent virgin binder is found for compatible binders. A significant deviation from the linear relationship could be an indication of incompatibility. These ideas and others could be used in this subtask to develop a simple and practical test for compatibility.

The compatibility of RAP binders and virgin binders can also be measured by using Automated Flocculation Titrimetry (AFT) and Atomic Force Microscopy (AFM). The AFT measurements can be made on various blends of RAP binder and virgin binder and basically evaluate the solubility characteristics of the materials. The AFT measurements will be coordinated and correlated with the rheological measurements. The AFM can be used to investigate the compatibility of the blended binders on a nanoscale. Recent developments in AFM research have revealed important aspects of asphalt behavior upon thermal cycling that can be applied to RAP and virgin blended binders.

The compatibility of RAP and virgin binders, both rheological and chemical, will consider the actual blending of the binders that takes place in hot-mix plants by comparing laboratory blending samples with samples of RAP mix obtained from hot-mix plants. WRI will work on evaluation of a chemical-based test while UNR and UW will share responsibility of developing a rheology-based test for compatibility.

An experimental plan was developed to cover the activities to be conducted under Subtask E2b-2. The objective of this subtask is to develop a test that is capable of evaluating the degree of compatibility between the RAP binder and the virgin binder.

- Three levels of compatibility might be present in HMA mixtures with RAP material:
    - Chemical and physical compatibility between RAP binder and virgin binder: use always.
    - Chemical and physical incompatibility between RAP binder and virgin binder: do not use at anytime.
    - Chemical incompatibility but physical compatibility between RAP binder and virgin binder: use with caution on long-term durability.
- WRI researchers will work with a team of industry experts to identify materials that fit the three classes of compatibility identified above.
- WRI researchers will obtain samples from the identified sources.
- WRI researchers will develop a chemical test that is capable of identifying the three types of compatibility/incompatibility of HMA mixtures containing RAP.

<u>Subtask E2b-3: Develop a Mix Design Procedure</u>

This subtask will concentrate on developing a mix design procedure for HMA mixtures containing RAP materials. The mix design procedure will follow the Superpave Volumetric Mix Design Method. It is anticipated that some changes will have to be made to the Superpave method to account for factors such as: mixing and compaction temperatures and the number of gyrations, etc. This subtask will obtain RAP materials from 10 different sources to cover a wide range of pavement age, environmental conditions, and material sources. These sources will be used to develop a standard mix design method that is applicable to HMA mixtures containing RAP materials at various levels of 15, 30 and 45 percent.

The mix design method will use the recommendations of Subtasks E2b-1 and E2b-2 in terms of the appropriate methods to evaluate the binder and aggregates in the RAP materials and assessing the compatibility between the virgin and RAP binders. The final product of this subtask will be a complete mix design system for HMA mixtures containing RAP materials that includes the following components:

- A process to evaluate the properties of the RAP binder
- A process to measure the specific gravity of the RAP aggregate
- A process to identify the appropriate mixing and compaction temperatures
- Recommendations for the number of gyrations
- Mix design criteria

<u>Subtask E2b-4: Impact of RAP Materials on Performance of Mixtures</u>

This subtask will evaluate the impact of RAP materials on the performance of the final mix in terms of fundamental properties and resistance to distresses. In order for HMA mixtures containing RAP materials to be widely accepted, the agencies should be able to evaluate their fundamental properties and their potential long-term performance. In other words the agencies need to be able to input the fundamental properties of the RAP mixtures into the AASHTO MEPDG and use the appropriate performance models to conduct the final structural design.

This subtask will conduct an experimental program to evaluate the fundamental properties and resistance to distresses of the RAP mixtures that were used and designed in Subtask E2b-3 using the following technologies:

- Evaluate the dynamic modulus master curves of short-term and long-term aged mixtures
- Evaluate the resistance of the short-term and long-term aged mixtures using the tests recommended by the Consortium research on moisture damage
- Evaluate the resistance to rutting using the repeated load triaxial test on short-term aged mixtures
- Evaluate the resistance to fatigue using the flexural beam fatigue test on long-term aged mixtures and/or the tests recommended by the Consortium research on fatigue
- Evaluate the resistance to thermal cracking using the thermal stress restrained specimen test on long-term aged mixtures and/or the tests recommended by the Consortium research on thermal cracking

The final product of this subtask will be a database of the fundamental properties and performance characteristics of HMA mixtures containing RAP materials from 10 different sources at four levels of RAP contents of 0, 15, 30, and 45 percent.

Subtask E2b-5: Field Trials

This subtask will conduct field trials of the developed system. In cooperation with Granite Construction Inc. and state highway agencies, field test sections will be produced and constructed following the system developed in this research. During the construction of the field test sections, the plant produced HMA mixtures containing RAP materials will be evaluated in terms of their properties and performance characteristics (i.e. rutting, fatigue, and thermal cracking) following the systems developed in the previous subtasks.

The long-term performance of the field test sections will be monitored in cooperation with the state highway agencies and the data will be used to validate the design and evaluation systems developed in this research.

During the construction of the field trials, data will also be collected to achieve two additional goals: RAP source acceptance and RAP source variability. It will be unrealistic to expect the agencies to conduct rutting, fatigue, and thermal cracking tests on each RAP source. This subtask will attempt to develop an acceptance guideline based on simple tests either on the entire RAP mix or on RAP components. This subtask will also identify the tests to be used to assess the variability of the RAP stockpiles. The potential tests for measuring the variability of the RAP stockpiles will have to be practical and reliable.

An experimental plan was developed to cover the activities to be conducted under Subtask E2b-5. The objective of this subtask is to early evaluate the field performance of HMA mixtures with 40 percent RAP material designed without changing the binder grade and with the appropriately changed binder grade.

- Construct field test sections at five different locations in the U.S.
  - Palm Springs, CA: Granite Construction
  - West Texas, TX: Granite Construction
  - Alabama or Florida: NCAT
  - Wisconsin or Minnesota: UWM
- It is desired to have field projects at the above locations that include 40 percent RAP materials in two test sections:
  - One test section with 40 percent RAP using the same binder grade for the project
  - One test section with 40 percent RAP using the appropriately changed binder grade
  - Each test section will consist of 500 tons of mix (i.e. one transport of 20 tons binder).

- UNR and NCAT will provide support for the design and evaluation of the mixtures.

Major Findings from Year 1

The Year 1 activities of this work element concentrated on the following areas:

- Conduct a literature review on the evaluation and performance of RAP mixtures
- Develop experimental plans
- Identify and obtain materials for the various experiments
- Conduct laboratory evaluations

Literature Review: The literature review covered the evaluation and performance of RAP mixtures throughout the U.S. It covered the various efforts that have been conducted to evaluate the properties of RAP materials (i.e. aggregates and binders) and the various laboratory tests that have been used to evaluate the properties of the RAP containing mixtures. The literature review is still in progress and it is planned to be completed toward the middle of Year 2.

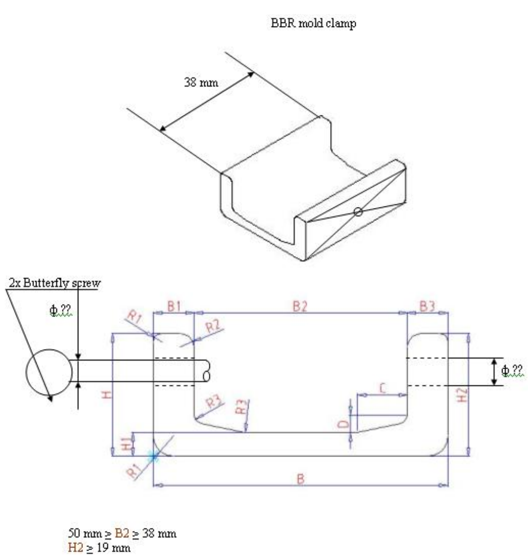
Experimental Plans: Experimental plans were developed to cover the activities to be conducted under Subtasks E2b-1, E2b-2, and E2b-5. The plans have been described under the individual subtasks in the previous sections.

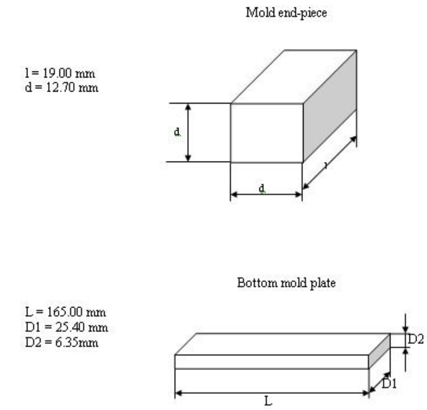
Identify Materials: The following RAP sources were identified and sampled in Year 1.

- One RAP source from South Carolina that fits the category of unmodified-stiff.
- One RAP source from Southern California that fits the category of unmodified-very stiff.

Conduct Laboratory Evaluations: Two laboratory evaluations were conducted during Year 1: Evaluation 1 assessed the feasibility of using the BBR for testing passing #8 RAP mortar and Evaluation 2 assessed the feasibility of using 40 percent RAP without changing the binder grade.

Evaluation 1: In an effort to identify the feasibility of using the BBR for testing RAP mortars, samples were prepared composed of RAP (-#8) material and virgin binder. BBR beam specimens were a challenge to make using the RAP mortar. The -#8 aggregate in the mortar was too large for the standard BBR beam specimen dimensions. Modification of the BBR beam specimen dimensions were made by reconfiguring the standard BBR mold pieces to create a specimen with end cross-sectional dimensions of ~12.7mm x 12.7mm. This configuration involved using 3 of the standard bottom mold pieces and 4 standard mold end pieces. BBR beam specimens were successfully produced using this mold arrangement, which led to the development of a modified BBR beam specimen mold. The following is the mold shop drawings and also a picture of the finished product.





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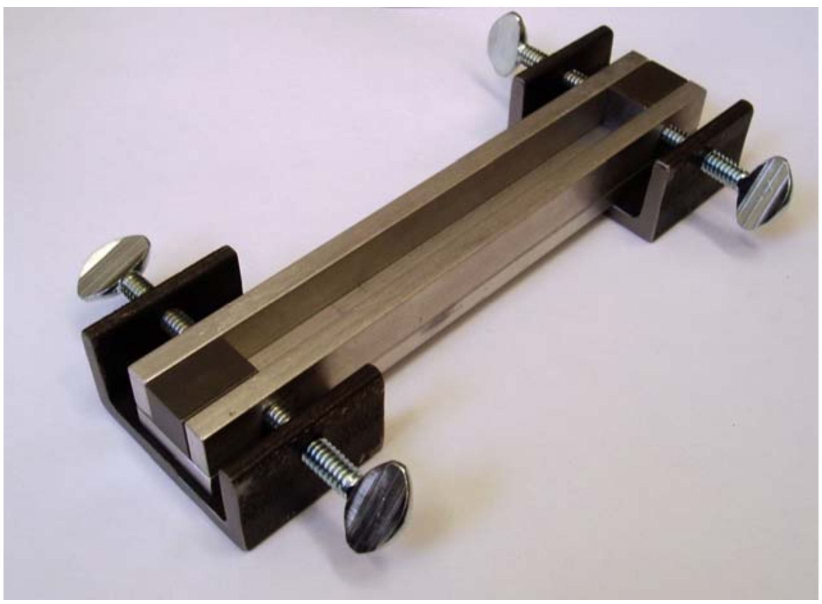
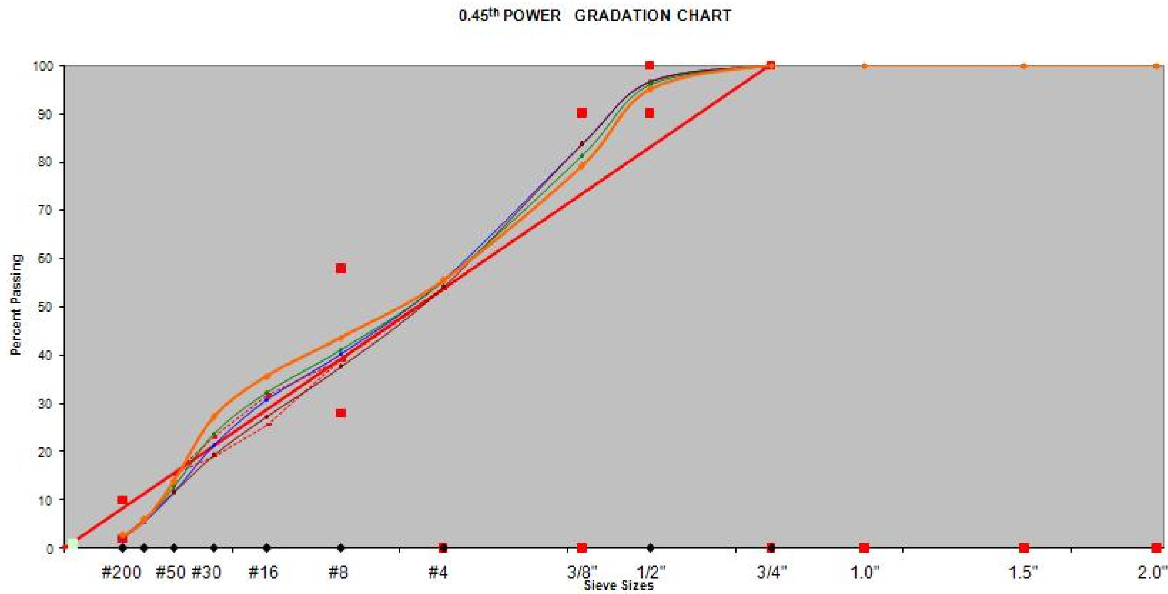


Evaluation 2: Using a single Wisconsin HMA plant aggregate source, three comparable HMA mixtures were developed that meet WisDOT 12.5 mm E-3 mix design specifications. The four aggregate mixture components were: a 5/8" granite rock, manufactured sand, a natural sand and RAP. The three mixtures that were developed were a "Virgin", 20 percent RAP, and 40 percent RAP. Using the same aggregates and blending the mixes so that the final mixture gradations were similar allowed the three mixes to be evaluated based on the percentage of RAP that was incorporated into the mix. The following graphic shows the mixture gradation of the three mixes.



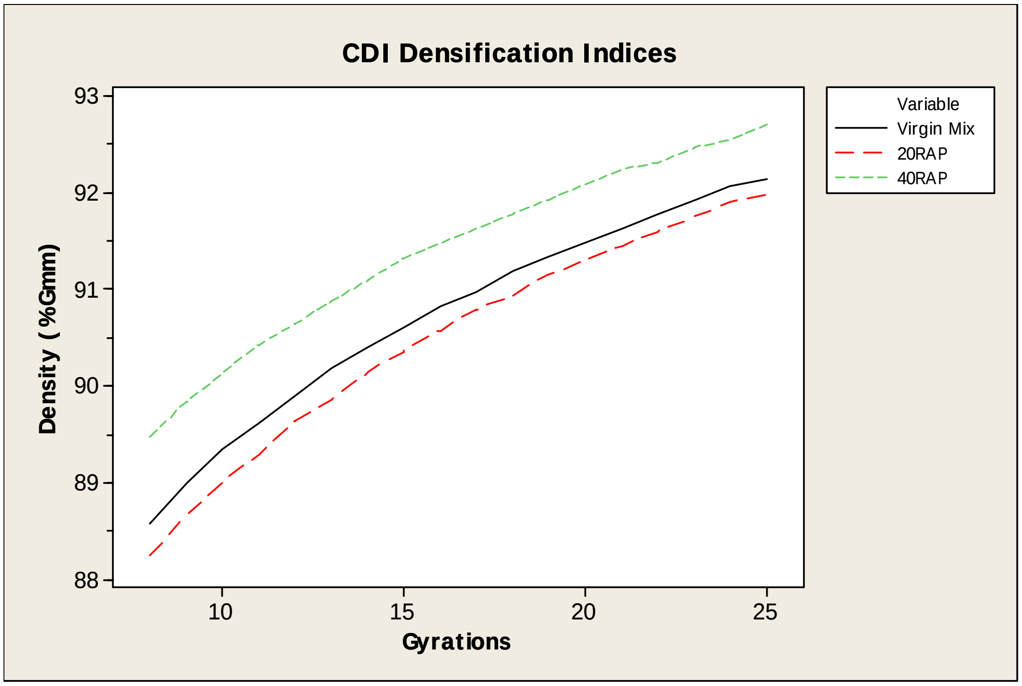
All of the mixtures met WisDOT specifications for an E-3 Superpave mix, showing that it is possible to make a HMA mixture with 40 percent RAP content. The same virgin binder (PG58-28) was used for all three mixes, e.g. no binder grade adjustments for the RAP mixes. After completion of the mix designs, test specimens were made so that the three mixtures could be evaluated based upon moisture damage testing (AASHTO T-283), Superpave gyratory compactor (SGC) compaction data analysis (CDI and TDI), and a low temperature indirect tension testing. The following are the results from the moisture damage testing:

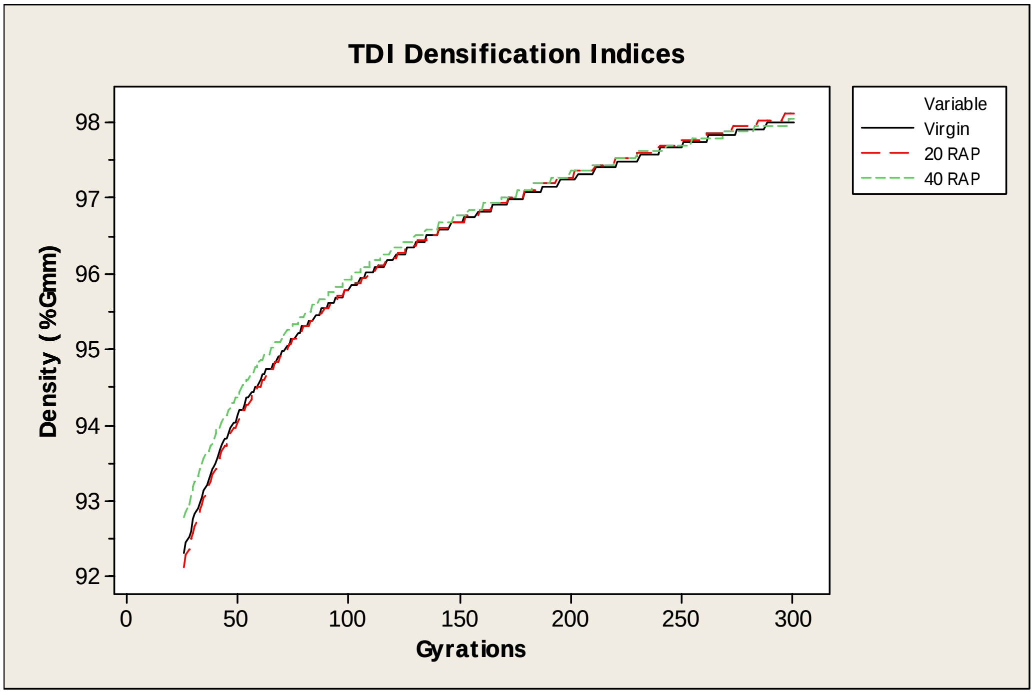
Moisture Damage Analysis

Specimen	Condition	t	D	P	S_t	TSR
Virgin 1	wet	4.83	6	8350	183	
Virgin 2	wet	4.82	6	8900	196	
Virgin 3	dry	4.79	6	8700	193	
Virgin 4	dry	4.79	6	9300	206	95.14
20% RAP a	wet	4.67	6	9600	218	
20% RAP b	wet	4.79	6	8800	195	
20% RAP c	dry	4.72	6	9900	223	
20% RAP d	dry	4.75	6	9350	209	95.74
40% RAP a	wet	4.64	6	8800	201	
40% RAP b	wet	4.66	6	8800	200	
40% RAP c	dry	4.74	6	9200	206	
40% RAP d	dry	4.72	6	9300	209	96.77

This testing shows that all of the mixes pass the moisture damage specification requirements, but also that there is no significant difference between the mixtures.

The next set of testing utilized the SGC compaction data by analyzing it to compute the compaction densification index (CDI) and the traffic densification index (TDI). This analysis can be done graphically by comparing the SGC compaction curves over the appropriate gyration intervals. The following graphics show the results of the CDI and TDI analysis respectively.





The CDI graphic shows that the area under the 40 percent RAP curve is the largest, indicating that it would be the most difficult to compact and work with during the paving process. The 20 percent RAP and Virgin mixtures are fairly similar, indicating that it would probably be difficult to distinguish between the two mixes in the field. The TDI graphic shows that the area under the 40 percent RAP curve is slightly larger, indicating that it would be the most resistant to traffic rutting. The SGC compaction data analysis indicates that HMA mixtures with higher amounts of RAP tend to be stiffer than comparable virgin mixes.

A final mixture performance test was conducted on the three mixes. The test involved freezing the test specimens to 0°C for 12 hours and testing their tensile strength using an indirect tension test. The results of the testing are as follows:

Low Temperature IDT Analysis					
Specimen	t	D	P	S_t	Avg S_t
Virgin 1	4.65	6	6700	153	
Virgin 2	4.68	6	8100	184	168
20% RAP 1	4.67	6	8300	189	
20% RAP 2	4.64	6	7300	167	178
40% RAP 1	4.54	6	8300	194	
40% RAP 2	4.6	6	7900	182	188

These testing results indicate that all three mixtures exhibit statistically similar tensile strength properties at 0°C temperature.

In summary, the findings from the initial mix design and mixture performance testing that was done indicate that the use of high percentages (up to 40%) of RAP without changing the PG grade of the virgin binder does not appear to have detrimental effects on the performance of the HMA mixture in resisting moisture damage and thermal cracking. However, two facts must be noted on this evaluation: (1) the RAP is from Wisconsin which may not be highly aged, and (2) the fatigue resistance of these mixtures will have to be evaluated.

A cost analysis using these mix designs was also done to identify potential HMA mix material cost savings by utilizing RAP. The costs used in this analysis are representative for Wisconsin at the time of the analysis and are summarized below:

Mixture	Rock	Man Sand	Natural Sand	RAP	Mixture Aggregate Cost	Mixture %AC	Virgin %AC Added	Total Mixture Cost
Virgin	25%	65%	10%	0%	$6.85	4.8%	4.8%	$23.65
20% RAP	25%	50%	5%	20%	$6.35	4.7%	3.9%	$20.00
40% RAP	25%	30%	5%	40%	$5.65	3.8%	2.2%	$13.35

As the table indicates, there is ~15 percent cost savings between the 20 percent RAP and the Virgin mixture mainly due to a 0.9 percent reduction in virgin asphalt usage. However, a 40 percent RAP mixture was able to be designed with similar mixture volumetrics as the virgin mix by using 2.6 percent less virgin asphalt than the virgin mix. This results in an overall savings of ~43 percent per ton of mixture produced using a virgin asphalt price of $350 per ton. The aggregate savings accounts for ~12 percent of the total ~43 percent cost savings.

Year 2 Work Plan

During Year 2, the research team will continue the literature review, continue the laboratory evaluation of the RAP materials, and obtain materials from the various RAP sources. UNR, UW-M, and AAT researchers will work on developing a laboratory test method to evaluate the properties of RAP binder without resorting to the extraction and recovery process of the asphalt binder from the RAP materials. As indicated in the experimental plan, this objective will be achieved by evaluating the properties of the mortar portion or the full RAP material and using these properties to identify the properties of the RAP binder.

During Year 2, the UNR and NCAT researchers will identify the most reliable method of evaluating the properties of RAP aggregates. The three commonly used techniques of extracting the aggregates from the RAP materials will be evaluated and the one that induces the least impact to the properties of the aggregates will be recommended.

WRI researchers will work on developing a system to identify the compatibility between the virgin and RAP binders. Also in Year 2, the field trial projects will be identified.

The work on the mix design procedure for HMA mixtures containing high RAP contents will start in the third quarter of Year 2.

The ARC research on RAP mixtures will be coordinated with the NCHRP project: 09-46: Improved Mix design, Evaluation, and Materials Management Practices for Hot Mix Asphalt with High Reclaimed Asphalt Pavement Content. The ARC lead researcher (P.E. Sebaaly) is an observing member of the NCHRP Project Panel D09-46 and will share the findings of the ARC research activities.

Year 2 Milestones

The following milestones will be realized in Year 2:

- Identify a system to evaluate the properties of RAP binder
- Identify a system to evaluate the properties of RAP aggregates
- Identify a system to assess the compatibility between virgin and RAP binders

Budget

The estimated budget for this work element is $1,730,000 over the five years. The work will be conducted by the University of Nevada, University of Wisconsin-Madison, Western Research Institute, Advanced Asphalt Technologies, Granite Construction (Cost Share), National Center for Asphalt Technology, and the Wisconsin Asphalt Pavement Association (Cost Share).

Cited and Related References

Bonaquist, R., 2007, Can I Run More RAP? National Asphalt Pavement Association. *HMAT*, 12(5).

Carter, A., and M. Stroup-Gardiner, 2007, Indirect Tension Relaxation Test to Evaluate the Effect of the Addition of RAP to HMA Mixes. American Society of Civil Engineers. *Journal of Materials in Civil Engineering*, 19(3).

Hajj, E.Y., P.E. Sebaaly, and R. Shrestha, 2007, A Laboratory Evaluation on the Use of Recycled Asphalt Pavements in HMA Mixtures. Western Regional Superpave Center, University of Nevada, Reno, Final Report.

Huang, B., G. Li, D. Vukosavljevic, X. Shu, and B. Egan, 2005, Laboratory Investigation of Mixing Hot-Mix Asphalt with Reclaimed Asphalt Pavement. *Transportation Research Record, Journal of the Transportation Research Board No. 1929*.

Kennedy, T., W. Tam, and M. Solaimanian, 1998, Effect of Reclaimed Asphalt Pavement on Binder Properties Using the Superpave System. Center for Transportation Research, The University of Texas at Austin. FHWA/TX-98/1250-1.

McDaniel R., and T. Nantung, 2005, Research Pays Off: Designing Superpave Mixes with Locally Reclaimed Asphalt Pavement: North Central States Jointly Fund Study. Transportation Research Board, TR News No. 239.

McDaniel, R., G. Huber, and V. Gallivan, 2006, Conserving Resources and Quality with High RAP Content Mixes. National Asphalt Pavement Association. *HMAT*, 11(6).

McDaniel, R., A. Shah, G. Huber, and V. Gallivan, 2007, Investigation of Properties of Plant-Produced RAP Mixtures. Transportation Research Board. Transportation Research Board 86th Annual Meeting.

National Cooperative Highway Research Program, 2001, *Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method: Technician's Manual*, Transportation Research Board, Report 452.

National Asphalt Pavement Association, 2007, Designing HMA Mixtures with High RAP Content: A Practical Guide.

National Asphalt Pavement Association, 2007, Recycling Hot-Mix Asphalt Pavements.

Sargious, M., and N. Mushule, 1991, Behaviour of Recycled Asphalt Pavement at Low Temperatures. Ottawa Canada National Research Council. *Canadian Journal of Civil Engineering*, Vol. XVIII No. III.

Schreck, R., 2007, More RAP in HMA: Is it Worth It? The 2007 Virginia RAP Initiative. National Asphalt Pavement Association. *HMAT*, 12(4).

Sebaaly, P.E., and R. Shrestha, 2004, A Literature Review on the Use of Recycled Asphalt Pavements in HMA Mixtures. Western Regional Superpave Center, University of Nevada, Reno, Final Report.

Shen, J., and J.A. Miller, 2007, Effects of Rejuvenating Agents on Superpave Mixtures Containing Reclaimed Asphalt Pavement. American Society of Civil Engineers. *Journal of Materials in Civil Engineering*, 19(5).

Sondag, M. S., 2000, Investigation of Recycled Asphalt Pavement Mixtures. University of Minnesota, Final Report.

Stroup-Gardiner, M., and C. Wagner, 1999, Use of RAP in Superpave HMA Applications. Transportation Research Record 1681, pp. 1-9.

Vukosavljevic, D., 2006, Fatigue Characteristics of Field HMA Surface Mixtures Containing Recycled Asphalt Pavement (RAP). Thesis (M.S.) – University of Tennessee, Knoxville.

Zofka, A., M. Marasteanu, X. Li, T. Clyne, and J. McGraw, 2005, Simple Method to Obtain Asphalt Binders Low Temperature Properties from Asphalt Mixtures Properties. *Journal of the Association of Asphalt Paving Technologists*, vol. 74.

Work Element E2c: Critically Designed HMA Mixtures

Work Element Lead: Peter Sebaaly and Elie Hajj

<u>Introduction</u>

Field performance data from the Westrack project and other pavements indicate that every HMA mix has a critical temperature and a critical loading rate beyond which the mixture will become highly unstable. Therefore, it is recommended that the critical temperature and critical loading rate be identified for every HMA mixture. Once these two critical conditions are identified, they must be checked against the expected field conditions where the HMA mix will be placed. An HMA mix should not be placed at locations where its critical conditions are expected to be violated.

Furthermore, it is believed that the critical conditions of an HMA mix can be significantly influenced through changes in binder content, binder properties, and aggregates gradation. This process will allow the mix design engineer to design excellent performing HMA mixtures for mainline traffic and traffic on off-ramps and at intersections with changes that can be accommodated in the production process without major interruptions, such as slightly modify the binder properties or slightly reduce the binder content as the construction approaches the intersection.

Relationship to FHWA Focus Areas

This research effort fits under the FHWA Focus Areas of Optimize Pavement Performance and Advanced Quality Systems.

Hypothesis

The strength and performance of HMA mixtures can be optimized by loading them below their critical conditions as depicted by the combination of temperature and loading rate.

Objectives

The objective of this research effort is to establish a practical test method to identify the critical temperature and critical loading rate of HMA mixtures. The test will be based on fundamental properties of the HMA mixture and consistent with the Superpave mix design method. The developed test method should be simple enough to be implemented as part of the mix design process.

Experimental Design

The following subtasks will be completed in order to achieve the objective of this research effort.

Subtask E2c-1: Identify the Critical Conditions

As the HMA mix is placed at a given project location, it will be simultaneously subjected to the local environmental conditions and traffic loading. Due to the viscoselastic nature of the HMA mix, its behavior is highly dependent on both temperature and rate of loading. The pavement temperature is related to the air temperature through a relationship that has been established and verified based on the data from the Long Term Pavement Performance (LTPP) studies. This relationship has been accepted in the Superpave system. The loading rate of the HMA mix depends on the speed of the traffic using the facility. The loading rate varies from short under freeway traffic to long under urban traffic.

Low temperature coupled with a short loading rate is the best condition for an HMA mixture while high temperature coupled with a long loading rate represents the worst condition. In reality the combination of temperature and loading rate varies over a wide range. Identifying the temperature of the HMA mix is relatively simple since it only depends on the location of the pavement and the air temperature. However, identifying a loading rate represents a more difficult challenge since the mixed nature of traffic loading has to be included. This subtask will use dynamic mechanistic analysis of flexible pavements subjected to various traffic speeds to identify the loading rates that are applicable to the various road facilities (i.e. freeways, urban streets, intersections, and off ramps).

An experimental plan was developed to cover the activities to be conducted under Subtask E2c-1. The objective of this subtask is to define the critical loading conditions under a moving truck load. This objective will be met through a mechanistic analysis of the HMA pavement as it is subjected to moving loads at various speeds and under braking and non-braking conditions.

- Use the 3D-Move software to evaluate the stress conditions under dynamic loads within the HMA layer.
- Analyze the following pavement structures:
  - 4" HMA over 6" base
  - 6" HMA over 8" base
  - 8" HMA over 10" base
- Analyze the following geometries:
  - Level road
  - 4 percent grade road
- Analyze the following speeds:
  - 60 mph without braking
  - 40 mph without braking
  - 20 mph with and without braking
  - 2 mph with braking
- Tire-Pavement Pressure Distribution
  - Uniform
  - Non-uniform
- Analyze the following HMA mixtures:
  - One aggregate source: Lockwood (andesite)
  - Intermediate Superpave gradation with ½" nominal max size
  - Three binders: PG52-22, PG58-22, PG64-22
- Analyze the following HMA layer temperature
  - 40°C
  - 50°C
  - 60°C
  - 70°C
- Conduct Superpave mix designs for the three mixtures for 6 millions ESALs and for a top lift.
- Subject the mixture to Superpave short-term aging.

- Measure the E* Master Curves for all three mixtures.
- Use the measured properties of the HMA mixtures in the 3D-Move analyses.
- Use a modulus of 35,000 psi and 15,000 psi for the base and subgrade, respectively.
- Use the 18-wheeler truck configuration at 125 psi inflation pressure.
- Evaluate the distributions of vertical displacements, vertical and lateral stresses within the HMA at the surface and 1/2" depth increments for the top 2" of the HMA layer and at 1" increment thereafter within the influence zone of the loaded tires.
- Analyze the data to identify the following:
    - Time of loading throughout the HMA
    - Magnitude of the confining and deviator pressures throughout the HMA layer

Subtask E2c-2: Conduct Mixtures Evaluations

The objective of this subtask is to determine the critical combination of temperature and loading rate for HMA mixtures. The critical combination is defined as the one that creates an unstable HMA mix exhibiting excessive permanent deformation. Figure E2c.1 shows the development of permanent strain in an HMA sample tested under the repeated load triaxial (RLT) test. It can be seen that the permanent deformation goes through three phases: initial phase with a high rate of permanent deformation but short duration, a secondary phase where the permanent deformation is linear with a long duration, and tertiary phase where the permanent strain is increased exponentially. It is believed that the formation of the tertiary phase is an indication of an unstable HMA mix.

The repeated load triaxial test is the most representative test of actual field conditions. The deviator and confining stresses can be varied to simulate the actual state of stresses within the HMA layer while simultaneously changing the temperature and the rate of loading. It is proposed that the RLT test be used to evaluate a variety of HMA mixtures ranging from weak to strong mixtures to identify their critical temperatures and rates of loading. The permanent deformation curves similar to the one shown in figure E2c.1 will be developed for each mixture under the various combinations of temperature and rate of loading as determined in Subtask E2c-1.

An experimental plan was developed to cover the activities to be conducted under Subtask E2c-2. The objective of this subtask is to evaluate the critical conditions of HMA mixtures defined as the critical combination of testing temperature and loading rate under the repeated load triaxial (RLT) testing conditions.

- Use the same three mixtures that were designed under Subtask E2c-1.
- Test the mixtures in the RLT at various temperatures of 40, 50, 60, and 70^{o}C and at the state of stresses and loading times that were determined in subtask E2c-1.
- Analyze the RLT of the various mixtures in terms of the relationship between the permanent axial strain as a function of number of load cycles.

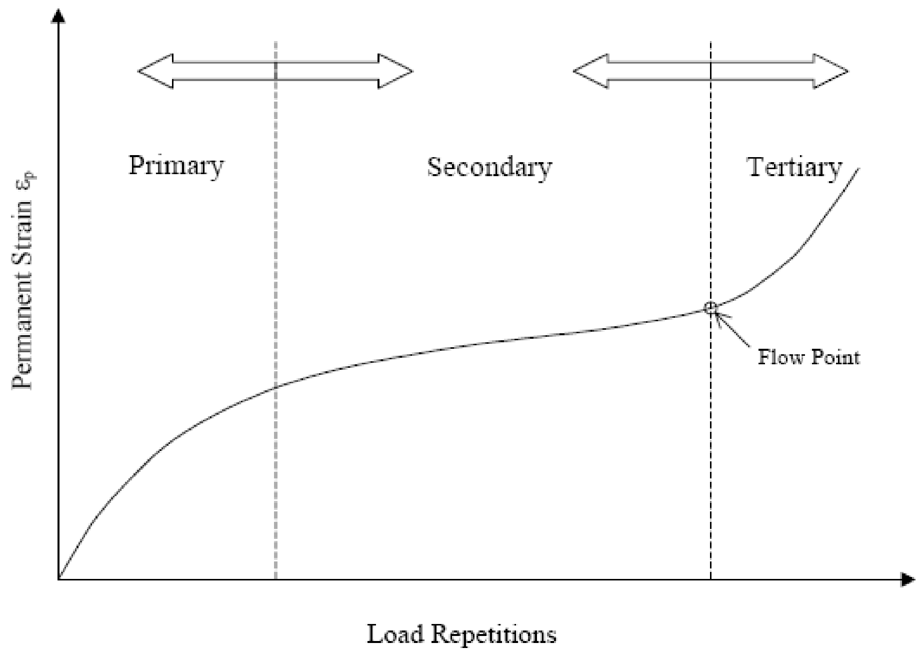


Figure E2c.1. Typical repeated load permanent deformation behavior of pavement materials.

Subtask E2c-3: Develop a Simple Test

One disadvantage of the RLT test is its complexity since it requires accurate control of the deviator and confining stresses for the duration of the test which makes it an unpractical test for routine applications.

This subtask will use the evaluation data from the RLT tests conducted in subtask E2c-2 to investigate the possibility of developing a simpler version of the test. At this point, the researchers believe that a test that can be conducted in the Simple Performance Tester (SPT) may be feasible with some adjustments. This will have the advantage of conducting the critical conditions test in the same equipment used for the dynamic modulus test which will make it easier to implement as part of the mix design process. If the SPT proves unfeasible, then other tests will be investigated.

A detailed experimental plan will be developed prior to beginning this subtask.

Subtask E2c-4: Develop Standard Test Procedure

The objective of this subtask will be to develop a standard test procedure to be used for the identification of the critical conditions of HMA mixtures. The standard procedure will be developed in AASHTO format and submitted to AASHTO for approval.

A detailed experimental plan will be developed prior to beginning this subtask.

Subtask E2c-5: Evaluate the Impact of Mix Characteristics

The objective of this subtask is to identify the mix characteristics that impact the critical temperature and loading rate of HMA mixtures. This subtask will use the test procedure developed in Subtask E2c-4 to assess the impact of the various mix properties on the critical conditions.

It is anticipated that mix properties such as binder grade and content and aggregate properties and gradation may play a major role on the critical temperature and loading rate of HMA mixtures. The work conducted under this subtask will identify the various mix properties and their corresponding levels that have significant impact on the critical conditions of the HMA mix. Through this effort, it will be feasible to recommend changes in the mix properties that will improve their critical behaviors.

For example if an HMA mix is performing well under mainline traffic but it is experiencing severe rutting at the intersection, then it is possible that it is reaching its critical loading rate under slow-stop traffic for the given location (i.e. temperature). The data generated in this subtask will help identify the necessary changes in mix properties that will improve its resistance to rutting at the intersection.

It is anticipated that this research effort will identify some mix properties that can be easily modified during production and that will lead to significant improvement in the response of the HMA mix under critical conditions. The research under this subtask will also cover other failure modes of the HMA mix in order to avoid improving the resistance of the mix to one mode of failure while at the same time jeopardizing its resistance to the other failure modes.

A detailed experimental plan will be developed prior to beginning this subtask.

Major Findings from Year 1

The Year 1 activities of this work element concentrated on the following areas:

- Developed experimental plans for subtasks E2c-1 and E2c-2. The plans have been presented in the Experimental Design section.
- Conducted theoretical modeling as described in the experimental plan for subtask E2c-1.

Year 2 Work Plan

During Year 2, the researchers will continue the development of the critical loading times and loading rates for the various combinations of HMA mixtures and pavement structures according to the experimental plan for subtask E2c-1. The data will be summarized in tables and charts that are simple to use by practicing engineers.

In subtask E2c-2, the researchers will conduct laboratory testing of the three HMA mixtures under the stress conditions of the various loading times and loading rates as determined from the mechanistic analyses. The laboratory testing will be conducted in the repeated load triaxial test. Additional HMA mixtures will also be evaluated.

Budget

The estimated budget for this work element is $600,000 over the five years. The work will be conducted by the University of Nevada.

Work element E2d: Thermal Cracking Resistant Mixes for Intermountain States

Work Element Lead: Peter Sebaaly (UNR) and Codrin Daranga (UW-M)

Introduction

Thermal cracking in asphalt pavements is caused when internal tension stresses during restrained thermal deformations are greater than the tensile strength of the asphalt binder. The thermal cracking phenomenon is hastened when temperatures become lower than the binder glass transition temperature. Glass transition occurs when the liquid component of the asphalt binder freezes to a solid, restricting segmental motion within the material's molecule (Brandrup and Immergut 1975; Odian 1991; Bonemazi et al. 1996). Any attempt to deform the frozen structure results in brittle fracture.

Oxidation raises the glass transition temperature of the binder, and therefore, decreases its resistance to thermal cracking. The impact of oxidation is two fold: the introduction of polar groups and the decrease in the amount of oily fractions. However, there is a big question whether oxidation only occurs within the top one inch of the pavement surface or it actually progresses throughout the depth of the HMA layer. The two common sources of information on this issue provide contradicting recommendations. Coons and Wright (1968) concluded that binder oxidation occurs only in the top inch of the pavement below which the binder is left virtually unaffected by years of use and environmental exposure. However, Glover et al. (2005) indicated that binders can in fact age well below the pavement surface and that the hardening of the binder is virtually unabated over time. Recent SHRP program studies on binder glass transitions and subsequently University of Wisconsin-Madison studies on glass transitions of binders and mixtures have shown that sources of asphalt binders, modification, aging, and aggregate properties can alter the glass transition behavior significantly. In addition, recent University of Wisconsin-Madison studies (pooled fund program TPF-05) showed that thermal cycling has an important effect on the thermal cracking behavior of pavement mixtures. Results indicate that the coefficient of contraction for mixtures could be significantly different from coefficients of expansion and thus thermal cycling needs to be modeled carefully for more accurate prediction of thermal stresses and cracking.

These recent results on aging and glass transition behavior merit a fresh look at the prediction of thermal cracking models. In addition, the increasing use of modified binders, particularly polymer and acid modified binders, require a more in depth evaluation of these factors for better understanding of thermal behavior and cracking prediction of pavement mixtures.

Relationship to FHWA Focus Areas

This research effort supports the FHWA Focus Areas of Optimize Pavement Performance and Advanced Quality Systems.

Hypothesis

Field performance data indicate that HMA mixtures in the intermountain region of the U.S. experience severe thermal cracking distresses that are not well covered by the current technology. The intermountain region experiences significant hardening of the asphalt binder coupled with extreme thermal cycling, and highly absorptive aggregate leading to thermal cracks that are six inches wide.

Objectives

The objective of this research effort is to develop a binder/mix evaluation and testing system that can effectively simulate the long term properties of HMA mixtures in the intermountain region and to assess the impact of such properties on the resistance of HMA mixtures to thermal cracking.

Experimental Design

The objective of this work element is to develop a system that simulates the field aging and thermal cracking process of HMA mixtures in the intermountain region. First the binder aging kinetics when there is free access to atmospheric oxygen will be evaluated, followed by an evaluation of the impact of aggregate and mixture properties on the aging of the binder in the mix. The findings of both evaluations, together with intermountain region data on pavement temperature variations with time and depth will be used in a mixture aging model, developed in Work Element Subtask F1c-3, to simulate the aging of asphalt binders in HMA mixtures placed in the intermountain region of the U.S.

The intermountain region of the U.S. was defined as covering the following states: West Texas, New Mexico, Colorado, Wyoming, Montana, Idaho, Utah, Arizona, California, and Nevada.

The intermountain region represents a unique environment that impacts HMA mixtures in a manner that is different than the other regions of the U.S. This unique environment is defined as follows:

- Large daily temperature changes (low-high)
- High rate of daily temperature changes
- Wide range of seasonal temperatures
- Low humidity
- High number of freeze-thaw cycles

In addition, the aggregates available in the intermountain region exhibit unique properties that may have large impact on the aging characteristics of HMA mixtures. These include:

- Highly absorptive aggregates
- Siliceous aggregates

As a result of the combined impacts of the unique environment and properties of available aggregates, HMA mixtures in the intermountain region are subjected to some unique conditions that can be summarized as follows:

- Unique temperature profile throughout the depth of the HMA layer
- Significantly more aging of the asphalt binder
- Higher thermal stresses within the HMA layer

It is believed that the combinations of the above listed conditions and factors result in severe thermal cracking of HMA mixtures in the intermountain region of the U.S. As a result it became common to identify HMA pavements in the intermountain region experiencing thermal cracks that are in access of 6 inches wide and continue to widen as the pavement ages.

In order to achieve the objectives of this research effort, the following subtasks will be completed.

Subtask E2d-1: Identify Field Sections

This subtask will identify the extent of thermal cracking in HMA pavements located within the intermountain region of the U.S. Several HMA pavements will be identified at various locations within the intermountain region and their performance for the past 10-15 years will be collected and analyzed. A concerted effort will be made to select pavement sections that coincide with the LTPP SPS sections in the intermountain region. The research team will consult with FHWA and Nichols Consulting Engineers to select the appropriate LTPP SPS sites in the intermountain region. The performance of the selected pavement sections will be collected from the pavement management systems (PMS) of the corresponding owner agencies and the LTPP databases. The selected pavements will cover a wide range of pavement age, environmental conditions, and traffic loadings. Since thermal cracking develops in the form of transverse cracks which highly resembles reflective cracking, special efforts will be made to separate the two modes of distress.

An Experimental plan was developed to cover the activities to be conducted under Subtask E2d-1. The objective of this subtask is to collect and report actual temperature history and profile throughout the depth of HMA pavements within the intermountain region of the U.S. This objective will be achieved by identifying HMA pavements throughout the intermountain region with measured temperature hourly histories and profiles throughout the depth of the HMA layer. The following steps will be completed.

- Identify HMA pavements at various locations within the intermountain region of the U.S. that have information regarding the HMA temperature histories and profile. This will be achieved by contacting:
    - Nichols Consulting Engineers for LTPP SPS sites in the intermountain region
    - Nevada Automotive Test Center (NATC) for the Westrack project
- Collect mixture and binder properties for the various sites that offers the temperature histories and profiles, if available

Subtask E2d-2: Identify the Causes of the Thermal Cracking

This subtask will obtain samples from the various pavement sites that are experiencing thermal cracking and conduct laboratory testing to identify the causes of the thermal cracking failure. The following tests will be conducted on the samples obtained from the various sites.

- Compare the environmental conditions at the site with the critical temperatures of the binder used during construction as specified by the Superpave PG system.
- Measure the temperature profile throughout the depth of the HMA.
- Measure the volumetric properties of the samples from the various sites.
- Measure the fracture temperature of the mix using the thermal stress restrained specimen test (TSRST) conducted on field samples.
- Extract and recover the binder from the samples at 1.0” depth increments and measure their rheological properties following the Superpave PG system and the master curves of G’, G”, and G*.
- Test the recovered binders for oxidation, solvent removal, and low shear rate limiting viscosity.
- Evaluate the extent of binder oxidation as a function of depth of the HMA layer.
- Measure the glass transition behavior of extracted binders and of mixtures at cooling and heating rates that resemble the conditions of the pavement sections that are sampled.

The activities of this subtask will be closely coordinated with the activities of other Consortium partners on aging of HMA mixtures that will be conducted under the fatigue and moisture damage areas.

Subtask E2d-3: Identify an Evaluation and Testing System

The objective of this subtask is to identify a system to evaluate and test HMA mixture’s resistance to thermal cracking in the intermountain region. It is anticipated that HMA pavements in the intermountain region are subjected to significant hardening of the asphalt binder coupled with extreme thermal cycling, and highly absorptive aggregate leading to thermal cracks.

Based on the data generated from Subtasks E2d-1 and E2d-2, the researchers will work on developing an evaluation and testing system to simulate the actual conditions in the intermountain region. At this point the researchers anticipate that the work under this subtask will cover the following parameters:

- A binder aging system that simulates the field aging process of HMA mixtures in the intermountain region.
- The impact of fillers on the aging characteristics of the HMA mix.
- The impact of air voids on the aging characteristics of the HMA mix.
- The impact of highly absorptive aggregates on the aging characteristics of the HMA mix.

Using the data from the above experiments, a thermal cracking test will be developed that simulates the actual tensile mode of loading that is experienced by the HMA layer. Attentions will be paid to the following aspects.

<u>Thermal Expansion Coefficient Measurements</u>
There are two values for the thermal expansion coefficient: one below and one above the glass transition temperature. This is valid for both binders and mixes. The evaluation of thermal expansion coefficients are conducted using an apparatus developed at University of Wisconsin-Madison. The apparatus monitors the dilatometric properties of mixes and binders while the samples are subjected to a prescribed temperature program. By plotting the length (for mix samples) or volume (for binder samples) vs. temperature, the thermal coefficients of expansion are given by the two slopes in the bilinear function.

<u>Low Temperature Mix Strength Properties Measurements</u>
This testing is performed exclusively on mix samples and it is referred to as: "Thermal Stress Restrained Specimen Test (TSRST)." A mixture bar is fixed mounted using a solid steel frame so as to restrict thermal contraction. When the sample is cooled, the restricted deformation by the solid steel frame triggers the generation of tensile stresses. These stresses are measured using a load cell. The temperature will continue to drop until the sample is driven to failure. The tensile stresses are plotted against the temperature to allow the evaluation of the mixture behavior prior to and at failure. If the test described in the previous paragraph does not impose any moving restrictions on the sample, this test imposes maximum moving restriction. In this way, the two tests complement each other, allowing the complete characterization of the pavement mixture thermal behavior.

<u>Monitoring of Carbonyl Growth</u>
In order to better gauge the oxidative aging in asphalt binders, the carbonyl peak growth must be monitored. This is usually done using Fourier Transformed Infrared Spectroscopy (FTIR) technique. Currently we do not own or have ready access to such instrument, but we are in the process of developing a working relationship with the chemistry department at the University of Wisconsin-Madison, in order to gain access to FTIR testing. Even though we do not foresee any problems in developing such a relationship, in the event that we will not be able to gain access to FTIR testing, this work will be carried out by subcontracting it to WRI.

The activities of this subtask will be closely coordinated with the activities of other Consortium partners on aging of HMA mixtures that will be conducted under the fatigue and moisture damage areas.

An Experimental plan was developed to cover the activities to be conducted under Subtask E2d-3. Three experiments will be conducted: the first experiment to evaluate the aging of binders in the intermountain region, the second experiment to evaluate the impact of aggregates properties on aging of binders, and the third experiment to evaluate the impact of mixtures properties on the aging of binders.

E2d-3.a: Evaluate Long-Term Aging of Asphalt Binders Subjected to Free Atmospheric Oxygen: The objective of this experiment is to evaluate the aging characteristics (oxidation and hardening kinetics) of intermountain region asphalt binders when they have full access to atmospheric oxygen. The following steps will be conducted:

- Obtain the following asphalt binders:
    - Neat PG64-22
    - Neat PG64-22 + 3 percent SBS polymer (using the same PG64-22)
    - Polymer modified PG64-28 (using the same PG 64-22) that meets the grades of NV, CA and UT.
- Blend the PG64-22 with hydrated lime at 10 percent and 20 percent by weight.
- Subject a 1 mm film of each of the asphalt binders to long-term oven aging at 50°C, 60°C, 80°C, and 100°C for a various time periods. Prior to aging the matrix, check for potential volatile loss during aging. Weigh samples to the nearest 0.001gram before and after aging to determine weight gain or loss. Individual samples at each temperature will be removed from the aging oven according to the following schedule:
    - 50ºC: Remove samples after 60, 120, 200 and 320 days
    - 60ºC: Remove samples after 30, 60, 100 and 160 days
    - 80ºC: Remove samples after 7.5, 15, 25 and 40 days
    - 100ºC: Remove samples after 44, 90, 150 and 240 hours
- Measure the following properties for the aged binders at each of the 50°C, 60°C, 80°C, and 100°C (the aging temperatures should be precise to within 0.1 °C):
    - Carbonyl growth (UWM) to determine binder reaction rates and activation energies.
    - Rheological properties following the Superpave PG system and the master curves of G', G", and G* (UNR), measurements of the low shear rate viscosity, and multiple stress creep recovery (MSCR) (UWM).
    - Strength properties at low temperature using the single edge notch bending (SENB) (UWM).
    - Thermal expansion coefficient (UWM).

E2d.3.b: Evaluate the Impact of Aggregate Absorption on the Aging of the Asphalt Binder: The objective of his experiment is to evaluate the impact of aggregate absorption on the long-term aging properties of the binder in the HMA mix. This subtask will assess the impact of the unique characteristics of the intermountain aggregates on the aging characteristics of asphalt binders in the HMA mix. The following steps will be conducted:

- Select aggregates with different mineralogy from four different sources within the intermountain region.
- Develop an intermediate Superpave gradation for each of the aggregate sources.
- Measure the specific gravity and absorption of the blend aggregates.
- Calculate the surface area of each blend aggregates.
- For each of the blend gradations conduct the following:
    - Mix each of the blend aggregates with each of the two extreme asphalt binders identified in E2d-1.a at a constant binder content (i.e. variable film thickness).
    - Mix each of the blend aggregates with each of the two extreme asphalt binders identified in E2d-1.a at the required binder content to achieve a constant film thickness (i.e. variable binder content).
- Measure the E* master curve and TSRST fracture properties of compacted mixtures before aging and after 3, 6, and 9 months of long-term oven aging at 60°C. This aging does not need to be as precise as the binder aging kinetics ovens because the state of aging will be determined by recovering the binder. Age the loose mixture following AASHTO R30, 4hr aging.
- Compare the mechanical properties of HMA mixtures before and after long-term oven aging.
- Extract and recover the binder from the tested mixture at each aging level and determine the binder's level of oxidation and hardening (carbonyl and DSR properties). The extraction and recovery process will be done using a solvent system maximize binder recovery and in a way that minimizes changes to the binder and assures virtually complete solvent removal.

E2d-3.c: Evaluate the Impact of HMA Mix Characteristics on the Aging of the Asphalt Binder: The objective of this experiment is to evaluate the impact of intermountain region mixture characteristics on the long-term aging characteristics of the asphalt binder. As the asphalt binder is placed in the HMA mix, it will have a limited access to oxygen. Therefore, the binder aging kinetics that is based on free access to atmospheric oxygen will have to be modified to simulate real field conditions of HMA pavements. The following steps will be conducted:

- Aggregate Sources: select two aggregate sources based on the recommendations of E2d-3.b.
- Gradation: develop an intermediate and fine Superpave gradations for each of the aggregate sources.
- Measure surface area and specific gravity.

- Binders: Select three binders – two extremes and one intermediate as identified in subtask 1.a.
- Mineral Fillers: none, Lime, and regular limestone.
- Conduct Superpave mix designs for all combinations of mixtures based on 6 millions ESALs for a top lift: 36 mixtures (2 agg. x 2 grad. x 3 binders x 3 fillers).
- Air-Voids: prepare compacted samples from each mixture at three levels of air-voids – 4, 8 and 11 percent. Age the loose mixture following AASHTO R30, 4hr aging.
- Measure the E* master curve and TSRST fracture properties for three replicate samples of the compacted mixtures before aging and after 3, 6, and 9 months of long-term oven aging at 60°C. This aging does not need to be as precise as the binder aging kinetics ovens because the state of aging will be determined by recovering the binder).
- Loose mix: prepare a loose mix and subject it to the various long term aging periods prior to compaction. Measure the E* master curve of the aged loose mix after compaction.
- Compare the mechanical properties of HMA mixtures before and after long-term oven aging.
- Extract and recover the binder from the tested mixture at each aging level and determine the binder's level of oxidation and hardening (carbonyl and DSR properties). The extraction and recovery process will be done in a way that maximizes binder recovery and minimizes changes to the binder and assures virtually complete solvent removal.

<u>Subtask E2d-4: Modeling and Validation of the Developed System</u>

This subtask will develop a software program for prediction of critical cracking temperatures using the input variables measured in subtask E2d-3. The software will include variables that are found to be important in subtask E2d-3 and that have shown clear role in predicting the performance observed in the field.

The subtask will also include validation of the testing and modeling system. The validation process will be conducted in the laboratory based on the use of the TSRST. Although the SHRP research concluded that the TSRST is too complex to become a production test, it is clear that the test can be used effectively to evaluate stress build up and cracking under well controlled variables. In addition, this subtask will make a concentrated effort to validate the developed system on a national basis. Some national pavement sites will be identified and used for this validation effort.

<u>Subtask E2d-5: Develop a Standard</u>

This subtask will develop a standard testing procedure for the system developed in Subtask E2d-3 and validated in Subtask E2d-4. The standard will be prepared in AASHTO format.

Major Findings from Year 1

The Year 1activities of this work element concentrated on the following areas:

- Develop experimental plans
- Identify and obtain materials for the various experiments
- Identify field sections in the intermountain region
- Conduct laboratory evaluations

Experimental Plans: Experimental plans were developed to cover the activities to be conducted under Subtasks E2d-1, E2d-2, and E2d-3. The plans have been described under the individual subtasks in the previous sections.

Identify Materials: During Year 1, the materials and testing conditions for the experimental plans were selected as described under the individual subtasks. The aggregates and asphalt binders have been obtained.

Field Sections: During Year 1, the researchers worked with the western region LTPP contractor (Nichols Consulting Engineers) to identify LTPP field sections that are located in the intermountain region and that can be used in this research. The criteria for selecting the LTPP sites included: located within the intermountain region, availability of hourly temperature profiles throughout the depth of the HMA layer, availability of materials properties, and availability of long-term performance data. The following LTPP sites have been identified for this work element:

- Arizona: 041024, 04(0113, 01114)
- New Mexico: 351112
- Colorado: 081053
- Utah: 491001
- Nevada: 320101
- Wyoming: 561007
- Idaho: 161010
- Montana: 300114, 308129
- Texas: 481122

The temperature profiles throughout the HMA layer have been extracted from the LTPP database and were analyzed to calculate the rate of temperature changes at various depths in the HMA layer as a function of time of day and year. Figure E2d.1 shows a typical temperature rates data for an LTPP section in Arizona.

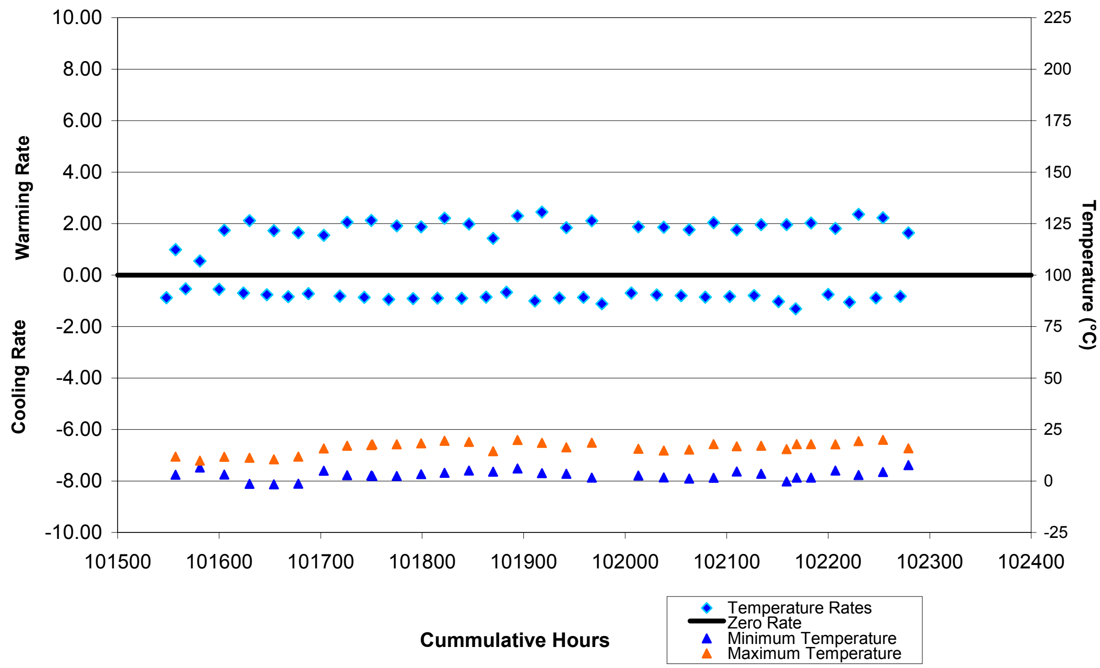


Figure E2d.1. Pavement temperature rates along with the maximum and minimum daily temperatures for section 040113 in Arizona at sensor 1 (depth = 1.7 inches) for January of 2004.

Conduct Laboratory Evaluations: The glass transition behavior of asphalt binders and mixtures is an essential component for the prediction of thermal cracking of pavements. For many decades this subject has been studied, however published results are very limited. Measuring thermo-volumetric properties of asphalt paving materials is not simple and there are no standard methods for conducting such measurements. During Year 1, a dilatometric system for measuring binder properties was used to study the glass transition of ten binders and a length change measuring system was used to measure the glass transition of asphalt mixtures. Results show a variation in the glass transition behavior as function of the binder grade and modification. Furthermore, the glass transition temperature T_g of the mixtures does not correlate with binder glass transition properties, which highlights the importance of aggregate characteristics and mixture compaction data in defining mixture thermo-volumetric properties. It is also found that the contraction and dilation behavior of mixtures shows a hysteretic response. These findings hint at a need for fundamental understanding of the effect of aggregate interaction in the thermal behavior of asphalt mixtures and they also shed some light on the important aspect of thermal cracking of pavements and the measurements needed for better modeling.

We have developed a finite difference model that simulates the temperature gradient and strain distribution in 2.5-in by 2.5-in cross-section mix specimen during thermal cycling. This finite difference model solves the heat diffusion equation:

$$\frac{\partial T(x,z,t)}{\partial t} = k \cdot \left(\frac{\partial^2 T(x,z,t)}{\partial x^2} + \frac{\partial^2 T(x,z,t)}{\partial z^2} \right)$$

by discretizing it both in the space and time:

$$\frac{T(x_i, z_i, t_{i+1}) - T(x_i, z_i, t_i)}{\Delta t} = k \cdot \left(\frac{T(x_{i+1}, z_i, t_i) - 2T(x_i, z_i, t_i) + T(x_{i+1}, z_i, t_i)}{\Delta x^2} + \frac{T(x_i, z_{i+1}, t_i) - 2T(x_i, z_i, t_i) + T(x_i, z_{i-1}, t_i)}{\Delta z^2} \right)$$

where T(x,z,t) is the temperature specimen in space and time, k is the thermal diffusivity, and Δx, Δz, and Δt are the space and time discretization intervals. By applying the chamber temperature as the time-varying boundary condition, the distribution of temperature throughout the specimen during heating and cooling cycles can be calculated (figure E2d.2). Furthermore, the combination of local temperatures with thermal expansion coefficients (including different thermal expansion coefficients above and below the glass transition temperatures) permit calculating both local and global thermal strains for any asphalt mixture specimens.

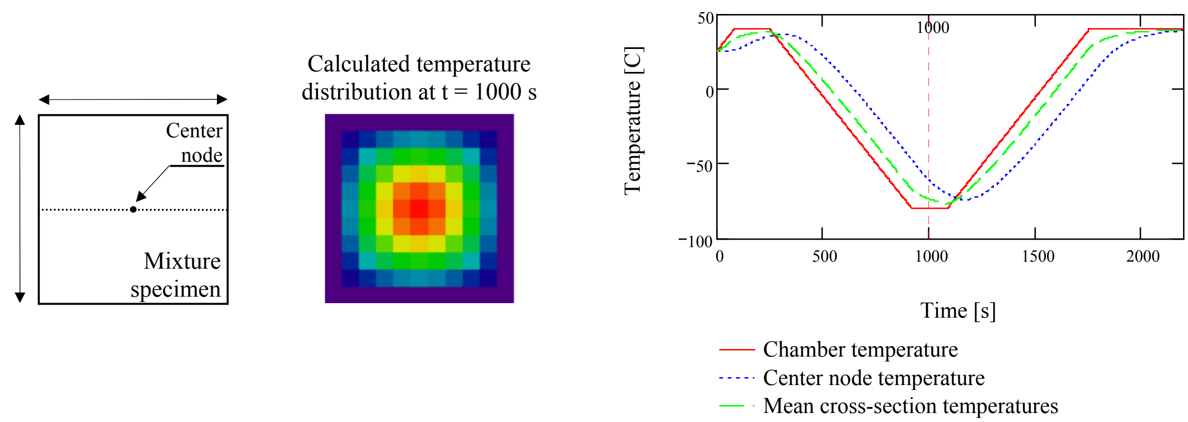
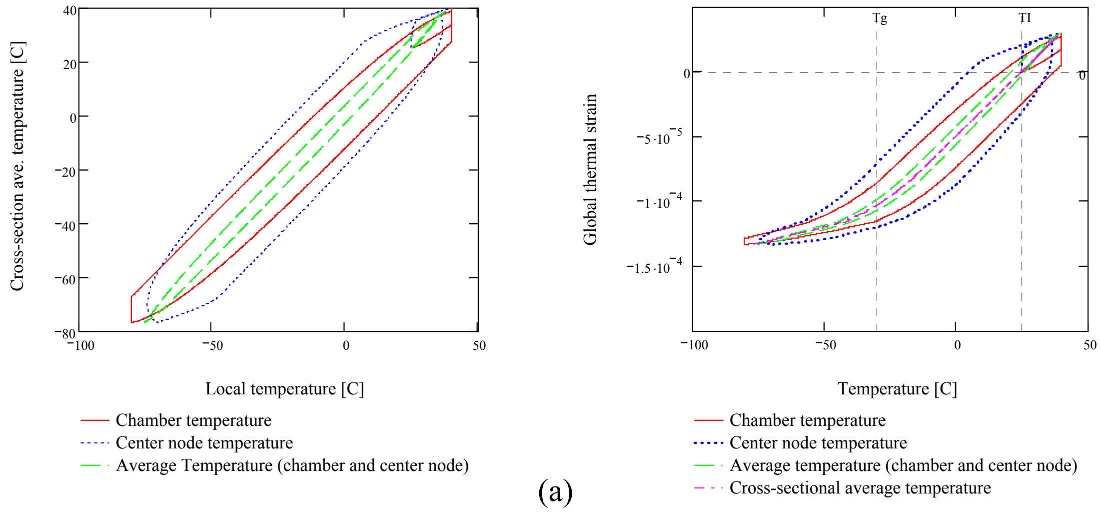


Figure E2d.2. Finite difference model of temperature distribution on asphalt mixture specimens.

The ability to evaluate the temperature node by node across the specimen cross-section shows that using a single thermocouple to characterize the thermal behavior a whole specimen could mask the true response of the asphalt mixture. For example, figure E2d.3a shows how local measurements cannot be used to match the average temperature distribution in the specimen. This is important as the average temperature distribution controls the overall thermal deformation. For example, figure E2d.3b shows the calculated thermal strain of a specimen plotted using thermal expansion for temperatures above and below the glass transitions temperature (Mamlouk et al. 2005; Ojo et al. 2008). Plotting these results versus local temperatures (either inside or outside the specimen, or the average of the two measurements), yield a loop response while the cross-sectional average represents the true diving mechanism and it eliminates the looping in the response. That is, experimental measurements must be combined with numerical modeling to properly evaluate the response the asphalt mixture system.



(a) (b)

Figure E2d.3. Modeled (a) thermal temperatures and (b) strain. The selection of local or global temperatures for the evaluation of system response may control the data interpretation.

Year 2 Work Plan

During Year 2, the research team will continue working on the various experimental plans.

- The data from the LTTP sites will be analyzed and used in the development of the temperature profile algorithm for the intermountain region.
- The long-term oven aging of the binders will continue.
- The impact of aggregate properties on the aging of the binder will be completed.
- The impact of mixtures properties on the aging of the binders will start.
- The UW-M will improve the testing apparatus as shown in figure E2d.4. Efforts will be placed on securing access to a FTIR machine and run preliminary FTIR testing in order to evaluate the quality of the results obtained. Depending on these findings, a decision will be made whether to continue with the FTIR testing at the University of Wisconsin-Madison or contract it out to WRI. As part of the Year 2 work plan, the testing methodology for this instrument will be improved.

Year 2 Milestones

The following milestones will be realized in Year 2:

- Complete the analyzes of the LTPP data
- Analysis of the available data on the long-term aging of binders
- Evaluate the impact of aggregate properties on the aging of binders
- Develop an effective thermal test system for HMA

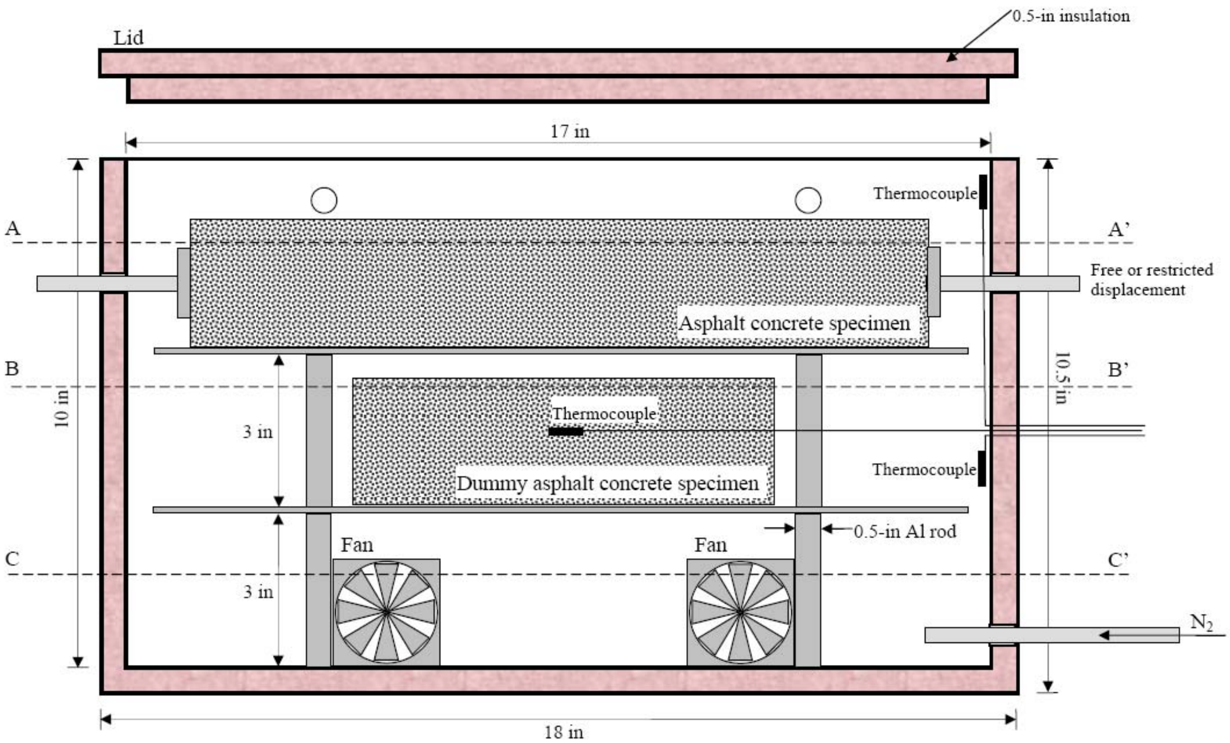


Figure E2d.4. View of the proposed improved thermal testing apparatus

<u>Budget</u>

The estimated budget for this work element is $750,000 for the University of Nevada and $355,000 for the University of Wisconsin-Madison over the five years. Drs. C. Petersen and C. Glover will work as consultants for the University of Nevada and Drs. J. Epps and A. Hand from Granite Construction Inc. will provide a cost share contribution.

<u>Cited and Related References</u>

Bonemazi, E., V. Braga, R. Corrieri, C. Giavarini, and F. Sartori, 1996, Characteristics of Polymers and Polymer-Modified Binders. *Transportation Research Record 1535*: 36-47.

Brandrup, J., and E. H. Immergut, 1975, *Polymer Handbook*.

Coons, R. F., and P. H. Wright, 1968, An Investigation of the Hardening of Asphalt Recovered from Pavements of Various Ages. *AAPT*, 37: 510.

Glover, C. J., R. R. Davison, C. H. Domke, Y. Ruan, P. Juristyarini, D. B. Knorr, and S. H. Jung, 2005, Development of a New Method for Assessing Asphalt Binder Durability with Field Validation. Report FHWA/TX-03/1872-2, Texas Transportation Institute, College Station, TX.

Mamlouk, M. S., Witczak, M. W., Kaloush, K. E., and Hasan, N., 2005, Determination of Thermal Properties of Asphalt Mixtures. *Journal of Testing and Evaluation*, March 2005, 33(2).

Odian, G., 1991, *Principles of Polymerization*. New York/Chichester/Brisbane/Toronto/ Singapore, John Willey & Sons, Inc.

Ojo, J. O., D. Fratta, H. U. Bahia, C. Daranga, and M. Marasteanu, 2008, "Thermo-Volumetric Properties of Asphalt Binders and Mixtures". 6th RILEM International Conference on Cracking in Pavements (accepted for publication - refereed).

Work element E2e: Design Guidance for Fatigue and Rut Resistance Mixtures

Subtask Lead: Dr. Donald W. Christensen, P.E.

<u>Introduction</u>

There is an urgent need to provide additional guidance to engineers concerning the design of fatigue and rut resistant mixtures. Excellent progress in understanding the relationship between mixture volumetric factors and pavement performance was made in National Cooperative Highway Research Program (NCRHP) Projects 9-25 and 9-31. In these projects, models based on volumetric composition and binder properties were developed for:

- Dynamic modulus
- Rutting resistance
- Fatigue cracking resistance
- Permeability

These models have been used to establish the general design criteria that are incorporated in the new Mix Design Manual for HMA that is being produced in NCHRP Project 9-33.

Further improvement of some of these models is needed to address specific shortcomings that were identified in subsequent validation efforts, and to expand the range of mixtures (nominal maximum aggregate size, compaction level, aggregate type, binder grade, modifier type etc.) used in the model development.

<u>Relationship to FHWA Focus Area</u>

This research effort supports the FHWA Focus Area of Optimize Pavement Performance.

<u>Hypothesis</u>

Models relating mixture composition and binder properties to performance can be used to design and evaluate HMA mixtures for high traffic levels.

Objective

The objective of this research is to develop a document containing supplemental design guidance for HMA mixtures for high traffic levels where a high resistance to rutting and fatigue cracking is needed. This document would supplement the general design guidance included in AASHTO M323 and the new Mix Design Manual for HMA being prepared in NCHRP 9-33. The design guidance will be based on improved models relating mixture composition and binder properties to pavement performance.

Experimental Design

The following subtasks will be completed in order to achieve the objective of this research effort.

Subtask E2e-1: Identify Model Improvements

The models that were developed in NCHRP Projects 9-25 and 9-31 were validated by AAT in NCHRP Project 9-33 using available data from test roads and accelerated loading facilities including: the FHWA ALF, MinnRoad, NCAT, and Westrack. Additionally some of the models have been independently evaluated by other researchers. In this subtask, the results from these validation and evaluation efforts will be reviewed to identify a prioritized list of model improvements that should be considered in this project.

Subtask E2e-2. Design and Execute Laboratory Testing Program

Based on the results of Subtask E2e-1 and the available budget, specific laboratory experiments will be designed to improve the existing model. These experiments will consider a range binders, modifiers, aggregates, mixture gradations, etc so that the resulting data can be used to develop robust models. Sufficient replication will be included to allow estimates of the precision of the resulting models to be made.

Materials for each experiment will be procured. The necessary laboratory testing will be performed and the results of the testing will be assembled into databases for subsequent statistical analysis.

Subtask E2e-3. Perform Engineering and Statistical Analysis to Refine Models

In this subtask engineering and statistical analyses will be performed to refine the models developed in NCHRP Projects 9-25 and 9-31. The primary analysis technique will be regression with the model parameters selected based on engineering principles so that the parameters have specific physical significance and are factors that can be controlled in HMA mixture design.

Subtask E2e-4. Validate Refined Models

The refined models will be validated using laboratory data from other sources and pavement performance data from various accelerated loading facilities, test roads, and the LTPP program.

Subtask E2e-5. Prepare Design Guidance

In this subtask a report providing guidance for the design of mixtures for high traffic applications will be developed. This report will be prepared as a supplement to the Mix Design Manual for HMA that is being developed in NCHRP 9-33. If appropriate, a Standard Recommended Practice for Design of Mixtures for High Traffic Levels will be prepared based on the report and submitted to the Mixtures and Construction Expert Task Group for consideration as an AASHTO Recommended Practice.

Major Findings from Year 1

Subtask E2e-1, Identify Model Improvement, is essentially complete and the findings from this Subtask have been used to prepare preliminary laboratory experiments addressing needed improvements for each of the models. The recommended improvements are summarized in table E2e.1 and described in greater detail in the following sections.

Table E2e.1. Summary of recommended improvements to the NCHRP Project 9-25 and 9-31 Composition to Engineering Property Models.

Model	Recommended Improvement
Hirsch Model for Dynamic Modulus	Curing time
	Low stiffness stress dependency
	Limiting maximum modulus
Resistivity Model for Rutting Resistance	Incorporate MSCR binder characterization
Continuum Damage Fatigue Model	Healing
	Damage tolerance
Permeability	Expand data set
	Aggregate size effect

Hirsch Model for Dynamic Modulus

Estimating the modulus of HMA is useful for a variety of purposes. It can serve as an aid during HMA testing, so that stress and strain levels can be properly set at the beginning of test procedures, including dynamic modulus, creep and fatigue testing. Estimates of |E*| values can be used in preliminary pavement designs, or for non-critical, low-volume pavement designs. Modulus estimates are also potentially useful in a variety of research situations, since many other HMA properties, such as fatigue resistance and rut resistance, are related to modulus.

The Hirsch model for estimating the modulus of hot-mix asphalt (HMA) was developed by engineers at Advanced Asphalt Technologies, LLC (AAT) as part of NCHRP Projects 9-25 and 9-31. It has been evaluated by several researchers independent of AAT and found to be more accurate and more rational than other similar models. There are however a number of improvements that can be made to the Hirsch model to improve its accuracy:

1. The modulus values of HMA specimens appear to gradually increase with time after specimen compaction. This is similar to curing of Portland cement concrete specimens, although not nearly as pronounced. This increase is probably due to a number of effects, including steric hardening of the asphalt binder, and continued, slow absorption of binder by the aggregate. The accuracy of the Hirsch model—and most other models for estimating HMA modulus values—could be significantly improved if the effect of curing time on HMA modulus could be at least approximately quantified.

2. Although it is generally assumed that the modulus of HMA is independent of stress level at relatively low stress levels, in reality, it is likely that some stress dependency exists even at very low stress levels at high temperatures and/or low loading frequencies/long loading times. The lower equilibrium modulus in the Hirsch model (and other similar models, such as the Witczak model) is assumed to be constant, but in fact probably varies slightly with stress level. The structure of the Hirsch model is such that this non-linearity can easily be accounted for if adequate data is collected to characterize typical stress dependency in HMA.

3. An important feature of the Hirsch model is the upper equilibrium modulus, or glassy modulus value. This is the maximum modulus value reached by an HMA at high frequencies/short loading times and/or low temperatures. The value of this limiting modulus is approximately 4 million psi. It is assumed constant in the Hirsch model, but as explained in item 1 above, probably varies somewhat with curing time. Another important factor affecting the glassy modulus of an HMA mix is the aggregate type used in the mixture. Theoretically, the maximum modulus for most HMA mixtures should be directly related to the modulus of the aggregate. Unfortunately, the data set used to develop the Hirsch model was not well suited for evaluating this effect. Being able to estimate the relationship between aggregate type and the glassy modulus of a mixture would significantly improve the accuracy of the Hirsch model.

Resistivity Model for Rutting Resistance

The resistivity/rutting model was developed during NCHRP Projects 9-25/9-31 as a way of relating HMA composition to rut resistance. The model predicts that rutting resistance increases with decreasing VMA, increasing aggregate surface area, decreasing in-place (or as tested) air voids), increasing design air voids, and increasing asphalt binder modulus or viscosity. The nature of the model is consistent with the results of other studies relating HMA composition and properties to rut resistance. The model is promising, with in-place rutting predictions within about a factor of two of observed values. However, the model does not deal well with modified binders; in order to obtain reasonable accuracy, an indicator value must be used to allow for significantly greater rut resistance for polymer-modified binders as compared to non-modified binders. Recently, the multiple-stress creep and recovery (MSCR) test has been proposed as an alternative to the standard dynamic shear rheometer (DSR) test for evaluating and specifying the properties of binders at the critical temperature for rutting, T_c. The MSCR test directly measures permanent and non-permanent deformation in a binder at two different stress levels, and potentially is much more useful in characterizing the flow properties of modified binders as they relate to HMA rut resistance.

Continuum Damage Fatigue Model

During NCHRP Projects 9-25, 9-31 and 9-33, a model for estimating the fatigue resistance of HMA mixtures was developed based upon continuum damage theory (CDT). The model related certain fundamental constants in the CDT fatigue model to various aspects of HMA composition, including effective binder content, design and in-place/as tested air voids, and binder properties. The model was verified by independently predicting the results of flexural fatigue tests, with a degree of accuracy approaching that of typical fatigue tests. The CDT model is potentially very useful, and also can be applied in rapid laboratory fatigue testing of HMA mixtures. There are however two improvements needed in the CDT fatigue model in order to make it useful in predicting the performance of HMA mixtures in situ. These two improvements involve a better understanding of damage tolerance and healing. CDT does a very good job of predicting how the modulus of an HMA mixture degrades under continued loading. This is certainly important in understanding fatigue damage in flexible pavements, but it is not sufficient for a thorough understanding of this failure mode. CDT predicts the way modulus decreases due to micro-cracking and other forms of micro-damage. It does not address crack propagation, or even the point at which micro-cracks coalesce into a major flaw and crack propagation begins to occur. Damage tolerance refers to the amount of damage an HMA mixture can withstand before macro-cracking, or crack propagation occurs; this is often referred to as "localization" in CDT terminology. Healing is equally important to understanding the manner in which fatigue damage occurs in real flexible pavement systems. CDT tests are generally performed by applying a continuous sinusoidal load to a specimen. In real pavement system, loading is not continuous, but sporadic, with numerous opportunities for healing to occur in the HMA. Although some preliminary work with promising results has been performed on developing a practical model for modeling healing within the context of CDT, additional work is needed to verify the principle concepts of this model and to refine it.

Permeability

A model to estimate mixture permeability was also developed in NCHRP Projects 9-25/9-31. This model relates the coefficient of permeability to the air void content and surface area of the mixture. Since this model was developed, a substantial amount of additional permeability data has been published by other researchers. This additional data will be complied and the model will be fit to the expanded database. Emphasis will be placed on quantifying the nominal size effect reported by other researchers.

<u>Year 2 Work Plan</u>

The laboratory testing program, Subtask E2e-2, will be initiated in Year 2 of the project and continue through Year 3. Preliminary experimental designs for each of the model improvements have been designed as described below.

Research To Improve the Hirsch Model for Dynamic Modulus

The objective of this work is to refine the Hirsch model by addressing three items: (1) curing time, (2) limiting modulus, and (3) stress dependency. The curing time experiment will involve |E*| measurements on a variety of HMA mixtures, over a range of temperatures and frequencies, at specific times—ranging from 1 day to several months. The limiting modulus experiment will involve testing a similarly broad range of mixtures, made with a wide range of aggregate types, but at high frequencies and low temperatures. The stress dependency experiment will also involve testing a wide range of HMA mixtures, but in this case, the testing will focus on high temperatures and low frequencies, and will be done using a range of applied stress levels.

Hirsch Model Experiment 1: Curing Time Experiment

In this experiment, the change in |E*| values over time will be monitored for 6 to 10 different HMA mixtures. Dynamic modulus measurements will be made at temperatures of 4, 20 and 40°C, using a frequency sweep from 0.01 through 10 Hz. Three specimens from each mixture will be tested. Specimens will be stored at a temperature of 25 ± 3°C, and tested at curing times of 1, 3, 7, 28 and 90 days. Potential aggregates to be included in this experiment include Pennsylvania limestone, Pennsylvania gravel, Pennsylvania greywacke/sandstone, Virginia limestone, Virginia diabase, and Virginia granite. Two different binder grades will be included in the experiment, a PG 64-22, and a polymer-modified PG 76-22. Data will be analyzed by plotting |E*| values as a function of curing time and developing simple mathematical models to characterize the change in modulus with time. Statistical methods will be applied to determine if observed differences in |E*| values with curing time, temperature, frequency, aggregate, etc., are statistically significant. Ultimately, the goal of this experiment is to develop a simple mathematical model that can be used in conjunction with the Hirsch model to account for the effect of curing time on modulus values of HMA concrete.

As discussed below, specimens prepared and tested during this experiment will also be used in the stress sensitivity experiment. A total of six specimens for each mixture will be prepared—three will be initially used in this experiment; once this is complete, they will be subjected to stress sensitivity testing. The other three will be tested after 7 days curing in the stress sensitivity experiment.

Hirsch Model Experiment 2: Limiting Modulus Experiment

The purpose of this experiment is to determine if the limiting ("glassy") modulus of HMA is related to the modulus of the aggregate used, and if a simple approach can be developed to account for this variation in the Hirsch model. The working hypothesis of this experiment is that aggregate modulus can be related reasonably well to specific gravity and/or absorption values. To establish this relationship, a focused literature search will be performed using the internet and the library facilities at The Pennsylvania State University. The goal of this literature search will be to establish a reasonably good predictive model relating aggregate specific gravity and/or absorption to modulus. If such a relationship can be established, this experiment will move forward to laboratory testing. Laboratory testing will involve making dynamic modulus (|E*|) measurements at the lowest possible temperatures and highest possible frequencies, while maintaining reasonable accuracy. Six to 10 mixes will be tested. The aggregates selected will exhibit a range of modulus values, as predicted using the relationship developed during the literature search. In order to ensure that the HMA modulus values are as high as possible, a single binder will be selected which exhibits unusually high low-temperature stiffness. Potential binder grades, for example, include PG 70-16 and PG 76-10. The objective of the data analysis will be to confirm the relationship determined in the literature search between aggregate specific gravity and/or absorption and aggregate modulus—aggregate modulus, in this case, being directly related to the observed limiting modulus of the HMA mixtures. Limiting modulus value will be determined using a variety of approaches. One technique will involve plotting |E*| values vs. phase angle; the limiting |E*| value is then the value when the phase angle is zero. Another approach would be to fit the resulting |E*| data as a function of frequency to a function with a horizontal asymptote at high frequencies; the limiting modulus value is then the value of the horizontal asymptote. The final goal of the data analysis for this experiment is a simple mathematical function which can be used to estimate the aggregate modulus (as used in the Hirsch model) from the aggregate specific gravity and/or absorption. Specimens prepared for this experiment, once it is complete, will then be used in the stress sensitivity testing described below.

Hirsch Model Experiment 3: Stress Dependency Experiment

The objective of this experiment is to determine the effect of increased stress on the value of |E*| at high temperatures and/or low frequencies for a variety of mixtures. Tests will be performed at 40 °C using a frequency sweep of from 0.01 to 10.0 Hz, at three different stress levels, centered about the typical stress used for dynamic modulus tests at high temperature. As described above, the mixes tested will be those tested during Hirsch Model Experiments 1 and 2. Specimens from Experiment 2 will include (for each mixture) 3 specimens not used in the curing time experiment, tested for stress dependency at 7 days curing time, and 3 specimens tested after conclusion of the curing time experiment, after 90 to 120 days curing time. Specimens from each mix included in Experiment 3 will be tested for stress dependency after the conclusion of the low-temperature testing, at a curing time of 7 to 14 days. Data analysis will involve various mathematical and/or statistical techniques to determine the value of the lower limiting modulus, as a function of mix composition and applied stress level.

Research to Improve the Resistivity Model for Rutting Resistance

The purpose of this work is to determine if using data from the MSCR test in the resistivity/rutting model will improve its accuracy for all asphalt binders, modified and non-modified. The original resistivity/rutting model was formulated using viscosity as the binder input property, but the current model has been formulated to use |G*|/sin δ as the input property, in part to try to improve the effectiveness of the model in estimating the rut resistance of HMA made with polymer-modified binders. In this work, viscosity values calculated from the MSCR test at two applied stress levels (100 and 3,200 Pa) will be used as input in the resistivity/rutting model in predicting the rut resistance of various HMA mixtures, as characterized using the simple performance test/flow number test.

Six to 6 to 10 different binders will be characterized using the MSCR test. The majority of the binders tested will be modified, using a variety of different polymer types. Then HMA specimens made with these binders will be tested using the SPT/flow number test. For each binder, specimens will be prepared using two different aggregates; however, all binders will not necessarily be combined with the same two aggregates, so that a wide range of aggregate types can be included in the study. Testing will be done on three replicate specimens for each binder/aggregate combination.

Resistivity Model Experiment 1: MSCR Tests

In this experiment MSCR tests will be performed on 6 to 10 different asphalt binders. The majority of these binders will be modified, using various types of polymer, including SBS, Elvaloy, and PE. The standard protocol for the MSCR test, as promoted by the Federal Highway Administration (FHWA) will be followed. Standard PG grading will also be performed on the binders.

Resistivity Model Experiment 2: SPT/Flow Number Tests

In this experiment, SPT/flow number tests will be performed on various HMA mixtures made using the binders tested in Resistivity Model Experiment 1. Two different aggregates will be combined with each binder to produce two different HMA mixtures. A variety of aggregates will be used, including limestone, diabase and gravel. A total of 12 to 20 different HMA mixtures will be tested; three specimens will be tested for each mixture. Current standard protocols for the SPT/flow number test will be followed.

Data analysis will be performed as part of this experiment. This analysis will include calculation of viscosity values from the MSCR data and using this as input for the rutting/resistivity model to calculate estimated rutting rates. Flow numbers will then be compared to these estimated rutting rates, using graphical and statistical (regression) techniques. As a comparison, rutting rate predications will also be made using $|G^*|/\sin \delta$ values. The objective of the data analysis will be to determine if using the MSCR test data significantly improves the accuracy of the resistivity/rutting model for polymer-modified binders.

Research to Improve the Continuum Damage Fatigue Model

The purpose of this work is to refine the CDT fatigue model by addressing damage tolerance and healing. The proposed effort can be broken down into experiments: (1) Literature Review, (2) Uniaxial Fatigue Tests with Rest Periods, (3) Uniaxial Fatigue Tests to Localization, and (4) Data Analysis.

Experiment 1 will involve a review of research results of NCHRP 9-25, 9-31 and 9-33 pertaining to the CDT fatigue model. Other recent research publications pertaining to CDT, damage tolerance and healing will also be reviewed. Experiment 2 will involve uniaxial fatigue testing of 4 to 6 HMA mixtures with rest periods, to evaluate the effect of healing on damage accumulation. Experiment 3 will involve uniaxial fatigue testing carried out until localization occurs, so that the damage tolerance of each mixture can be characterized. Experiment 4 will consist of data analysis, which will focus on evaluating the current preliminary models for damage tolerance and healing, and refining them as needed.

Literature Review

In this experiment, Dr. Christensen will review various reports and publications dealing with the CDT fatigue model as developed during NCHRP Projects 9-25, 9-31 and 9-33. He will also review other recent publications dealing with CDT, damage tolerance and fatigue. The results of this literature review will be summarized in a short report, approximately 10 to 20 pages in length, and including recommendations concerning revisions and/or refinements in this work plan.

Uniaxial Fatigue Tests with Rest Periods

In this experiment, uniaxial fatigue tests will be performed using different ratios of loading:rest periods. Tests will be performed at two temperatures, typically, 20°C and 4°C, although this may vary depending on the asphalt binder grade used in the HMA being tested. Three sets of tests will be performed: no rest periods, and with 1:2 and 1:4 loading:rest periods. Tests will also be performed at high and low strain levels. A total of four to six mixtures will be tested; these will each consist of a different aggregate and binder; a range of aggregate types and binder grades (including two polymer-modified binders) will be included in the mixtures tested. The specific test conditions will be determined based upon estimates of the fatigue properties of the HMA mixtures, once they are selected and designed.

Uniaxial Fatigue Testing to Localization

In this experiment, the same HMA mixtures tested in the rest period experiment will be subjected to fatigue loading until failure. Testing will be done at high and low temperatures (typically, 20°C and 4°C, although this may vary with binder grade). The strain level will start at a low level, and gradually increase, to ensure that damage will accumulate gradually and that localization will occur within a reasonable time. Specific test conditions will be determined on the basis of the results of the rest period experiment; this will ensure that test conditions are optimal for ensuring gradual accumulation of damage leading to localization within a reasonable time.

Data Analysis

This experiment will involve analysis of the data generated during the laboratory testing. CDT techniques will be used in analyzing data. The general concept will be to develop an effective model of damage rate as a function of the load:rest period ratio and other pertinent factors, such as binder rheological characteristics. Additionally, the observed damage tolerance, as indicated by the damage ratio at localization, will be related to various characteristics, such as modulus and phase angle for the binder and mix. The objective in both cases will be to develop simple models that can be used to predict the behavior of HMA both in the laboratory and in situ.

Research to Improve the Permeability Model

The objective of this work will be to improve the permeability model developed in NCHRP Projects 9-25/9-31 using published permeability test data from other studies. Since the permeability model was developed other research studies have reported permeability data on a wide range of mixtures. These data will be added to the current data base and the permeability model will be reformulated using the expanded data set. Particular attention will be place on quantifying the effect of nominal maximum aggregate size on permeability. The work will consist of two experiments: (1) compile permeability data from various publications, and (2) statistical analysis.

Compile Permeability Data

Several researchers have recently reported results from permeability testing. In this experiment, published permeability data will be located and added to the database originally developed in NCHRP Projects 9-25/9-31.

Statistical Analysis

A variety of statistical and graphical techniques will be used to analyze the expanded permeability data set and develop an improved model for predicting HMA permeability from mixture composition and mixture volumetric data.

Year 2 Milestones

No.	Description	Planned Date
1.	Complete Continuum Damage Literature Review	5/31/08
2.	Finalize Experimental Designs and Select Materials	6/30/08
3.	Collect Materials for Laboratory Testing	8/31/08
4.	Initiate Laboratory Testing	9/1/08
5.	Compile Additional Permeability Data	12/31/08
6.	Complete Permeability Model Development	3/20/09

Budget

The estimated budget for this work element is $371,500 over the five years. The work will be conducted by Advanced Asphalt Technologies, LLC.

Engineered Materials Year 2	Year 2 (4/2008-3/2009)												Team
	4	5	6	7	8	9	10	11	12	1	2	3	
(1) High Performance Asphalt Materials													
E1a: Analytical and Micro-mechanics Models for Mechanical behavior of mixtures													TAMU
E1a-1: Analytical Micromechanical Models of Binder Properties										P	JP	P	
E1a-2: Analytical Micromechanical Models of Modified Mastic Systems										P	JP	P	
E1a-3: Analytical Models of Mechanical Properties of Asphalt Mixtures			P	P	JP					P	JP	P	
E1a-4: Analytical Model of Asphalt Mixture Response and Damage										P	JP	P	
E1b: Binder Damage Resistance Characterization													UWM
E1b-1: Rutting of Asphalt Binders													
E1b-1-1: Literature review													
E1b1-2: Select Materials & Develop Work Plan		DP, P					P						
E1b1-3: Conduct Testing							P						
E1b1-4: Analysis & Interpretation						JP			P			JP	
E1b1-5: Standard Testing Procedure and Recommendation for Specifications													
E1b-2: Feasibility of Determining rheological and fracture properties of thin films of asphalt binders and mastics using nano-indentation													UWM
E1b-2i. Literature Review and Identification of Equipment													
E1b-2ii. Exploratory Use of Nanoindentation Devices							M&A					JP	
E1b-2iii. Conduct of Exploratory Tests on Binder Specimens										P		P	
E1b-2iv. Compare the Binders Responses with DSR													
E1b-2v. Develop & Design Testing Setup													
E2a: Comparison of Modification Techniques													UWM
E2a-1: Literature Review Report							P					P	
E2a-2: Develop a new system for classification of additives													
E2a-3: Conduct testing and propose models									DP			P	
E2a-4: Write an asphalt modification manual													
E2a-5: Develop database for effect of additives													
E2c: Critically Designed HMA Mixtures													UNR
E2c-1: Identify the Critical Conditions				JP						D		F	
E2c-2: Conduct Mixtures Evaluations													
E2c-3: Develop a Simple Test													
E2c-4: Develop Standard Test Procedure													
E2c-5: Evaluate the Impact of Mix Characteristics													
E2d: Thermal Cracking Resistant Mixes for Intermountain States													UWM/UNR
E2d-1: Identify Field Sections							D		F				
E2d-2: Identify the Causes of the Thermal Cracking													
E2d-3: Identify an Evaluation and Testing System													
E2d-4: Modeling and Validation of the Developed System													
E2d-5: Develop a Standard													
E2e: Design Guidance for Fatigue and Rut Resistance Mixtures													AAT
E2e-1: Identify Model Improvements													
E2e-2: Design and Execute Laboratory Testing Program					JP					P			
E2e-3: Perform Engineering and Statistical Analysis to Refine Models													
E2e-4: Validate Refined Models													
E2e-5: Prepare Design Guidance													
(2) Green Asphalt Materials													
E2b: Design System for HMA Containing a High Percentage of RAP Material													UNR
E2b-1: Develop a System to Evaluate the Properties of RAP Materials													
E2b-1.b: Develop a System to Evaluate the Properties of the RAP Binder		P		JP						P			
E2b-2: Compatibility of RAP and Virgin Binders													
E2b-3: Develop a Mix Design Procedure													
E2b-4: Impact of RAP Materials on Performance of Mixtures													
E2b-5: Field Trials													
E1c: Warm and Cold Mixes													UWM
E1c-1: Warm Mixes													
E1c-1i: Effects of Warm Mix Additives on Rheological Properties of Binders													
E1c-1ii. Effects of Warm Mix Additives on Mixture Workability and Stability				JP	P				D		DP	F	
E1c-1iii. Mixture Performance Testing													
E1c-1iv. Develop Revised Mix Design Procedures													
E1c-1v. Field Evaluation of Mix Design Procedures and Performance Recommendations													
E1c-2: Improvement of Emulsions' Characterization and Mixture Design for Cold Bitumen Applications													
E1c-2i: Review of Literature and Standards				JP,P		D			F				
E1c-2ii: Creation of Advisory Group													
E1c-2ii: Identify Tests and Develop Experimental Plan												P, DP	
E1c-2iv. Develop Material Library and Collect Materials.													
E1c-2v. Conduct Testing Plan													

Deliverable codes	Deliverable Description
D: Draft Report	Report delivered to FHWA for 3 week review period.
F: Final Report	Final report delivered in compliance with FHWA publication standards
M&A: Model and algorithm	Mathematical model and sample code
SW: Software	Executable software, code and user manual
JP: Journal paper	Paper submitted to conference or journal
P: Presentation	Presentation for symposium, conference or other
DP: Decision Point	Time to make a decision on two parallel paths as to which is most promising to follow througjh

Work planned
Work completed
Parallel topic

Engineered Materials Year 2 - 5	Year 2 (4/08-3/09)				Year 3 (4/09-3/10)				Year 4 (04/10-03/11)				Year 5 (04/11-03/12)				Team
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	
(1) High Performance Asphalt Materials																	
E1a: Analytical and Micro-mechanics Models for Mechanical behavior of mixtures																	TAMU
E1a-1: Analytical Micromechanical Models of Binder Properties				P, JP	JP	P	P	JP	M&A	D	F,SW						
E1a-2: Analytical Micromechanical Models of Modified Mastic Systems				P, JP	JP	P	P		M&A	JP	D	F,SW					
E1a-3: Analytical Models of Mechanical Properties of Asphalt Mixtures	P	P,JP		P, JP	JP	P	P	M&A		D	SW,JP	F					
E1a-4: Analytical Model of Asphalt Mixture Response and Damage				P, JP	JP	P	P		M&A	D	F,JP	SW					
E1b: Binder Damage Resistance Characterization																	UWM
E1b-1: Rutting of Asphalt Binders																	
E1b-1-1: Literature review																	
E1b1-2: Select Materials & Develop Work Plan	DP, P		P														
E1b1-3: Conduct Testing			P			JP	D	F									
E1b1-4: Analysis & Interpretation		JP	P	JP	P			M&A			JP						
E1b1-5: Standard Testing Procedure and Recommendation for Specifications										P		DP	P	D	JP	F	
E1b-2: Feasibility of Determining rheological and fracture properties of thin films of asphalt binders and mastics using nano-indentation																	
E1b-2i. Literature Review and Identification of Equipment							D	F									
E1b-2ii. Exploratory Use of Nanoindentation Devices		M&A		JP	M&A,SW	JP											
E1b-2iii. Conduct of Exploratory Tests on Binder Specimens			P	P						JP		P					
E1b-2iv. Compare the Binders Responses with DSR														JP			
E1b-2v. Develop & Design Testing Setup															D	P,F	
E2a: Comparison of Modification Techniques																	UWM
E2a-1: Literature Review Report		P		P		P	D	F									
E2a-2: Develop a new system for classification of additives						P											
E2a-3: Conduct testing and propose models			DP	P			JP	P			JP						
E2a-4: Write an asphalt modification manual						P			P			P			D	P,F	
E2a-5: Develop database for effect of additives						P			P			P			D	P,F	
E2c: Critically Designed HMA Mixtures																	UNR
E2c-1: Identify the Critical Conditions		JP		D, F													
E2c-2: Conduct Mixtures Evaluations									D, F	JP							
E2c-3: Develop a Simple Test													D, F	JP			
E2c-4: Develop Standard Test Procedure													D, F				
E2c-5: Evaluate the Impact of Mix Characteristics																D, F	
E2d: Thermal Cracking Resistant Mixes for Intermountain States																	UWM/UNR
E2d-1: Identify Field Sections			D, F														
E2d-2: Identify the Causes of the Thermal Cracking									D, F	JP							
E2d-3: Identify an Evaluation and Testing System												D, F	JP				
E2d-4: Modeling and Validation of the Developed System																D, F	
E2d-5: Develop a Standard																D, F	
E2e: Design Guidance for Fatigue and Rut Resistance Mixtures																	AAT
E2e-1: Identify Model Improvements																	
E2e-2: Design and Execute Laboratory Testing Program		JP		P				D,F									
E2e-3: Perform Engineering and Statistical Analysis to Refine Models						JP		P				D,F					
E2e-4: Validate Refined Models										JP		P					
E2e-5: Prepare Design Guidance															M&A	D,F	
(2) Green Asphalt Materials																	
E2b: Design System for HMA Containing a High Percentage of RAP Material																	UNR
E2b-1: Develop a System to Evaluate the Properties of RAP Materials		JP		P	D, F	JP											
E2b-1.b: Develop a System to Evaluate the Properties of the RAP Binder	P			JP	P			GP									
E2b-2: Compatibility of RAP and Virgin Binders					D, F	JP											
E2b-3: Develop a Mix Design Procedure									D, F	JP							
E2b-4: Impact of RAP Materials on Performance of Mixtures										JP						D, F	
E2b-5: Field Trials																D, F	
E1c: Warm and Cold Mixes																	
E1c-1: Warm Mixes																	
E1c-1i: Effects of Warm Mix Additives on Rheological Properties of Binders.																	UWM
E1c-1ii. Effects of Warm Mix Additives on Mixture Workability and Stability		JP,P	D	F,DP													UWM
E1c-1iii. Mixture Performance Testing						JP		P, DP									UW/UNR
E1c-1iv. Develop Revised Mix Design Procedures										JP	P						UW/UNR
E1c-1v. Field Evaluation of Mix Design Procedures and Performance Recommendations														JP	D	P,F	UW/UNR
E1c-2: Improvement of Emulsions' Characterization and Mixture Design for Cold Bitumen Applications																	UWM
E1c-2i: Review of Literature and Standards		JP, D	F														
E1c-2ii: Creation of Advisory Group																	
E1c-2ii: Identify Tests and Develop Experimental Plan				P, DP				P, DP									
E1c-2iv. Develop Material Library and Collect Materials.																	
E1c-2v. Conduct Testing Plan						JP											
E1c-2vi. Develop Performance Selection Guidelines										JP	D	P, F					
E1c-2vii. Validate Guidelines														JP	P		
E1c-2viii. Develop CMA Mix Design Procedure												P					
E1c-2ix. Develop CMA Performance Guidelines														JP	D	F	

Deliverable codes
D: Draft Report
F: Final Report
M&A: Model and algorithm
SW: Software
JP: Journal paper
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DP: Decision Point

Deliverable Description
Report delivered to FHWA for 3 week review period.
Final report delivered in compliance with FHWA publication standards
Mathematical model and sample code
Executable software, code and user manual
Paper submitted to conference or journal
Presentation for symposium, conference or other
Time to make a decision on two parallel paths as to which is most promising to follow througjh

Work planned
Work completed
Parallel topic

PROGRAM AREA: VEHICLE-PAVEMENT INTERACTION

The interaction between pavement surface and the loading vehicle plays a significant role in both the structural performance (i.e. resistance to fatigue, rutting, and moisture damage) and functional performance (i.e. resistance to skid, noise, and roughness) of pavements. The interaction at the tire-pavement interface represents the final link in the vehicle pavement interaction system, and it controls the distributions of both normal and shear stresses that are transferred to the pavement structure. The loads generated by the moving vehicle are dynamic in nature, and they invoke a dynamic response from the pavement structure which is greatly impacted by the inertia of the pavement structure and the viscoelastic behavior of the hot mix asphalt (HMA) layer.

The more accurate and more realistic predictions of the stresses at the tire-pavement interface and pavement responses under dynamic vehicle loads offer numerous advantages to the FHWA Strategic Roadmap and to the entire pavements/materials engineering community.

The Consortium will work on three elements of vehicle pavement interaction: (a) Workshop on Super-Single Tires, (b) Pavement Response Model Based on Dynamic Analyses, and (c) Mix design to enhance safety. The Workshop on Super-Single Tires will be conducted in the first year while the other two elements will start in year 2.

Category VP1: Workshop

Work element VP1a: Workshop on Super-Single Tires

This effort will organize and hold a workshop on super-single tires usage and their impact on highway pavements. The University of Nevada will work with FHWA to organize the workshop. The following guidelines will be followed:

- The workshop will be held in October, 2007 in the U.S.A.
- The total number of workshop participants will be 12.
- FHWA will supply a list of potential participants.
- UNR and FHWA will identify the final list of participants.
- UNR will invite the workshop participants.
- Participants will make their own travel arrangements.
- UNR will cover travel expenses for the invited participants.
- UNR will prepare a summary of the workshop.

Major Findings from Year 1

The workshop was held at the FHWA Turner-Fairbank Highway Research Center (TFHRC) in McLean, VA on October 25 and 26, 2007. The minutes of the meeting will be published on the Consortium website, www.ARC.unr.edu, after they are forwarded from FHWA.

Year 2 Work Plan

There is no activity planned for year 2.

Budget

The cost for the workshop will be covered by the UNR budget and will be no more than $50,000.00.

Category VP2: Design Guidance

Work element VP2a: Mixture Design to Enhance Safety and Reduce Noise of HMA

Task Lead: Dante Fratta

Introduction

One important emphasis of the new transportation bill is safety. Although safety, comfort, and noise control are known to be direct functions of macro- and micro-texture, there are no significant efforts on integrating these design parameters into asphalt pavement mixtures (Bernhard and Wayson 2005; Guisik and Bahia 2006). It is also not well known if binders and mastics can change friction characteristics and pavement sound generation and absorption. University of Wisconsin-Madison researchers have been working with a number of DOTs in the Midwest to look at new procedures for measuring macro- and micro-texture and enhancing the methods for estimating micro-texture.

Micro-texture is the fine-scale (≤ 1 mm depth) grittiness on the surface of the coarse aggregates. The micro-texture makes direct tire-pavement contact and thus provides the resistance to skidding on the prevailing road surface. Macro-texture is the large-scale roughness that is present on the pavement surface due to aggregate arrangements and provides the drainage ability of the pavement. The combination of macro- and micro-textures, and their changes with traffic and climate factors, make up the overall resistance to skidding. Furthermore, the proper macro-texture contributes to the reduction of roadway noise. Quiet pavement-tire systems have been implemented in Japan and many European countries because of the strong regulatory framework created by the European Community (EU). Several innovative techniques employed in Denmark, the Netherlands, France, Italy, and the United Kingdom have been able to reduce noise level in ranges that vary from 3 to 17 dB (Danish Road Institute 2005; Gibbs et al. 2007). Promising noise-reduction techniques include the use of porous elastic pavements (e.g., single and double layers porous asphalt, stone mastic asphalt, silent block pavements, etc.), recycled porous layers, emulsified asphalt concrete surfacing, use of a dense or semi-dense gradation in low-to-medium speed traffic roadways, and texturing of newly constructed concrete pavements for enhanced skid resistance and reduced pavement-tire noise.

This work element will focus on evaluating and modifying mixture design procedures to enhance safety and noise-reduction properties of asphalt mixtures for flexible pavements. In particular, this work element will develop a laboratory test procedure or a prediction model for the evaluation of macro- and micro-textures of asphalt pavements. It will also focus on comparing these measurements with field measurements of skid resistance and pavement-tire noise. Results from this work will evolve into the development of pavement mixture design protocols that will not only include structural strength and durability, but also traffic safety, comfort and reduced pavement-tire noise.

Relationship to FHWA Focus Areas

This research effort supports the flowing FHWA Focus Areas:

- Advanced Quality Systems: Further development of test methods and design procedures that are more related to actual pavement performance.
- Environmental Stewardship: Reducing noise of pavements is an environmental issue.

Hypothesis

The mixture design of asphalt mixtures (including binder types and aggregates) can be revised to include procedures to enhance driving safety and comfort while reducing noise generation. A holistic pavement mixture design protocol can incorporate mechanical strength, durability, safety, and improved roadway environment (noise) properties of asphalt mixtures.

Objectives

The overall objectives of this work element are:

- To study the state of the art on pavement-tire fiction coefficient and quiet pavement-tire design techniques.
- To develop a surrogate laboratory test to measure pavement macro- and micro-texture and predict safety and noise related properties.
- To establish criteria for the holistic mixture design protocol that optimizes mechanical properties, durability, skid resistance, and noise generation.

The final result of this work element will be the development of a mixture design protocol that will incorporate macro- and micro-structure of mixtures that produce pavement surface layers with enhanced frictional response while reducing pavement-tire noise levels.

Experimental Design

In order to achieve the objectives this work element the following subtasks will be completed.

Subtask VP2a-1: Evaluate common physical and mechanical properties of asphalt mixtures with enhanced frictional skid characteristics

A literature review of the salient physical and mechanical characteristics of the pavement mixtures with improved skid characteristics will be collected to document the overall properties of asphalt pavements designs. Emphasis will be placed on aggregate properties and binder requirements for mixture types that improve not only frictional skid properties but also reduce cost and improve durability and comfort. Examples are Open Graded, Porous Asphalts, and Pavement Friction Courses. The most recent NCHRP reports and worldwide literature will be covered.

Subtask VP2a-2: Evaluate pavement macro- and micro-textures and their relation to tire and pavement noise-generation mechanisms

There are a number of tire-pavement noise generation (e.g., thread vibration, air pumping, slip stick, and stick snap) and noise enhancement mechanisms (Bernhard and Wayson 2005). Quiet noise designs typically address these two issues and include surface textures of less than 10 mm, below surface textures, greater porosity (to reduce high frequency noise), and elastic surfaces. A complete literature review will be performed on both traffic noise generation mechanisms and noise reducing designs. Emphasis will be placed in technologies that reduce traffic noise in more than 5 dB and have a durability of more than 15 years. The results of this task will be compiled and evaluated along with the results from Task 1 to select best practices for pavement mixtures with enhanced skid friction behavior and reduced noise generation.

Subtask VP2a-3: Develop a laboratory testing protocol for the rapid evaluation of the macro- and micro-texture of pavements

Currently there is no system capable of measuring texture profiles for a laboratory-prepared sample. Because of the difficulty in measuring micro-texture profiles, a surrogate for measuring micro-texture is required. The development of such a procedure would enable researchers and engineers to estimate macro- and micro-texture of pavements in order to predict both the dry and wet frictional skid and/or noise reduction designs of pavements. The developed laboratory testing protocol will be correlated to traditional texture tests.

Subtask VP2a-4: Run parametric studies on tire-pavement noise and skid response

Using the data collected in Subtasks VP2a-1 and VP2a-2 and the laboratory testing protocol developed in Subtask VP2a-3, a set of parametric studies for different pavement mixtures will be performed to evaluate the correlation between measured macro- and micro-textures and the skid resistance and pavement-tire noise levels. The pavement mixtures to be tested in this task will be selected in coordination with consortium research activities performed parallel to this work element. This will be done not only to evaluate noise-reducing pavement mixture design, but also to incorporate construction cost and durability in the pavement system design and help create a more holistic pavement mixture design protocol.

Subtask VP2a-5: Establish collaboration with established national laboratories specialized in transportation noise measurements. Gather expertise on measurements and analysis

To complement the capabilities of the consortium with other expertise available in the country, the University of Wisconsin-Madison researchers will reach to nationally recognized laboratories and centers. A leading example is Purdue University's Institute for Safe, Quiet and Durable Highways. This institute's expertise on measurement and analysis will be leveraged to enhance the development of quiet pavement mixture designs. The University of Wisconsin-Madison researchers will establish collaboration initiatives to allow measuring the pavement-noise levels obtained with proposed holistic pavement mixture designs.

Subtask VP2a-6: Model and correlate acoustic response of tested tire-pavement systems

Results obtained in Subtasks VP2a-4 and VP2a-5 will be correlated to pavement mixture design parameters (e.g., gradation, maximum aggregate size, angularity, binder type, etc.). The obtained physical/engineering correlations will be used to constrain numerical models for the evaluation of frictional skid, noise generation mechanisms and pavement/tire noise-reduction designs. These results will be incorporated into a new asphalt mixture design protocol.

Subtask VP2a-7: Proposed optimal guideline for design to include noise reduction, durability, safety and costs

The parametric studies performed and the correlations and models obtained from previous tasks will be analyzed in combination with other work items in the consortium to maximize research resources and the use of the developed data and expertise. These parametric studies and designs will help in the development of improved frictional and noise-reducing mixture designs while maintaining/increasing comfort and reducing construction costs. State DOTs and nationally recognized laboratories and centers will be contacted to collect feedback about the practicality and the merits of the holistic pavement mixture designs.

Major Findings from Year 1

During Year 1, the materials and testing conditions for the plan were selected and are shown in table VP2a.1. In addition, the proposed tests on these materials are shown in table VP2a.2.

The University of Wisconsin-Madison research team performed an extensive literature review of the state of the art in the areas of skid resistance and quiet pavement. Emphasis was placed on evaluating commonality of parameters that have shown in practice to enhance skid resistance. The evaluation of parameters has helped not only in establishing the commonality of interacting factors, but it also helped in developing areas of research needs. A preliminary summary table is presented in table VP2a.3.

The research team has also evaluated different testing methodology for the characterization of surface parameters and acoustic properties of pavement mixtures.

Table VP2a.1. Matrix of materials and conditions.

Neat Binders	PG 58-28	Maximum Aggregate Size	19 mm
	PG 64-22		12.5 mm
Modifiers	SBS		9 mm
	Crumb Rubber		4.75 mm
Mineral Aggregates	Limestone	Aggregate Angularity	Cubical
	Sandstone		Rounded
Aggregate Gradation	Coarse		
	Fine		
	Gap-graded		

Table VP2a.2. Proposed tests on asphalt binders and mixes.

Skid resistance	Skid friction: Modified British Pendulum (dry and wet surfaces)	Noise Absorption	Noise absorption: Waveguide (dry and wet surfaces)
	Surface characterization: Surface profiling		
	Surface characterization: Sand Patch (index tests)		

Acoustic properties of asphalt mixtures: The established parameter for laboratory measurement of acoustic properties is the sound absorption behavior pavement mixtures.

To evaluate the sound absorption behavior of pavement surfaces, the research team is evaluating and designing an impedance tube (waveguide device) that will allow the testing of different asphalt mixture specimen geometries (6-in diameter specimens and slab specimen). The geometry and testing geometry that is being favored is the one proposed by NCAT (Sound absorption setup) (Hanson et al. 2004; Crocker et al. 2004), as this geometry allows testing of both specimen types.

This test will allow the evaluation of the acoustic properties of a large number of pavements mixtures, specially those mixtures that have the desirable strength and dynamic properties of pavements. Finally, to indirectly evaluate the sound absorption properties of asphalt pavements, permeability tests should be run to determine not only the acoustic absorption but also the drainage properties of the pavement. Drainage properties are important in the evaluation of skid friction and the aquaplaning susceptibility of the pavement surface.

Table VP2a.3. Asphalt mixture parameters and performance factors (taken from various sources shown in the References section of this document).

	Rutting Resistance	Fatigue Resistance	Moisture Damage Resistance	Thermal Cracking Resistance	Economy	Skid Resistance	Noise Reduction
Gradation (fine/coarse)	High number of contact points within the mix provide high internal friction that resists permanent deformation.	Gradations that have greater resistance to deformation distribute stresses more evenly and results in less damage from bottom-up cracking.			Fine aggregates are typically more cost effective. However, gradation affects aggregate structure in the pavement, controlling the compactive effort needed.	Coarse gradation increases skid resistance	Higher proportion of fines makes for smoother and quieter surfaces.
Aggregate angularity	High aggregate interlock provides a more structurally stable material that results in stiffer mixes	High aggregate interlock provides a more structurally stable material that results in stiffer mixes			Crushed aggregates are typically more expensive due to processing costs.	Increase angularity increases skid resistance	Smoother aggregates create less tire vibration from adhesive effects.
Aggregate mineralogy			Mineralogy controls hydrophilic (moisture susceptible) or hydrophobic (moisture resistance) of aggregates		Softer aggregates are cheaper to process. Availability of the type of aggregate ultimately drives price, however.		
Maximum aggregate size						Uniform gradation distribution may lead to denser structures and smoother surfaces that may yield lower drainage and reduced skid friction.	Smaller aggregates provide quieter characteristics due to smoother surfaces.
Binder properties	Superpave binder specifications are in place in order to ensure the binder is stiff enough at operating temperatures to resist permanent deformation	Binder can be highly susceptible to fatigue damage. Binders that have a combination of high damage resistance and high healing potential typically lead to good fatigue resistance.		Binder should be ductile at low temperatures in order to relax the stresses induced from thermal restraint. Also, aggregates themselves have no tensile strength, so the tensile strength added by the binder is mostly responsible for resistance to tensile thermal cracking.	Stiffer binders increase compactive effort at similar temperatures, so increased heating is needed to achieve the correct viscosity.		
Asphalt content	Low asphalt contents, known as "dry" mixes, are typically thought of to be more rutting resistant due to less lubrication between the aggregates due to the binder.			The asphalt content should control the expansion and contraction thermal coefficients.	Higher asphalt content increases cost of mix.		
Additives	Many additives are available to stiffen the binder at operating temps, which adds strength to the pavement.	Some polymer additives can add fatigue resistance to materials		Polymers that add ductility to the asphalt can help prevent brittle failure.		Unclear	High damping additives, such as elastic polymers and crumb rubber, have been used to aid in the dissipation of vibration energy. Also, polymers may be used in high void mixes to help increase structural stability.

Skid resistance characteristics. There are a number of both direct and indirect testing techniques to evaluate the skid friction properties of pavements. The direct testing techniques measure the friction coefficient (or a related parameter) of the pavement surfaces. These testing methodologies include the British pendulum (BP) (Liu et al. 2003; Noyce et al. 2007) and dynamic friction tester (DFT) (Brown et al. 2001). The research team will most likely favor the use of the British pendulum as it has simpler geometry for the monitoring of skid resistance on different asphalt mixtures. The instrument will be modified to accept the standard 150 mm-diameter geometry produced by the Superpave gyratory compactor, allowing the research team to evaluate the skid resistance characteristics of standardized asphalt mixture specimens.

Indirect methods include, for example, the sand patch method (SPM) (ASTM E965), circular texture meter (CTM) (Hanson and Prowell 2004), and Ames texture scanner (ATS) (Ames Engineering 2007). The SPM is an indirect and inexpensive measurement technique of the asphalt pavement surface macrostructure. The biggest problem with this methodology is that SPM yields an index parameter (mean texture depth – MTD) that may or may not be able to describe the complexity of the skid friction and noise generation and absorption (figure VP2a.1). Alternatively, the circular texture scanner and the Ames texture scanner use laser profilometry to completely profile the surface of the pavement. These profiling methodologies yield a number of surface measurement parameters that can be used to better correlated noise and skid friction behavior of asphalt pavements but at a greater cost. These portable instruments cost more than $12,000 per unit.

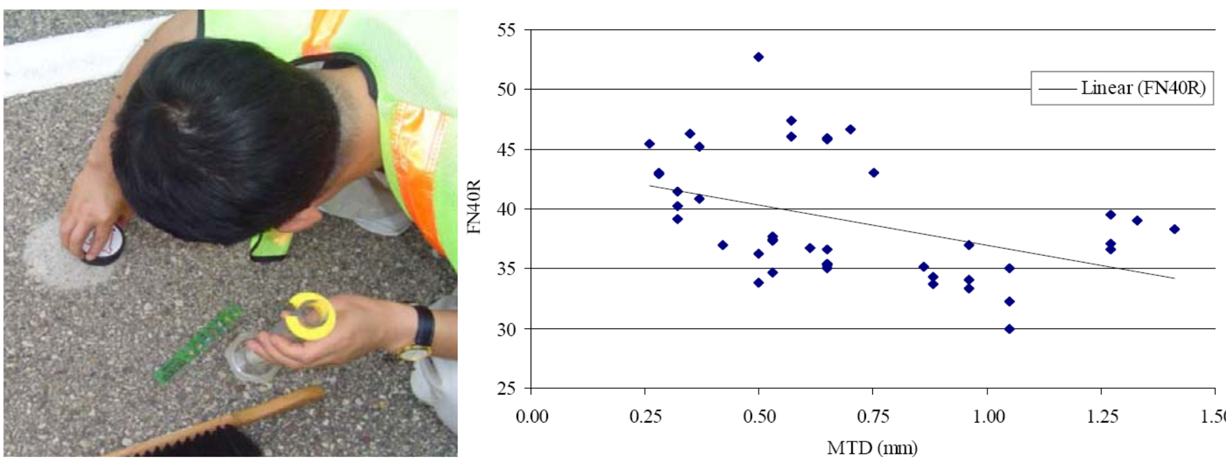


Figure VP2a.1. Photo and chart. Sand patch method and friction number (FN – tire type 40R) versus macro-texture texture depth (MTD) (Noyce et al. 2007).

<u>Year 2 Work Plan</u>

During Year 2, the research team will continue correlating mixture pavement design parameters with good practices on skid friction and low-noise pavements. The research team will also define a finite number of test methodologies to help evaluating the most important parameters for the development a surrogate test or several surrogate tests. Once the test methodologies are defined, the research team will develop a testing matrix to evaluate how binder and texture contribute to the design of skid resistant and quite pavement surface.

The evaluation of the data will be separated by skid resistance and quiet pavement characteristics. For the skid resistance, surface of asphalt pavements will be characterized with both a comprehensive (e.g., surface profiling parameter) and an index test (e.g., sand patch test), and these results will be correlated with direct skid resistance-measured parameters such as British pendulum tests. For quiet pavement behavior, the frequency analysis of noise generated and acoustic absorption will be evaluated by trying to match surface characteristics and mixture microstructures to be able to establish characteristics to reduce noise generation at the source. One of the surface parameters to be analyzed is the effect of negative and positive surface textures on both skid friction and quiet pavement behavior (e.g., noise generation and absorption – Newcomb and Scofield 2004).

Figure VP2a.2 depicts the research approach defined for this work element.

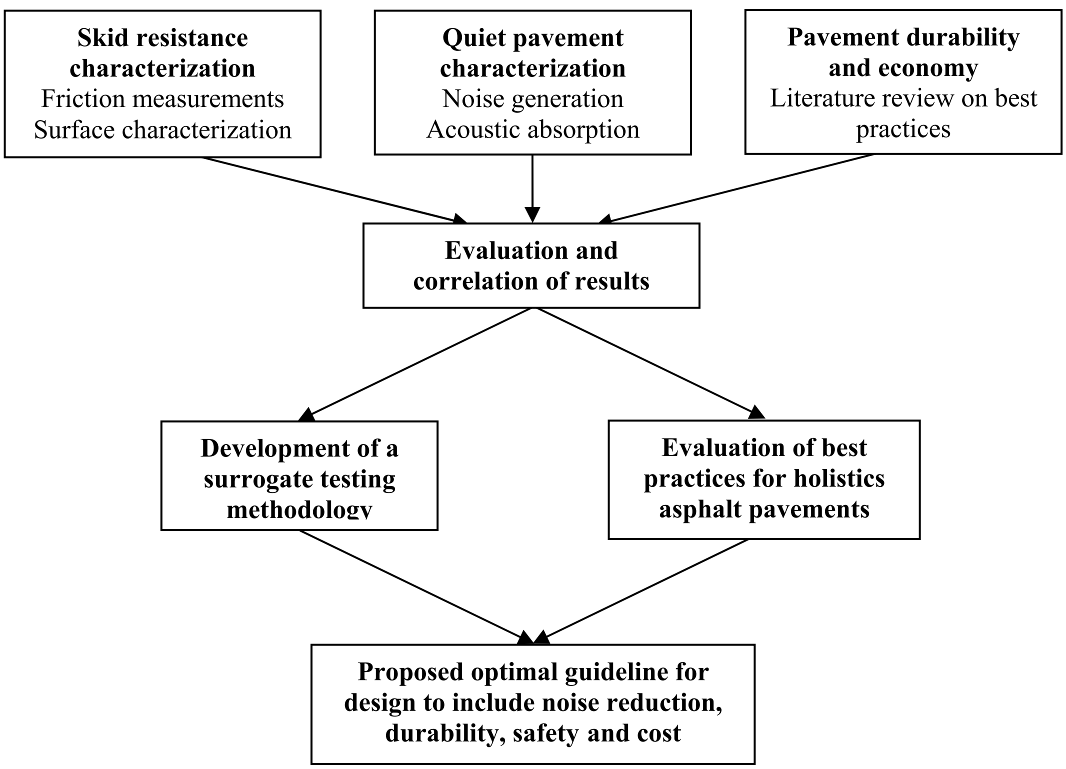


Figure VP2a.2. Chart. Flow chart for research approach.

Year 2 Milestones

- Complete report on review of literature
- Start tests on textures of materials
- Establish a lab test protocol
- Start running parametric studies on tire-pavement noise and skid response

Budget

The estimated budget for this subtask is $200,000 over the four years. The work will be conducted by the University of Wisconsin-Madison.

Cited and Related References

Ames Engineering, 2007, Company Web Site. URL: http://www.amesengineering.com/amestexturescanner.html.

Bernhard, R. J., and R. L. Wayson, 2005, "An Introduction to Tire/Pavement Noise". SQDH 2005-1 HL 2005-2. URL: http://meweb.ecn.purdue.edu/~sqdh/.

Brown, E. R., P. S. Kandhal, and J. Zhang, J., 2001, "Performance Testing for Hot Mix Asphalt" NCAT Report 01-05. National Center for Asphalt Technology. Auburn University, AL.

Crocker, M. J., D. Hanson, Z. Li, R. Karjatkar, and K. S. Vissamraju, 2004, Measurement of Acoustical and Mechanical Properties of Porous Road Surfaces and Tire and Road Noise. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1891, TRB, National Research Council, Washington, D.C., 2004, pp. 16–22.

Danish Road Institute, 2005, "Noise reducing pavements in Japan - study tour report". DRI-DWW Noise Abatement Program Road and Hydraulic Engineering Institute, 68 pages.

Gibbs, D. C., R. H. Iwasaki, R. J. Bernhard, J. F. Bledsoe, D. D. Carlson, C. Corbisier, F. W. Fults, T. M. Hearne, Jr., K. W. McMullen, D. E. Newcomb, J. H. Roberts, J. L. Rochat, L. A. Scofield, and M. E. Swanlund, 2007, "Quiet Pavement Systems in Europe". FHWA Report. URL: http://international.fhwa.dot.gov/quiet_pav/index.htm

Guisik, K., and H. U. Bahia, 2004, "Incorporating Road Safety into Pavement Management". MRUTC 04-04 Technical Report.

Hanson, D. I., R. S. James, and C. NeSmith, 2004, "Tire/Pavement Noise Study". NCAT Report 04-02, National Center for Asphalt Technology, Auburn University, AL.

Hanson, D. I., and B. D. Prowell, 2004, "Evaluation of Circular Texture for Measuring surface Texture of Pavements." NCAT Report 04-05. National Center for Asphalt Technology, Auburn University, Auburn, AL.

Jones, W., 2005, A Quiet Pavement – Coming to Highway Near You. *Asphalt*, Summer 2005, pp. 24-25.

Liu, Y., T. F. Fwa, and Y. S. Choo, 2003, Finite-Element Modeling of Skid Resistance Test. *Journal of Transportation Engineering*, 129(3), 316-321.

Newcomb, D. and L. Scofield, 2004, Quiet Pavement Raise the Roof in Europe. *Hot Mix Asphalt Technology*, September/October 2004, 22-28.

Noyce, D. A., H. U. Bahia, J. Yambo, J. Chapman, and A. Bill, 2007, Incorporating Road Safety into Pavement Management: Maximizing Surface Friction for Road Safety Improvements. MRUTC Project 04-04, 241 pages.

Work Element VP3a: Pavement Response Model to Dynamic Loads

Work element Lead: Peter Sebaaly

Introduction

The interaction between pavement surface and the loading vehicle plays a significant role in both the structural performance (i.e. resistance to fatigue, rutting, and moisture damage) and functional performance (i.e. resistance to skid, noise, and roughness) of pavements. The interaction at the tire-pavement interface represents the final link in the vehicle pavement interaction system, and it controls the distributions of both normal and shear stresses that are transferred to the pavement structure. The loads generated by the moving vehicle are dynamic in nature, and they invoke a dynamic response from the pavement structure which is greatly impacted by the inertia of the pavement structure and the viscoelastic behavior of the hot mix asphalt (HMA) layer.

The normal and shear dynamic stresses that are generated at the tire-pavement interface control the pavement response in terms of the stresses, strains, and deformations that are generated throughout the pavement structure. The tensile strains generated at the bottom of the HMA layer control the fatigue performance of the HMA pavement. The compressive stresses and strains generated throughout the various pavement layers (i.e. HMA, base, and subgrade) greatly influence the rutting performance of the HMA pavement. The shear stresses and strains generated within the HMA layer greatly control the shoving performance of the HMA pavement at intersections, on off-ramps, and at facilities that service slow moving heavy loads such as seaports and airports. The shear stresses at the tire-pavement interface play a major role in the friction resistance of the HMA pavement. In fact, the higher the shear stress the more friction will be developed at the tire-pavement interface, however, the higher shear stress will require an HMA mix that is more resistant to shear.

Relationship to FHWA Focus Areas

This research effort supports the FHWA Focus Areas of Pavement Surface Characteristics and Optimize Pavement Performance.

Hypothesis

The dynamic nature of the traffic loads coupled with the viscoelastic nature of the HMA mixture have significant impact on the performance of flexible pavements and must be properly considered in the analysis and design of such pavements.

Objectives

The objective of this effort is to develop a model to predict dynamic loads of moving vehicles and their effect on the response of flexible pavements. The proposed model will be used to conduct pavement analyses under special loading conditions such as: intersections and off-ramps, heavy loads at ports, and off-road equipment on highway pavements.

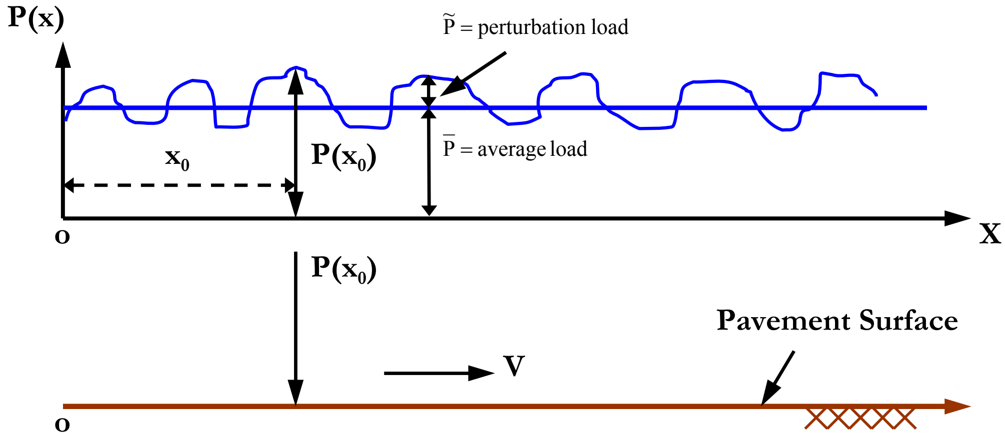
Experimental Design

The proposed model has three major components: dynamic loads, tire-pavement interface, and pavement response. The following subtasks describe the work to be conducted under each of the components.

Subtask VP3a-1: Dynamic Loads

The dynamic loads generated by truck traffic moving at certain speed are impacted by the following factors: truck suspension, road roughness, and speed. The combination of all four factors controls the magnitude of the dynamic loads that are delivered by a moving truck to the pavement surface.

Previous research efforts by FHWA and others showed that the dynamic load can be fully described by two components: nominal static wheel load and the standard deviation of perturbation load as described in figure VP3a-1.1. The dynamic load coefficient (DLC) is defined as the ratio of the standard deviation of the perturbation load over the nominal static load. Previous research efforts by FHWA and others had measured the DLC for various combinations of suspension, speed, and road roughness as shown in table VP3a-1.1.



Perturbation load in terms of dynamic load coefficient (DLC)
(Leblanc & Woodrooffe, 1995)

$$DLC = \frac{\text{Standard deviation of perturbation load}}{\text{Average or nominal static wheel load}}$$

Figure VP3a-1.1. Distribution of dynamic loads along a pavement section.

Table VP3a-1.1. DLC for different tractor suspension (Woodrooffe & LeBlanc).

Vehicle Speed km/h	Tractor Suspension Type								
	Air Bag			Four Spring (Leaf Spring)			Rubber Spring Walking Beam		
	S*	A*	R*	S	A	R	S	A	R
40 60 80	0.03 0.04 0.05	0.04 0.06 0.09	0.05 0.08 0.10	0.04 0.04 0.07	0.05 0.08 0.13	0.08 0.09 NA	0.04 0.04 0.07	0.08 0.08 0.22	0.08 0.11 0.25
40 60 80	0.03 0.04 0.05	0.04 0.06 0.09	0.05 0.08 0.10	0.04 0.04 0.07	0.05 0.08 0.13	0.08 0.09 NA	0.04 0.04 0.07	0.08 0.08 0.22	0.08 0.11 0.25
40 60 80	0.03 0.04 0.05	0.04 0.06 0.09	0.05 0.08 0.10	0.04 0.04 0.07	0.05 0.08 0.13	0.08 0.09 NA	0.04 0.04 0.07	0.08 0.08 0.22	0.08 0.11 0.25

* S = Smooth road; A = Average road; R = Rough road

Using the DLC data, the dynamic load at the tire-pavement interface can be estimated for any combination of suspension, speed, and road roughness. The next step will be to evaluate the impact of braking on the dynamic load at the tire-pavement interface. This is done by imposing the equilibrium dynamic equations of a truck moving at a constant speed and approaching a stopping condition over a pavement surface having a certain downward or upward slope. Solving the dynamic equilibrium equations will result in the distribution of dynamic loads on the various tires.

The objective of this subtask is to develop a system by which the pavement engineer can estimate the dynamic loads at the tire-pavement interface under any of the following combinations of conditions:

- Truck suspension type
- Truck speed
- Road roughness
- Braking conditions
- Pavement slope
- Truck type (single vs multi units)

Not all combinations of the above factors will be applicable for every situation. For example the dynamic loads generated by a truck traveling on a freeway will only be impacted by the suspension, speed, and roughness. On the other, the dynamic loads generated by a truck approaching a stopping condition on an off-ramp will be impacted by the pavement slope and the characteristics of the brake system.

This subtask will use all the available data from previous research conducted by FHWA and others to build a database that includes all available information on the impact of the various factors on the dynamic loads at the tire-pavement interface. The database will then be incorporated into the overall Pavement Response Model.

<u>Subtask VP3a- 2: Stress Distribution at the Tire-Pavement Interface</u>

The objective of this subtask is to define the distribution of normal and shear stresses at the tire-pavement interface. The distributions of the stresses at the tire-pavement interface are influenced by the following factors: load, tire type, and tire inflation pressure.

Previous research activities by FHWA and others have measured the distributions of the stresses at the tire-pavement interface for various tire types under multiple levels of loads and tire inflation pressure. This task will develop a database of all the available information on the distributions of stresses at the tire-pavement interface.

<u>Subtask VP3a-3: Pavement Response Model</u>

In order to properly simulate the impact of dynamic loads generated and delivered by traffic vehicles moving at various speeds on the response of the HMA pavement structure, a dynamic model of the multi-layer pavement structure must be used. The existing static multi-layer elastic solutions suffer from a multitude of limitations which make their ability to predict pavement responses very limited and less accurate. Some of these limitations include: the use of static uniform circular loads at the tire-pavement interface, the use of static elastic properties of the HMA layer, and ignoring the influence of vehicle speed and the inertia of the pavement structure. The finite-element and finite-layer theories are the two commonly used methods to simulate the dynamic behavior of the pavement structure. Such methods incorporate the non-uniform and non-circular normal and shear stresses at the tire-pavement interface, pavement inertia, and the viscoelastic properties of the HMA layer along with the dynamic nature of the moving loads to estimate the stresses, strains, and deformations generated throughout the pavement structure.

The proposed model is based on continuum-based "finite-layer" theory. The HMA layer is characterized as a viscoelastic material, while the base and subgrade layers are characterized as elastic materials. The normal and shear stresses at the tire-pavement interface can be modeled with any shape and any distribution. The vehicle loads are simulated as moving loads at a constant speed. The analytical model treats each pavement layer as a continuum and uses Fourier transform techniques to handle the complex normal and shear stresses at the tire-pavement interface.

Subtask VP3a-4: Overall Model

The objective of this subtask is to combine the three major components (i.e. dynamic loads, stress distributions at the tire-pavement interface, and the pavement response model) into an overall model that is capable to predict pavement responses to dynamic loads with the following characteristics: public domain, time efficient, user-friendly, and applicable to a wide range of problems.

The magnitude of vehicle dynamic loads will be provided by the database developed under Subtask VP3a-1. The stress distributions at the tire-pavement interface will be provided by the database developed under Subtask VP3a-2. And the pavement response model will use the theory developed under Subtask VP3a-3. This subtask will deliver a menu-driven computer software that combines all the components that have been described in the Subtasks along with the appropriate user manuals and training materials.

Major Findings from year 1

This work element did not start in Year 1.

Year 2 Work Plan

During Year 2, the research team will start on developing the electronic databases for the pressure distributions at the tire-pavement interface and the dynamic load coefficients.

Year 2 Milestones

The following milestones will be realized in Year 2:

- Identify the available data on the pressure distribution at the tire-pavement interface
- Identify the available data on the dynamic loads coefficients

Budget

The estimated budget for this work element is $300,000 over the five years. The work will be conducted by the University of Nevada.

Vehicle-Pavement Interaction

	Year 2 (4/2008-3/2009)												Team
	4	5	6	7	8	9	10	11	12	1	2	3	
(1) Workshop													
VP1a: Workshop on Super-Single Tires													UNR
(2) Design Guidance													
VP2a: Mixture Design to Enhance Safety and Reduce Noise of HMA													UWM
VP2a-1: Evaluate common physical and mechanical properties of asphalt mixtures with enhanced frictional skid characteristics												DP	
VP2a-2: Evaluate pavement macro- and micro-textures and their relation to tire and pavement noise-generation mechanisms												DP	
VP2a-3: Develop a laboratory testing protocol for the rapid evaluation of the macroand micro-texture of pavements					M&A							P	
VP2a-4: Run parametric studies on tire-pavement noise and skid response							JP						
VP2a-5: Establish collaboration with established national laboratories specialized in transportation noise measurements. Gather expertise on measurements and analysis													
VP2a-6: Model and correlate acoustic response of tested tire-pavement systems													
VP2a-7: Proposed optimal guideline for design to include noise reduction, durability, safety and costs													
(3) Pavement Response Model Based on Dynamic Analyses													
VP3a: Pavement Response Model to Dynamic Loads													UNR
VP3a-1: Dynamic Loads										JP			
VP3a-2: Stress Distribution at the Tire-Pavement Interface													
VP3a-3: Pavement Response Model													
VP3a-4: Overall Model													

Deliverable codes	Deliverable Description
D: Draft Report	Report delivered to FHWA for 3 week review period.
F: Final Report	Final report delivered in compliance with FHWA publication standards
M&A: Model and algorithm	Mathematical model and sample code
SW: Software	Executable software, code and user manual
JP: Journal paper	Paper submitted to conference or journal
P: Presentation	Presentation for symposium, conference or other
DP: Decision Point	Time to make a decision on two parallel paths as to which is most promising to follow througjh

Work planned
Work completed
Parallel topic

Vehicle-Pavement Interaction	Year 2 (4/08-3/09)				Year 3 (4/09-3/10)				Year 4 (04/10-03/11)				Year 5 (04/11-03/12)				Team
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	
(1) Workshop																	
VP1a: Workshop on Super-Single Tires																	UNR
(2) Design Guidance																	
VP2a: Mixture Design to Enhance Safety and Reduce Noise of HMA																	UWM
VP2a-1: Evaluate common physical and mechanical properties of asphalt mixtures with enhanced frictional skid characteristics				DP													
VP2a-2: Evaluate pavement macro- and micro-textures and their relation to tire and pavement noise-generation mechanisms				DP													
VP2a-3: Develop a laboratory testing protocol for the rapid evaluation of the macroand micro-texture of pavements		M&A		P													
VP2a-4: Run parametric studies on tire-pavement noise and skid response			JP			JP	D	P, F									
VP2a-5: Establish collaboration with established national laboratories specialized in transportation noise measurements. Gather expertise on measurements and analysis																	
VP2a-6: Model and correlate acoustic response of tested tire-pavement systems										JP	D	F					
VP2a-7: Proposed optimal guideline for design to include noise reduction, durability, safety and costs											D	P, F					
(3) Pavement Response Model Based on Dynamic Analyses																	
VP3a: Pavement Response Model to Dynamic Loads																	UNR
VP3a-1: Dynamic Loads			JP						D, F	JP							
VP3a- 2: Stress Distribution at the Tire-Pavement Interface									D, F	JP							
VP3a-3: Pavement Response Model					SW - b version								SW, JP				
VP3a-4: Overall Model													D	F			

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DP: Decision Point	Time to make a decision on two parallel paths as to which is most promising to follow througjh

Work planned
Work completed
Parallel topic

PROGRAM AREA: VALIDATION

INTRODUCTION

The concept of Validation may encompass several different areas. In the process of taking a fundamental scientific or engineering principle from theory to general use, there are many steps involved. Initially, the experimental process has to be developed and refined such that the experimental method can distinguish between different materials and provide useful information. As the method progresses toward development, the sample set to which the method is exposed generally expands to a much more diverse set. This expansion of the tested sample set is a form of validation. In this project, the application of a test method or procedure to a larger, more diverse sample set is considered to be development, rather than validation, although either label may be appropriate to describe this type of research activity.

Another type of Validation is the use of larger scale test facilities that incorporate a variety of materials in an accelerated loading environment. The accelerated loading is often accomplished using a large-scale load frame such as the ALF (Accelerated Load Facility) at the FHWA Turner-Fairbank Highway Research Center. Accelerated loading at larger scale facilities may also be accomplished by using full or partial scale load vehicles such as the third-scale model mobile loading simulator at Texas Transportation Institute. Some of the advantages of using larger scale accelerated facilities are that the testing is more representative of actual pavement loading compared with laboratory loading devices. The pavement materials used in larger scale loading facilities are generally produced with standard construction equipment using standard construction techniques, and the test sections may be highly instrumented in order to acquire the necessary data. As might be expected though, temperature control during testing is less precise than a laboratory setting, but the data are valuable because they are closer to real-life pavement conditions and are used to evaluate pavement performance. These sites provide a source of original materials collected at the time of construction from which physical property data and any other acquired data can be compared and used for performance prediction, a source of pavement core samples that can be tested as the pavement ages in service (although usually a short time period), a comparative assessment of the performance of different materials under accelerated loading that can be correlated with predicted performance, and sites where instrumentation devices, both new and existing, can be used to acquire pavement performance information. The Asphalt Research Consortium research team intends to use any available materials and data from larger-scale accelerated-loading test facilities in several work elements and also investigate the possibility of constructing new validation sites at accelerated loading facilities such as the Pecos (Texas) test site, a collaboration between Texas Transportation Institute and industry.

Validation can also be accomplished using full-scale validation sections constructed in coordination with State Departments of Transportation (DOT's) where specification-grade materials from different sources are compared. Five of these types of sites were constructed to date as part of the recently completed FHWA-sponsored project "Fundamental Properties of Asphalts and Modified-Asphalts II" by Western Research Institute. These sites provide exposure of the pavement to actual traffic loading and environmental conditions while being monitored annually using standard-format LTPP monitoring procedures. These sites have available a source of original materials collected at the time of construction from which physical property data can be compared and used for performance prediction, pavement core samples that can be tested as the pavement ages in service, a comparative assessment of the actual field performance of different materials that can be correlated with predicted performance, and sites where instrumentation devices, both new and existing, can be used to acquire pavement performance information. The Asphalt Research Consortium research team intends to use the existing WRI validation sites and also construct new sites in coordination with State DOT's to validate the research findings from this project.

Two additional areas of Validation are the continual assessment of the current SuperPave® specifications (M320, M323, and MP8) for appropriate updates/improvements, and the implementation of the Mechanistic-Empirical Pavement Design Guide (MEPDG). The advent of the multitude of "SHRP Plus" specifications in many states that are used to measure properties that State DOT's believe are important is the impetus that is behind the need to continually assess the current specification tests. As new methods of testing are developed by the Consortium and others to measure binder and mixture properties, the need exists to implement the best methods in a timely manner. The Consortium intends to work closely with FHWA, AASHTO, and others to keep the SuperPave® PG grading system up to date with the best methods. The Consortium also intends to use State DOT sites where they have implemented the Mechanistic-Empirical Pavement Design Guide (MEPDG) to validate the asphalt materials models.

HYPOTHESES

The Consortium working hypotheses for Validation are:

- Field validation sites built on public highways in cooperation with state DOT's that have a stored supply of original materials, documented location, and monitored performance are useful and necessary for validation of methods, models, and theories developed in research programs intended to improve asphalt pavement performance.
- Field validation using accelerated loading facilities to compare performance of compositionally different materials are also useful for validation of methods, models, and theories developed in research programs intended to improve asphalt pavement performance and offer the advantage of acquiring performance data in a shorter period of time.

OBJECTIVES

- Construct comparative pavement validation sites on public highways in cooperation with State DOT's or at accelerated loading facilities using compositionally different asphalts and perhaps different additives such as RAP, polyphosphoric acid, lime, or liquid anti-strip.

- Collect and store sufficient material from the construction of comparative pavement sites in order to support the research activities of the Consortium and other researchers as approved by the Consortium Program Manager and the AOTR.
- Monitor the comparative validation sites annually, or more often if necessary, to document pavement performance.
- Assist State DOT's with the implementation of the MEPDG. Validation through MEPDG Sites and Revisions of the MEPDG Asphalt Materials Models
- Continually assess the SuperPave® PG specifications for improvements derived from Consortium or other research.

EXPERIMENTAL DESIGN

Category V1: Field Validation

Work element V1a: Use and Monitoring of Warm Mix Asphalt Sections (Year 1 start)

The FHWA and FHWA Western Federal Lands is planning to construct two warm-mix asphalt sections and a hot-mix asphalt control section in a project on the road just inside the east gate of Yellowstone National Park in August 2007. It is planned for Consortium personnel to collect samples of the paving materials at the time of construction for use in the Engineered Paving Materials area and possibly other areas of research. The FHWA was not planning on annual monitoring of the sections; therefore, it is planned for the Consortium to establish two 500-foot performance monitoring sections within each different material that will be monitored using LTPP established procedures on an annual basis.

Major Findings from Year 1

Construction of two warm-mix asphalt sections and a control hot-mix asphalt section were completed in early September 2007 near the East Entrance to Yellowstone National Park (YNP) on U. S. Highway 14-16-20. After construction was completed, three 500-foot monitoring sections were established in each of the three different materials and initial monitoring data was obtained on each section. Samples of all construction materials were obtained during construction. The layout of the project is shown in figure V1a.1.

Year 2 Work Plan

It is planned to continue to monitor the sections for performance on an annual schedule. It is not planned to obtain core samples because the YNP officials are very sensitive to the appearance of the road. If distress starts to become moderate to severe, YNP officials may be asked if core samples can be obtained.

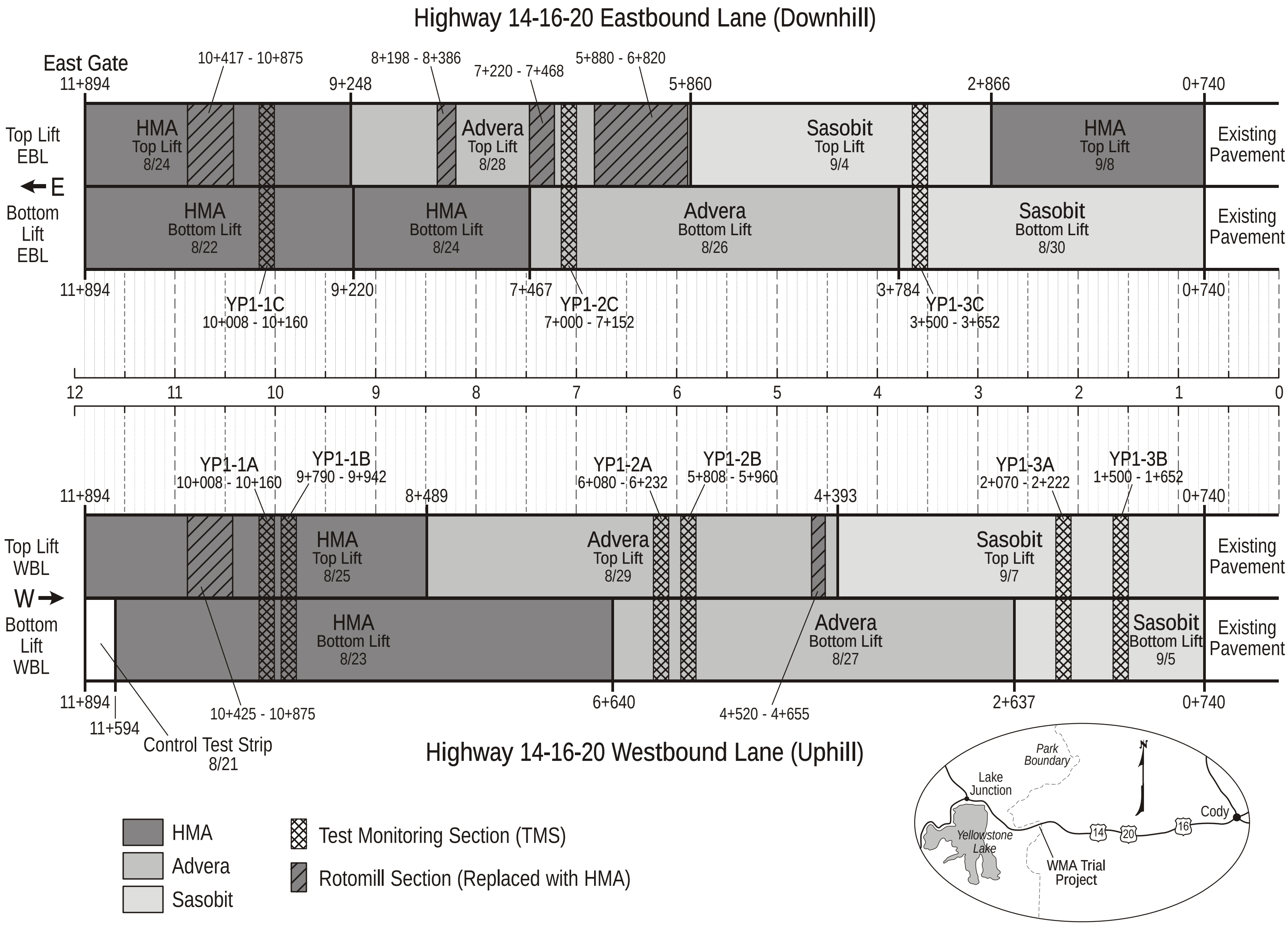


Figure V1a.1. Layout of the Yellowstone National Park Warm-Mix Asphalt project.

Work element V1b: Construction and Monitoring of additional Comparative Pavement Validation sites (Year 1 start)

Western Research Institute has constructed five comparative pavement validation sites in five states where different asphalt sources (different crude sources or different blends) are compared. The five sites were built in cooperation with state DOT's under a previous contract with FHWA entitled "Fundamental Properties of Asphalts and Modified Asphalts II". The sites are located in climate areas that can be labeled cold-dry, hot-dry, and cold-wet. These sites provide a source of original materials that were collected during construction, documented performance that is recorded on an annual basis, and serve as a mechanism to validate methods, models, and procedures that are developed as part of the Consortium research.

Construction of additional sites is desirable to have a more robust variation in environmental exposure, materials, and loading. It will be most advantageous to have the new validation sites constructed as early as possible to maximize service and monitoring during the period of this contract. This effort involves planning and coordination efforts with State DOT's and contractors. Substantially different asphalt sources also need to be identified at each new site to provide the most variability. The focus will be on projects where the different asphalt sources can be used throughout the full-depth of the asphalt pavement construction, especially on the surface. However, other types of construction, such as "mill and fill" can be acceptable provided the different asphalt sources are used on the surface. Each asphalt source will have two 500-foot performance monitoring sections that will be monitored throughout the pavement life. The 500-foot sections will be permanently marked and identified so future monitoring can provide meaningful data and samples. Sampling of all materials including: aggregate, asphalt, loose mix, and as-constructed cores will provide materials from which data can be obtained that can be used to predict pavement performance. The objective is the placement of field validation sites that are constructed using consistent engineering practices. Ideally, each site will contain four pavement sections that are constructed using asphalt binders obtained from different sources. The performance of the sites will be documented over many years of service and core samples will be obtained to evaluate the chemical, rheological, and mechanical properties as a function of service. The sites will also provide core samples that represent the changes the pavement undergoes during actual service with traffic loading and environmental exposure.

Major Findings from Year 1

Additional comparative validation sites were pursued with several state DOT's. WRI participated in sampling materials from four sections constructed at MnRoad using polyphosphoric acid (PPA). The sections were asphalt + PPA with a phosphate ester antistrip additive; asphalt + SBS polymer + PPA with a phosphate ester antistrip additive; asphalt + SBS polymer; and asphalt + Elvaloy polymer + PPA with a phosphate ester antistrip additive. Minnesota DOT performs performance monitoring and can take core samples if needed.

Year 2 Work Plan

Continue pursuit of additional comparative pavement sites with state DOT's or other agencies.

Category V2: Accelerated Pavement Testing

Work element V2a: Scale Model Load Simulation on small test track (Later start)

The Third-Scale Model Mobile Loading Simulator (MMLS3) has been successfully used by the TTI and NCSU research team to evaluate the fatigue and rutting performance of asphalt pavements under moving loads. The accurate control of temperature and loading provided by the MMLS3 and an instrumented pavement slab provides an excellent framework from which pavement response and performance models can be validated. In a recently completed research project funded by the NCDOT, the NCSU research team has demonstrated that the pavement performance under MMLS3 loading can be predicted using a set of mechanistic material and pavement models within a reasonable accuracy. In this research, the micromechanics model and the VEPCD-FEP++ model will be validated using the MMLS3. Both fatigue cracking and rutting performance will be evaluated.

Major Findings from Year 1

No activity during year one.

Year 2 Work Plan

This work element is included in the work plan because it is available at Texas A&M/TTI and it may be possible to get collaborative support from industry to obtain accelerated testing on materials that would be beneficial to the Consortium and FHWA. This work element is not going to be vigorously pursued in the work plan but will remain as a distinct possibility that is available for validation of tests, methods, or models from the Consortium research.

Work element V2b: Construction of validation sections at the Pecos Research & Testing Center (Later start)

The Pecos Research & Testing Center (RTC) is a collaboration between Texas A&M / Texas Transportation Institute and industry. The Consortium will investigate the possibility of constructing comparative pavement validation sections at the Pecos RTC. The Pecos RTC is suitable for applied research testing under controlled conditions. The 5,800-acre facility has nine distinct test tracks and a full range of support facilities.

Major Findings from Year 1

No activity during year one.

Year 2 Work Plan

This work element is included in the work plan because it is available at Texas A&M/TTI and it may be possible to get collaborative support from industry to obtain accelerated testing on materials that would be beneficial to the Consortium and FHWA. This work element is not going to be vigorously pursued in the work plan but will remain as a distinct possibility that is available for validation of tests, methods, or models from the Consortium research.

Category V3: R&D Validation

Work element V3a: Continual Assessment of Specification

Work Element Lead: Hussain Bahia

Introduction

For the past several years, the spread of the PG-Plus specifications has resulted in a concern about the future of the PG system. In the Consortium research, there will be several new procedures that will be developed to measure rutting of binders, fatigue of binders, cohesion, adhesion, and other possible tests. This work element will review and evaluate concepts and test methods resulting from Consortium and other efforts and evaluate their potential for future revisions of the performance graded binder specifications (AASHTO M320), the Superpave mixture specifications (AASHTO M 323), and the SMA mixture specification (AASHTO MP8).

This work element will focus on recommendations and building consensus for a sequence of gradual changes to improve the PG system and minimize, if not eliminate, the empirical tests that are being used today. This work element will include visits to various state highway agencies and coordination with FHWA, the Asphalt Institute, NAPA, and other stakeholders. This work item will also include close monitoring of the development of specifications in Europe and leveraging the evaluation and reviews done by the technical teams of the European Specification Harmonization project.

Relationship to FHWA Focus Areas

This work element is related to the following focus areas:

- Optimum Pavement Performance: Introducing methods for better characterization of modified asphalts.
- Advanced Quality Systems: Further development of test methods that are more related to actual pavement performance.

Hypothesis

The main reason for the evolution of the Superpave plus specifications is the lack of better options for filling the gaps in the current specifications. Understanding the tests used in the (plus) specifications and their scientific basis can help reduce the proliferation of such specifications. In addition, proactive response to the perceived gaps and building consensus on more scientific tests could keep the national standards more usable.

The implementation of new tests that have been developed since the introduction of PG grading can be significantly expedited if there is a proactive evaluation of gaps and proposals for new scientific tests.

Objectives

The objective of this work element is to recommend and build consensus for a sequence of gradual changes to improve the PG system and minimize the empirical tests that are being used today. This will result in better prediction of performance of asphaltic materials and pavements.

Experimental Design

The objective of this work element will be addressed by pursuing the following subtasks:

Subtask V3a-1: Evaluation of the PG-Plus practices and the motivations for selecting the "plus" tests.

Subtask V3a-2: Detailed analysis of all PG-Plus tests being proposed or in use today, documentation of benefits and costs of these tests, and comparison with new tests

Subtask V3a-3: Development of protocols for new binder tests and database for properties measured

Subtask V3a-4: Development of specification criteria for new tests based on field evaluation of construction and performance

Subtask V3a-5: Interviews and surveys for soliciting feedback on binder tests and specifications

Major Findings from Year 1

During Year 1, a review of the PG-Plus practices and a literature review were conducted to look at the most commonly used specifications. The work was done in three areas:

1. PG Rutting Parameter. The work on rutting was conducted in coordination with project on PG grading for airfield pavements sponsored by AAPTP (Project 04-02). Tables V3a.1 and V3a.2, taken from that study, gives a summary of the Plus specifications for the different states. Figures V3a.1 and V3a.2, also from the same study, compare elastic recovery and recovery from the MSCR test. It can be seen that the testing at various stresses (100 and 3200 Pa) does not make a significant difference in correlations with ER from ductility test. A higher stress level is required to show significant differences for the binders tested in this study.

Table V3a.1. Superpave-Plus specification details by state (Part I) (after project AAPTP 04-02).

State	Superpave Plus Specifications
Alabama	Polymer type (Elastomer), Quantity (%) and Quality (Measured with Infrared Trace)
Alaska	Softening point. Toughness & Tenacity at 25 ºC (Alaska DOT test method)
Arizona	Polymer type (SBS or CRA) Quantity (%) plus the following requirements: • For SBS modified: solubility in TCE, phase angle, elastic recovery at 10 ºC and softening point • For CRA modified: rotational viscosity, penetration ant 4ºC, softening point and resilience
Arkansas	Polymer type (Elastomer) and Elongation Recovery at 25 ºC
California	NO
Colorado	Ductility, Toughness & Tenacity at 25 ºC, Elastic Recovery at 25 ºC
Connecticut	NO
Delaware	Rotational viscosity at 165ºC
Florida	Spot Test, Smoke test, Phase Angle, Solubility in TCE, Absolute Viscosity at 60 ºC
Georgia	Phase Angle, Separation, Solubility in TCE
Hawai	NO
Idazo	Elastic Recovery at 25 ºC
Illinois	Separation, Force Ratio at 4 ºC, Toughness & Tenacity at 25 ºC, Elastic Recovery at 25 ºC
Indiana	NO
Iowa	NO
Kansas	Separation, Elastic Recovery at 25 ºC
Kentucky	Solubility in TCE, Elastic Recovery at 25 ºC
Louisiana	Solubility, Separation, Force Ductility Ratio, Force Ductility, Elastic Recovery at 25 ºC, Ductility at 2 5ºC
Maine	NO
Maryland	Critical cracking temperature
Massachusetts	Polymer type (SBR)
Michigan	Polymer type (SBS or SBR, others need approval), Solubility in TCE, separation, Elastic Recovery at 25 ºC, plus the following requirements: • For SBS modified: Force Ratio • For SBR modified: Toughness & Tenacity at 25 ºC
Minnesota	NO
Mississippi	Polymer type (SBS or SBR, others need approval), Quantity (%), Temperature - Viscosity Curve
Missouri	Separation, Elastic Recovery at 25 ºC
Montana	Ductility at 25 ºC

Table V3a.2. Superpave Plus specification details by state (Part II)

State	Superpave Plus Specifications
Nebraska	Phase Angle, Elastic Recovery at 25 ºC
Nevada	Ductility, Sieve, Toughness & Tenacity at 25 ºC, Polymer Content
New Hampshire	NO
New Jersey	Elastic Recovery at 25 ºC
New Mexico	NO
New York	Elastic Recovery at 25 ºC
North Carolina	Polymer type (Elastomer)
North Dakota	To implement in 2005
Ohio	Penetration at 25 ºC, Phase Angle, Separation, Homogeneity, Elastic Recovery at 25 ºC
Oklahoma	Separation, Solubility in TCE, Spot Test, Elastic Recovery at 25 ºC
Oregon	Only for Chip Seal Asphalt
Pennsylvania	Separation, Softening Point, Elastic Recovery at 25 ºC
Puerto Rico	
Rhode Island	NO
South Carolina	Polymer type (Elastomer)
South Dakota	Elastic Recovery at 25 ºC
Tennessee	Polymer type (Elastomer), Viscosity at 135 ºC (Contractor Plant Testing), Softening Point, Elastic Recovery at 10 ºC, Screen Test.
Texas	Elastic Recovery at 10ºC
Utah	Phase Angle, Elastic Recovery at 25 ºC
Vermont	NO
Virginia	Elastic Recovery at 25 ºC
Washington	NO
West Virginia	Elastic Recovery at 25 ºC
Wisconsin	To be implemented in 2005
Wyoming	Elastic Recovery at 25 ºC

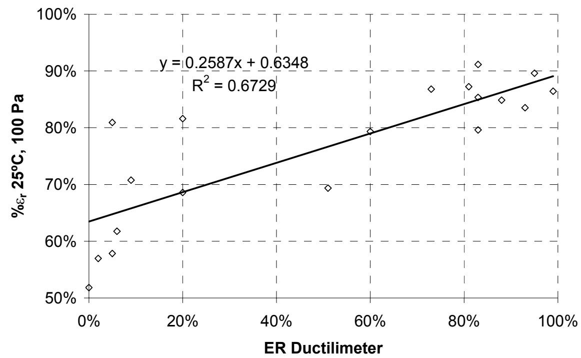


Figure V3a.1. Chart. ε_r% at 25 ºC and 100 Pa vs. ER (after project 04-02).

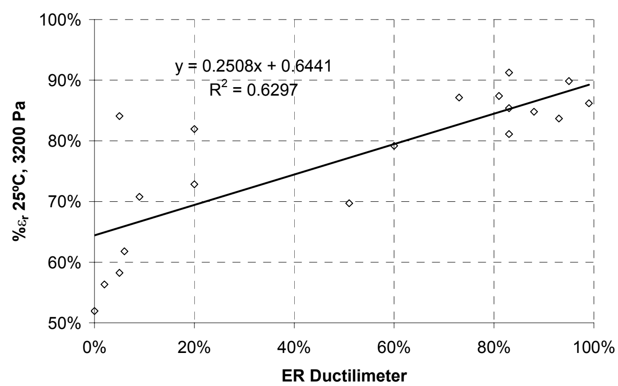


Figure V3a.2. Chart. ε_r% at 25 ºC and 3200 Pa vs. ER (after project 04-02).

2. PG Fatigue Parameter. There is little doubt that the current fatigue parameter G*.sinδ is not a good choice for measuring contribution of binder to fatigue resistance. In collaboration with FHWA, a set of binders was tested for binder fatigue and also for mixture fatigue. Results are shown in figure V3a.3. The binder fatigue testing was done using the time sweep in the DSR. It was observed that minor variation in the time setting of the time sweep could change fatigue behavior significantly. Figure V3a.4 shows the change in correlation when the testing sequence for the same binders, using the same DSR, was changed very slightly. Figure V3a.5 shows the results of the strain-controlled time sweep with various setting on the DSR. The results showed that any binder fatigue test that includes a time weep should consider the possible variation in load history.

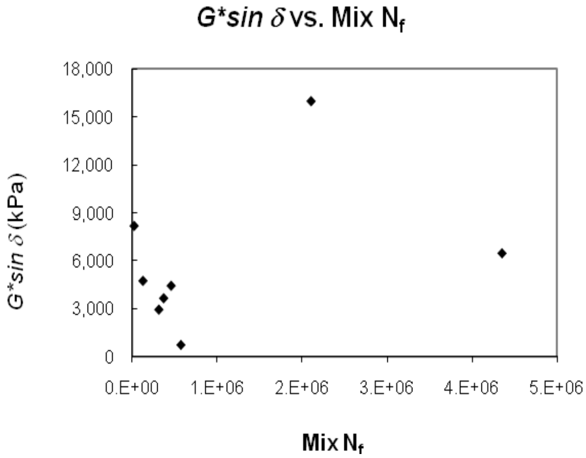
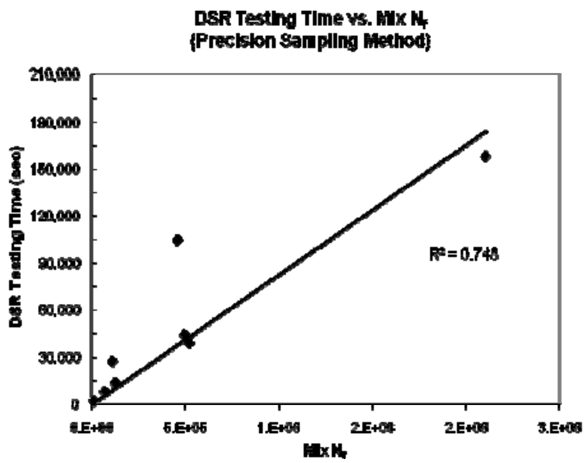
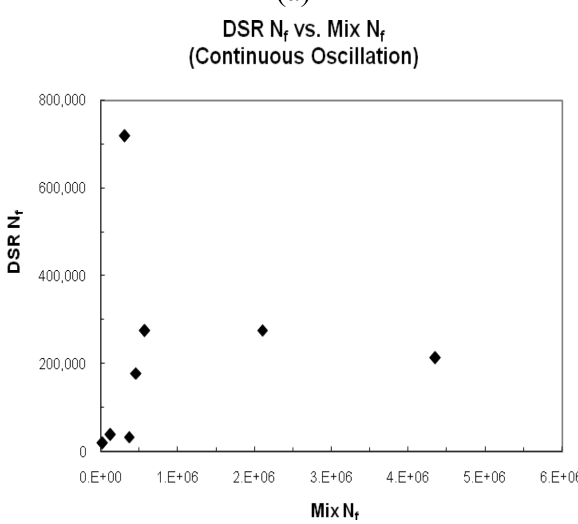


Figure V3a.3. Chart. Plot of *G*sin* δ values against mixture fatigue life.



(a)



(b)

Figure V3a-4. Chart. Plot of DSR testing time-to-failure against mixture cycles until failure for (a) the precision sampling method, (b) continuous oscillation.

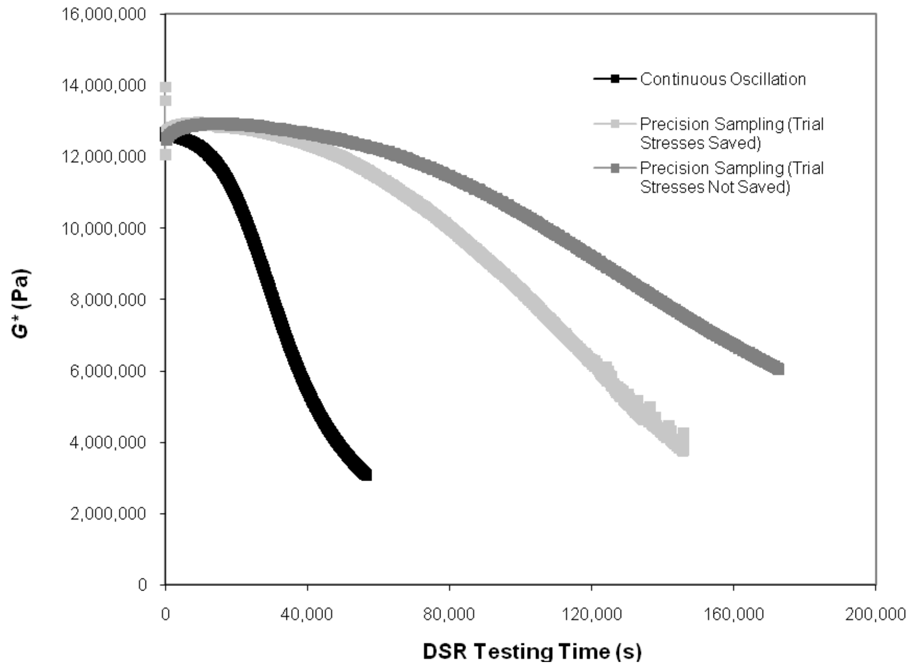


Figure V3a.5. Chart. Plot of binder stiffness against testing time for different types of fatigue tests

3. PG Low Temperature Parameters. There is no doubt that the majority of agencies are not using – and do not plan on using – the Direct Tension Test (DTT). It also appears that the equipment manufacturers are not selling the DTT, and it is almost impossible to get the existing machines serviced by the manufacturers. Therefore, here is a critical need for a failure test to replace the Direct Tension Test. There are two tests that were evaluated in Year 1 of the project: The Single Edge Notched Beam (SENB) test that is used in Canada and the ABCD test developed by Dr. S. Kim of Ohio University. The SENB test could be tested in a modified BBR machine. During Year 1 a plan for adding a stepped motor to the BBR to conduct a constant deformation test was developed. A look at the notched beam geometry and consideration of various steps for conducting the test was taken. It is clear that there is a great potential for simple modification of the BBR to conduct a version of the test while using a modified mold and notch procedure.

Year 2 Work Plan

During Year 2, the team will continue to evaluate the PG plus practices and conduct a thorough review of whether the new tests can replace the empirical tests used today to complement the PG specifications. The following specific tasks will be pursued:

1. Evaluate the MSCR test results and evaluate if they can be used to replace the elastic recovery. Continue to follow up with the criteria being proposed by FHWA and provide input to the binder ETG. Collect information about initial use of the MSCR tests by various state DOTs.

2. Coordinate work with the fatigue studies to propose a surrogate test using the DSR. The stress sweep and the binder monotonic tests are both promising and could yield a solution.
3. Work on further development of the SENB test and the modification of the BBR.
4. Evaluate the new aging procedure and the new procedure for estimating the mixing and compaction temperatures.

Figure V3a.6 depicts the research approach defined for this work element.

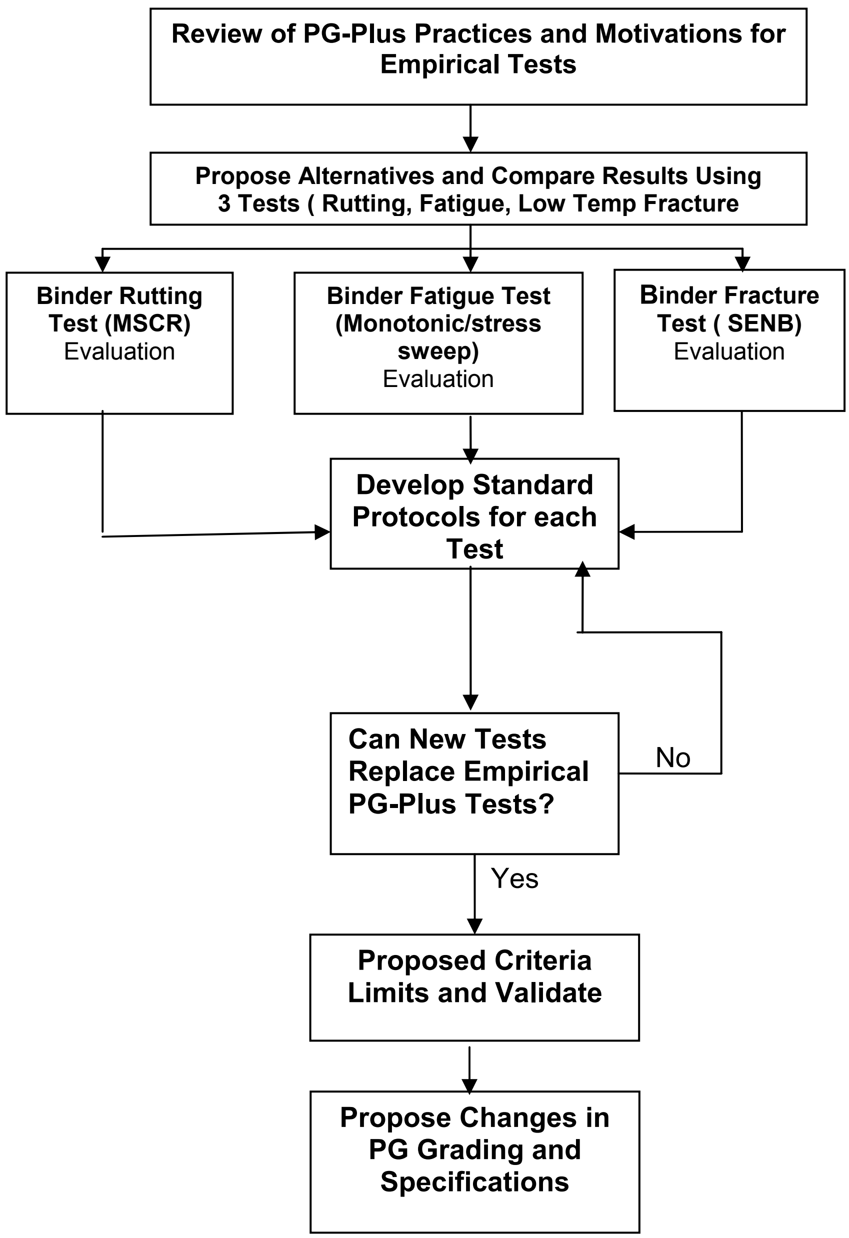


Figure V3a.6. Chart. Flow chart for research approach.

Year 2 Milestones

- Develop standard protocols for each of the three tests (rutting, fatigue, and LT cracking)
- Collect data using PG-Plus empirical data and new tests and provide technical and practical comparisons
- Contact DOTs using PG-Plus and collect feedback regarding the new tests

Budget

The estimated budget for this subtask is $400,000 over the next four years. The work will be conducted by the University of Wisconsin-Madison in collaboration with Advanced Asphalt Technologies (AAT).

Cited and Related References

Bahia, H. U., D. I. Hanson, M. Zeng, H. Zhai, M. A. Khatri, and R. M. Anderson, 2001, Characterization of Modified Asphalt Binders in Superpave Mix Design. Publication NCHRP 459, National Academy Press, Washington, D.C.

D'Angelo, J. Development of Standard Practice for Superpave Plus Specifications. Presented at the NEAUPG 2005 meeting.

Delgadillo, R., D-W Cho and H. Bahia, 2006, Non Linearity of Repeated Creep and Recovery Binder Test and the Relationship With Mixture Permanent Deformation. *In Transportation Research Records: Journal of the Transportation Research Board*, No 1962, TRB, National Research Council, Washington DC, pp. 3-11.

Drakos, C., R. Roque, and B. Birgisson, 2001, Effect of Measured Tire Contact Stresses on Near-Surface Rutting. *In Transportation Research Record: Journal of the Transportation Research Board*, No.1764, TRB, National Research Council, Washington, D.C., pp. 59-69.

Performance Graded Specifications & Test Method Tolerances. Combined State Binder Group (Iowa, Michigan, Minnesota, North Dakota, South Dakota & Wisconsin DOTs & Nebraska DOR), January 2006.

Reinke G., S. Glidden, S. Engber, and D. Herlitzka, 2005, Properties of Polymer Modified Bitumens Related to Mixture Resistance to Permanent Deformation. Presented at 4th Mexican Asphalt Congress. August 24-26, 2005, Guadalajara, Mexico.

Witczak, M. W., K. E. Kaloush, and H. Von Quintus, 2002, *Journal of the Association of Asphalt Paving Technologists*, 71: 671-691.

Work Element V3b: Validation of the MEPDG Asphalt Materials Models and Early Verification of Technologies Developed by ARC using new MEPDG Sites and Selected LTPP sites

Work Element Lead: Peter Sebaaly (UNR) and Hussain Bahia (UW-M)

Introduction

The mechanistic-empirical pavement design guide (MEPDG) has been recently developed to conduct structural designs for flexible and rigid pavements. The MEPDG uses a mechanistic approach that is empirically calibrated using field performance data to establish the required structural section for a given set of loading, materials, and environmental conditions.

The structural design for flexible pavements conducted through the MEPDG is based on the long-term performance of such pavements in rutting, fatigue, and thermal cracking. The constructed pavement is supposed to perform according to the design criteria established during the structural design process.

Several state highway agencies are currently in the process of implementing the MEPDG. These implementation efforts necessitate the design of flexible pavements using the guide and monitoring their long term performance to calibrate the mechanistic models based on the localized conditions. The MEPDG-designed and monitored flexible pavements represent an excellent opportunity for the Consortium to cooperate with the state agencies at two distinct levels: validation of the Consortium's research activities and updating of the fundamental models used by the MEPDG based on the Consortium's research activities. When coordination is done at the design stage the validation of current models, and the revisions for these models that could come out of the Consortium research, would be more effective.

In addition to the new sites, the LTPP program has a large number of sites that could be used for early verification of the technologies that are in advanced stages of development by the Consortium research members – or by other researchers – for improvement of specifications and design guidelines. Examples include binder tests that are being proposed for modified binders, the methods for measuring adhesion and cohesion, the binder fatigue tests, and others. These technologies are either already ready for validation or are very close to being ready. Using selected sites form the LTPP program for which excellent performance or premature failures have been observed could expedite the process of technology development and provide means for deriving specification limits or guidelines. The LTPP database can serve as basis for early validation because sections included in the database have had several years of traffic and aging.

Relationship to FHWA Focus Areas

The Validation work elements support the FHWA Focus Area of Optimizing Pavement Performance by providing a relationship between material property variation and pavement material performance in order to validate laboratory tests, performance models, and methods.

Hypothesis

The performance of the MEPDG designed flexible pavements coupled with the data generated by the Consortium research activities from LTPP sites can be effectively used to validate the research findings of the Consortium and to update the models used in the MEPDG. In addition, some of the existing LTPP sections can be used for early validation of the recently developed tests and properties.

Objectives

The objectives of this task are to cooperate with state highway agencies to design and construct flexible pavements using the AASHTO MEPDG. Also, to cooperate with the LTPP program to make use of selected performance and materials of selected sections. The constructed sections and the LTPP selected sections will be used to validate the findings of the research activities of the Consortium and to evaluate the models used in the MEPDG for possible revisions. The recommended revisions, if needed, will be based on new testing procedures proposed by the Consortium research.

Experimental Design

In order to achieve the objectives of this research effort, the following subtasks will be completed.

Subtask V3b-1: Design and Build Sections

This subtask will solicit state highway agencies that are willing to cooperate on designing and constructing flexible pavement sections using the AASHTO MEPDG. The solicited agencies will cover the various regions of the U.S.

This subtask will cooperate with the selected state agencies to design and build MEPDG sections. UNR will assist the agencies with the design of the sections using the MEPDG and will conduct the necessary testing for strength properties, fatigue, rutting, and thermal cracking. The agencies will construct the sections as designed. The sources and properties of the materials will be incorporated into the Materials Database.

It is well recognized that the 5 year period of the ARC contract is not long enough to develop sufficient long-term performance from the MEPDG sections. As part of this subtask, the ARC researchers will develop a long-term performance monitoring and implementation plan for the owner agency to follow after the completion of the ARC contract.

Subtask V3b-2: Additional Testing

This subtask will sample materials during the construction of the sections and will conduct additional testing on the field mixtures that will be used to validate the models generated from the Consortium research activities. This subtask will be conducted by researchers from UNR and UWM. Each member will conduct the necessary tests to validate their research efforts. The long-term performance data of the sections will be collected in cooperation with the owner agencies and used to validate the models/tests that will be developed throughout the research.

Subtask V3b-3: Select LTPP Sites to Validate New Binder Testing Procedures
(Note: Subtasks V3b-3 and V3b-4 were combined from the Year 1 plan)

This subtask will be focused on screening the available sections for which noticeable good or poor performance has been recorded, as well as for sections for which sufficient materials have been saved to allow binder and mixture testing. The sections will cover various climatic and traffic conditions and preferably include modified binder grades and variety of mixture types. The scope of the subtask cannot be estimated at this stage but an attempt will be made to have a significant number of sections for each type of pavement failure and in particular rutting, fatigue, and moisture damage. A work plan will be developed based on the test methods and the models that need to be validated. The main focus will be on models or test methods that are intended for filling some gaps in the specifications or the MEPDG models. The screening activity, if not covered by the LTPP program, will be conducted by individual Consortium partners based on the specific tests or models that they intend to validate. UNR will focus on low-temperature thermal cracking and UWM will focus on binder rutting and fatigue testing. Every effort will be made to coordinate the activities among Consortium members and with LTPP. The binder rutting and fatigue validation will start in Year 2.

Subtask V3b-4: Testing of Extracted Binders from LTPP Sections

Major Findings from Year 1

ARC team members reviewed the plans for the extracted binder testing that were recommended by the LTPP Materials Expert Task Group and LTPP Protocols P27 (DSR) and P28 (BBR). The recommended testing includes standard DSR and BBR testing of extracted binders at a single temperature selected based on the location of the LTPP project site. ARC team members believe that adding this data to the LTPP database will be of minimal value. Additionally ARC team members are having difficulty securing the necessary cost share to perform this testing.

Year 2 Work Plan

Considering recent efforts within the LTPP program to provide estimated dynamic modulus measurements for the LTPP sections, the ARC team recommends that the extracted binder testing plan recommended by the LTPP Materials Expert Task Group be reconsidered. The LTPP program currently has a project with Nichols Consulting Engineers to review various models and recommend an approach for estimating mixture dynamic modulus values for the LTPP database. Dr. Richard Kim, A ARC subcontractor, has a key role in this LTPP effort. If a model other than the original Witczak equation is used, it will likely require characterization of binder modulus master curves. To develop a binder modulus master curve requires testing at multiple temperatures and frequencies using the DSR and multiple temperatures using the BBR. This will require more material and effort than originally considered in the extracted binder testing plan recommended by the LTPP Materials Expert Task Group.

ARC team members will work with the FHWA LTPP Division and its contractors to develop an appropriate extracted binder testing plan and associated cost estimate. At this time consideration should be given to performing master curve testing and possibly MSCR testing on selected sections. ARC team members will then work with the FHWA to assess the potential for securing the 20 percent cost share necessary to perform this testing.

Subtask V3b-5: Review and Revisions of Materials Models

The first part of this subtask will review all past and current activities on the revisions and modifications of the materials models that are included in the MEPDG. Also, the proposed changes in binder specifications, the Superpave plus specifications, and mixture design practices will be reviewed and a report for defining the "gaps" will be issued. Based on these reviews, the researchers will identify any additional modifications or revisions that maybe needed.

For example, the equations used to determine the dynamic modulus (E*) from the binder properties will be validated for polymer-modified binders. The perceived shape of the E* Master Curve may vary significantly when it comes to polymer-modified mixtures. Using the testing data from Subtasks V3b-1 and V3b-2, the research team will evaluate the prediction equations and E* Master curves and modify them to accommodate polymer-modified binders and mixtures.

Subtask V3b-6: Evaluate the Impact of Moisture and Aging

This subtask will evaluate the effects of moisture and aging on material properties used in the MEPDG and the LTPP sections. This will lead to recommendations for revisions of models if needed based on our fundamental research results. The revised models could include cohesion, adhesion, trends in aging with effect of mineral surface, etc.

The current MEPDG does not incorporate the impact of moisture damage on the properties of the HMA materials. Also it has a good aging model that is based on changes in viscosity and could be modified to include some more fundamental properties. Also, the existing binder and mixture specifications have aging models based on the RTFO, which is not useful for many modified asphalts. In this subtask, researchers from UNR, AAT, UWM, and WRI will assess the gaps in the models and specifications and the need for revisions to the aging models and the need to incorporate the impact of moisture damage on the properties and behavior of HMA mixtures in the models of the MEPDG and in material specifications.

Major Findings from Year 1

During year 1, in Subtask V3b-1, the researchers initiated contacts with the MEPDG Lead States Team and several other state highway agencies to solicit their cooperation on this work element. At this point the following states have indicated their willingness to further consider their cooperation on this effort: New Jersey, Virginia, Texas, Nevada, Wisconsin, Idaho, Montana, and South Dakota. Other states that have been contacted but not responded yet include: New Mexico and Washington.

In Subtask V3b-3, the UWM team looked into the LTPP database for possible data retrieval. Some of the preliminary findings in the area of fatigue are ready to be validated. For instance, the fracture energy from the constant strain-rate tests has the potential to be used as an indicator to fatigue performance of asphalt binder. Fracture energy correlated well with the performance of asphalt binders at the FHWA ALF pavements, and validation of this finding is planned. LTPP SPS9 sections were designed to validate the Superpave mix design and materials. These sections could be good candidates for validation. A list of the sections is shown in table V3b-3.1.

The UWM team will coordinate with FHWA LTPP to procure the asphalt binder samples. A series of tests will be conducted (e.g. constant strain-rate tests). The parameters from these tests will be correlated with the field performance of these materials. It is noted that there are many variables affecting the field performance, such as climate, aggregate, traffic, thickness, base and soil conditions. To take into account the impact of these factors, as many samples as possible should be included for meaningful statistical analysis.

Table V3b-3.1. Possible LTPP sites for validation of findings.

SHRP_ID	PG_HIGH_TEMP	PG_LOW_TEMP	SOURCE_OTHER
0902	64	-28	Hudson Oil Company, Providence, RI
0903	64	-22	Hudson Oil Company, Providence, RI
0961	58	-34	Hudson Oil Company, Providence, RI
0962	58	-28	Hudson Oil Company, Providence, RI
0902	58	-28	Ultramar, St. Rumuald, QE
0902	52	-40	Bitumar, Montreal, QE
0903	58	-28	Ultramar, St. Rumuald, QE
0903	52	-34	Petro Canada, Montreal, QE
0901	64	-22	Citgo, Perth Amboy, NJ
0902	64	-22	Citgo, Perth Amboy, NJ
0902	58	-28	Suit-Kote, Cortland, NY
0903	64	-22	Citgo, Perth Amboy, NJ
0903	52	-28	Suit-Kote, Cortland, NY
0960	64	-22	Citgo, Perth Amboy, NJ
0960	64	-22	Citgo, Paulsboro, NJ
0961	64	-22	Citgo, Perth Amboy, NJ
0961	76	-28	Suit-Kote, Cortland, NY
0962	64	-22	Citgo, Perth Amboy, NJ
0902	64	-22	Citgo
0902	64	-22	Citgo
0902	64	-22	Citgo
0903	70	-22	Citgo
0903	70	-22	Citgo
0903	70	-22	Citgo
A902	58	-22	Shell Canada, Montreal
A902	52	-40	Bitumar, Montreal

SHRP_ID	PG_HIGH_TEMP	PG_LOW_TEMP	SOURCE_OTHER
A903	58	-22	Shell Canada, Montreal
A903	52	-34	Petro Canada, Montreal
0902	58	-40	McAsphalt ON
0903	58	-34	McAsphalt ON
0960	58	-28	McAsphalt ON
0961	58	-34	McAsphalt ON
0962	58	-40	McAsphalt ON
0902	58	-40	McAsphalt ON
0903	58	-34	McAsphalt ON
0960	58	-28	McAsphalt ON
0961	58	-34	McAsphalt ON
0962	58	-40	McAsphalt ON
0901	64	-22	Amoco, St.Louis
0901	64	-22	Amoco, St.Louis
0902	64	-28	Polymer Asphalt, St.Louis
0902	64	-28	Polymer Asphalt, St.Louis
0903	64	-28	Polymer Asphalt, St.Louis
0903	58	-28	Polymer Asphalt, St.Louis
0959	64	-22	Amoco, St.Louis
0959	64	-22	Amoco, St.Louis
0960	64	-22	Amoco, St.Louis
0960	64	-28	Polymer Asphalt, St.Louis
0961	64	-22	Amoco, St.Louis
0961	64	-22	Amoco, St.Louis
0962	64	-28	Polymer Asphalt, St.Louis
0962	70	-28	Polymer Asphalt, St.Louis
0963	64	-28	Polymer Asphalt, St.Louis
0963	64	-16	Polymer Asphalt, St.Louis
0964	64	-28	Polymer Asphalt, St.Louis
0964	64	-28	Polymer Asphalt, St.Louis
A901	64	-22	Polymer Asphalt, St.Louis
A901	64	-22	Polymer Asphalt, St.Louis
A902	64	-28	Polymer Asphalt, St.Louis
A902	64	-28	Polymer Asphalt, St.Louis
A959	64	-28	Polymer Asphalt, St.Louis
A959	64	-28	Polymer Asphalt, St.Louis
A903	58	-28	Polymer Asphalt, St.Louis
A903	58	-28	Polymer Asphalt, St.Louis
A960	70	-28	Polymer Asphalt, St.Louis
A960	70	-28	Polymer Asphalt, St.Louis
A961	64	-16	Polymer Asphalt, St.Louis
A961	64	-16	Polymer Asphalt, St.Louis
0902	64	-22	Marathon Oil; Memphis, TN

SHRP_ID	PG_HIGH_TEMP	PG_LOW_TEMP	SOURCE_OTHER
0903	58	-22	Marathon Oil, Memphis, TN
0903	70	-22	
0903	58	-22	
0902	64	-22	
0959	64	-10	
0901	64	-16	Citgo Savannah, GA
0902	64	-16	Citgo, Savannah, GA
0903	58	-16	Citgo, Savannah, GA
0959	76	-16	Citgo, Savannah, GA
0902	64	-16	
0903	64	-16	
A902	64	-16	
A903	64	-16	
B902	76	-10	EOTI / Neste Oil
B903	70	-10	Koch Asphalt
0902	64	-34	Montana Refining Company
0903	64	-22	Montana Refining Company
A902	52	-34	Husky Oil
A903	46	-34	Husky Oil

Year 2 Work Plan

During Year 2, in Subtask V3b-1, the research team will continue communicating with state highway agencies about their cooperation in this effort. Field projects will be identified in the states that indicated their willingness to participate and the process of design and materials testing and evaluations will start.

In Subtask V3b-3 in Year 2, the UWM team will procure the LTTP materials to validate the findings. The Year 2 work plan consists of two major parts: (a) a detailed experimental plan, and (b) an evaluation of the effectiveness of different analytical approaches based on the experimental results.

a. Detailed Experimental Plan of Materials and Tests.

   The experimental plan was designed to evaluate the factors that have potential to evaluate the performance of asphalt binders as well as asphaltic mixtures. The proposed tests are shown in table V3b-3.2.

b. Analytical Characterization of Behavior of Asphalt Binders and Mixes.

   The performance of the asphalt binders and asphaltic mixtures in the lab will be correlated with that of the materials in the field at LTPP sites. The lab test results will be analyzed using different analytical approaches. These analyses will determine the fundamental properties of asphalt binder that govern the damage resistance to fatigue. The tests that can provide indicators to field performance will be selected for possible implementation.

Table V3b-3.2. Proposed tests on asphalt binders and mixes.

Asphalt Binder	Time Sweep (TS)	Strain level	3%
			5%
			7%
		Frequency	1 Hz
			5 Hz
			10 Hz
	Monotonic Test (MT)	Shear Strain Rate	30%/min.
			45%/min.
			60%/min.
	Stress Sweep (SS)	Strain level	3%
			5%
			7%
		Frequency	1 Hz
			5 Hz
			10 Hz
Mix	Cyclic Test (CT)	Strain level	600 microstrain
			1000 microstrain
			1400 microstrain
		Frequency	1 Hz
			5 Hz
			10 Hz
	Monotonic Test (MT)	Constant Cross-head Rate	12.5 mm/min.
			25.4 mm/min.
			38.1 mm/min.
			50.8 mm/min.

Figure V3b-3.1 depicts the research approach defined for this work element.

Year 2 Milestones

Year 2 milestones for UNR will include the design and construction of MEPDG field projects during the summer 2008. For Subtask V3b-3, to be conducted by UW-M team, the milestones will include the following:

- Finalize the site selections for validation of findings
- Procure the LTTP binders for validation of the fracture energies concept
- Conduct the proposed tests on asphalt binders
- Validate the preliminary findings

Budget

The budget for all the work elements in the Validation area is estimated to be $5.0M over the five years of the project but is subject to the number of projects identified and completed.

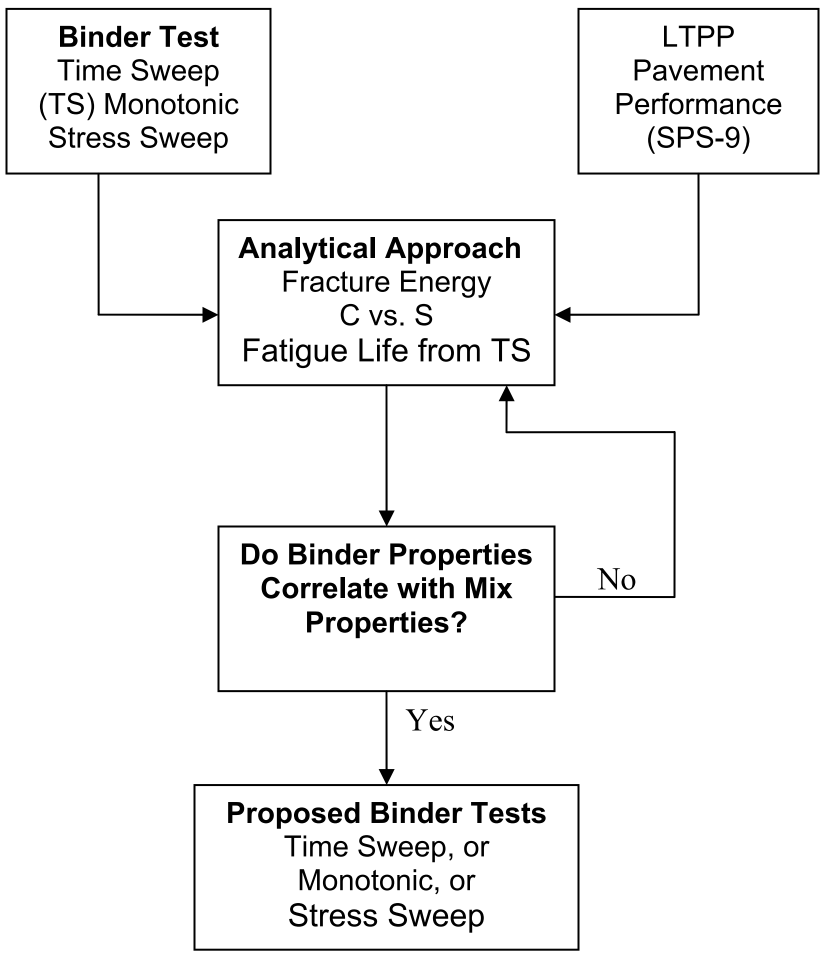


Figure V3b-3.1. Chart. Flow chart for research approach.

Validation	Year 2 (4/2008-3/2009)												Team
	4	5	6	7	8	9	10	11	12	1	2	3	
(1) Field Validation													
V1a: Use and Monitoring of Warm Mix Asphalt Sections													WRI
V1b: Construction and Monitoring of additional Comparative Pavement Validation sites													WRI
(2) Accelerated Pavement Testing													
V2a: Accelerated Pavement Testing including Scale Model Load Simulation on small test track													WRI
V2b: Construction of validation sections at the Pecos Research & Testing Center													WRI
(3) R&D Validation													
V3a: Continual Assessment of Specification													UWM
V3a-1: Evaluation of the PG-Plus practices and the motivations for selecting the "plus" tests.						P		D	F				
V3a-2: Detailed analysis of all PG-Plus tests being proposed or in use today, documentation of benefits and costs of these tests, and comparison with new tests									P				
V3a-3: Development of protocols for new binder tests and database for properties measured													
V3a-4: Development of specification criteria for new tests based on field evaluation of construction and performance													
V3a-5: Interviews and surveys for soliciting feedback on binder tests and specifications												JP	
V3b: Validation of the MEPDG Asphalt Materials Models and Early Verification of Technologies Developed by ARC using new MEPDG Sites and Selected LTPP sites													UNR/UWM/ WRI
V3b-1: Design and Build Sections													
V3b-2: Additional Testing													
V3b-3: Select LTPP Sites to Validate New Binder Testing Procedures				JP						P			
V3b-4: Testing of Extracted Binders from LTPP Sections													
V3b-5: Review and Revisions of Materials Models													
V3b-6: Evaluate the Impact of Moisture and Aging													

Deliverable codes	Deliverable Description
D: Draft Report	Report delivered to FHWA for 3 week review period.
F: Final Report	Final report delivered in compliance with FHWA publication standards
M&A: Model and algorithm	Mathematical model and sample code
SW: Software	Executable software, code and user manual
JP: Journal paper	Paper submitted to conference or journal
P: Presentation	Presentation for symposium, conference or other
DP: Decision Point	Time to make a decision on two parallel paths as to which is most promising to follow througjh

Work planned
Work completed
Parallel topic

Validation	Year 2 (4/08-3/09)				Year 3 (4/09-3/10)				Year 4 (04/10-03/11)				Year 5 (04/11-03/12)				Team
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	
(1) Field Validation																	
V1a: Use and Monitoring of Warm Mix Asphalt Sections																	WRI
V1b: Construction and Monitoring of additional Comparative Pavement Validation sites																	WRI
(2) Accelerated Pavement Testing																	
V2a: Accelerated Pavement Testing including Scale Model Load Simulation on small test track																	WRI
V2b: Construction of validation sections at the Pecos Research & Testing Center																	WRI
(3) R&D Validation																	
V3a: Continual Assessment of Specification																	UWM
V3a-1: Evaluation of the PG-Plus practices and the motivations for selecting the "plus" tests.		P	D,F														
V3a-2: Detailed analysis of all PG-Plus tests being proposed or in use today, documentation of benefits and costs of these tests, and comparison with new tests			P														
V3a-3: Development of protocols for new binder tests and database for properties measured					P		JP			P							
V3a-4: Development of specification criteria for new tests based on field evaluation of construction and performance								JP	P			JP	P		JP		
V3a-5: Interviews and surveys for soliciting feedback on binder tests and specifications				JP	P			JP	P		JP		P		D	F	
V3b: Validation of the MEPDG Asphalt Materials Models and Early Verification of Technologies Developed by ARC using new MEPDG Sites and Selected LTPP sites																	UNR/UWM
V3b-1: Design and Build Sections									D, F								
V3b-2: Additional Testing													D, F				
V3b-3: Select LTPP Sites to Validate New Binder Testing Procedures		JP			P					JP		P			D	F	
V3b-4: Testing of Extracted Binders from LTPP Sections																	
V3b-5: Review and Revisions of Materials Models																D, F	
V3b-6: Evaluate the Impact of Moisture and Aging																D, F	

Deliverable codes	Deliverable Description
D: Draft Report	Report delivered to FHWA for 3 week review period.
F: Final Report	Final report delivered in compliance with FHWA publication standards
M&A: Model and algorithm	Mathematical model and sample code
SW: Software	Executable software, code and user manual
JP: Journal paper	Paper submitted to conference or journal
P: Presentation	Presentation for symposium, conference or other
DP: Decision Point	Time to make a decision on two parallel paths as to which is most promising to follow througjh

Work planned
Work completed
Parallel topic

Appendix V1

Field Performance Site Table

Field Validation Site table

Work Element/ Subtask	Major Variable	Model to be Validated	Climate Location	Validation Parameter(s)	Material Retained	Monitoring Requirement	Remarks
V1b	Vary asphalt crude source	Asphalt Microstructural; Unified Continuum Damage; Micromechanics; Lattice; Aging	Hot-wet Hot-dry Cold-wet Cold-dry	Aging Permanent Deformation Fatigue Moisture Damage Low-temperature cracking	30 gallons of asphalt; 1200 lbs aggregate; 1200 pounds mix	LTPP protocol annually for 7 to 10 years if no failure; Core samples annually	5 to 6 sections at one site are probably the practical limit. Multiple sites needed for climate variation.
V1b	Vary High Temperature PG grade	Asphalt Microstructural; Unified Continuum Damage; Micromechanics; Lattice; Aging	Hot-wet Hot-dry	Aging Permanent Deformation Fatigue Moisture Damage	30 gallons of asphalt; 1200 lbs aggregate; 1200 pounds mix	LTPP protocol annually for 7 to 10 years if no failure; Core samples annually	5 to 6 sections at one site are probably the practical limit. At least 2 sites needed for climate variation.
V1b	Vary Low Temperature PG grade	Asphalt Microstructural; Unified Continuum Damage; Micromechanics; Lattice; Aging	Cold-wet Cold-dry	Aging Fatigue Moisture Damage Low Temperature cracking	30 gallons of asphalt; 1200 lbs aggregate; 1200 pounds mix	LTPP protocol annually for 7 to 10 years if no failure; Core samples annually	5 to 6 sections at one site are probably the practical limit. At least 2 sites needed for climate variation.
V1b	Compare Thick and thin structures	Asphalt Microstructural; Unified Continuum Damage; Micromechanics; Lattice; Aging	Hot-wet Hot-dry Cold-wet Cold-dry	Aging Fatigue Moisture Damage Low Temperature cracking	30 gallons of asphalt; 1200 lbs aggregate; 1200 pounds mix	LTPP protocol annually for 7 to 10 years if no failure; Core samples annually	2 to 3 sections at one site are probably the practical limit. Multiple sites needed for climate variation.
V1b	Vary aggregate mineralogy	Asphalt Microstructural; Unified Continuum Damage; Micromechanics; Lattice; Aging	Hot-wet Hot-dry Cold-wet Cold-dry	Aging Permanent Deformation Fatigue Moisture Damage Low-temperature cracking	30 gallons of asphalt; 1200 lbs aggregate; 1200 pounds mix	LTPP protocol annually for 7 to 10 years if no failure; Core samples annually	2 to 3 sections at one site are probably the practical limit. Multiple sites needed for climate variation.
V1b	Vary gradation	Asphalt Microstructural; Unified Continuum Damage; Micromechanics; Lattice; Aging	Hot-wet Hot-dry Cold-wet Cold-dry	Aging Permanent Deformation Fatigue Moisture Damage Low-temperature cracking	30 gallons of asphalt; 1200 lbs aggregate; 1200 pounds mix	LTPP protocol annually for 7 to 10 years if no failure; Core samples annually	2 to 3 sections at one site are probably the practical limit. Multiple sites needed for climate variation.

Work Element/ Subtask	Major Variable	Model to be Validated	Climate Location	Validation Parameter(s)	Material Retained	Monitoring Requirement	Remarks
V1b	Compare single polymer performance in different crude source asphalts	Asphalt Microstructural; Unified Continuum Damage; Micromechanics; Lattice; Aging	Hot-wet Hot-dry Cold-wet Cold-dry	Aging Permanent Deformation Fatigue Moisture Damage Low-temperature cracking	30 gallons of asphalt; 1200 lbs aggregate; 1200 pounds mix	LTPP protocol annually for 7 to 10 years if no failure; Core samples annually	3 to 4 sections at one site are probably the practical limit. Multiple sites needed for climate variation.
V1b	Compare single polymer performance in asphalts with different compatibility	Asphalt Microstructural; Unified Continuum Damage; Micromechanics; Lattice; Aging	Hot-wet Hot-dry Cold-wet Cold-dry	Aging Permanent Deformation Fatigue Moisture Damage Low-temperature cracking	30 gallons of asphalt; 1200 lbs aggregate; 1200 pounds mix	LTPP protocol annually for 7 to 10 years if no failure; Core samples annually	3 to 4 sections at one site is probably the practical limit. Multiple sites needed for climate variation.
V1b	Compare different polymers in single asphalt source	Asphalt Microstructural; Unified Continuum Damage; Micromechanics; Lattice; Aging	Hot-wet Hot-dry Cold-wet Cold-dry	Aging Permanent Deformation Fatigue Moisture Damage Low-temperature cracking	30 gallons of asphalt; 1200 lbs aggregate; 1200 pounds mix	LTPP protocol annually for 7 to 10 years if no failure; Core samples annually	3 to 4 sections at one site are probably the practical limit. Multiple sites needed for climate variation.
V1b	Compare polyphosphoric acid performance in different crude source asphalts	Asphalt Microstructural; Unified Continuum Damage; Micromechanics; Lattice; Aging	Hot-wet Hot-dry Cold-wet Cold-dry	Aging Permanent Deformation Fatigue Moisture Damage Low-temperature cracking	30 gallons of asphalt; 1200 lbs aggregate; 1200 pounds mix	LTPP protocol annually for 7 to 10 years if no failure; Core samples annually	5 to 6 sections at one site are probably the practical limit. At least 2 sites needed for climate variation.
V1b	Compare polyphosphoric acid strengths/concs in single asphalt source	Asphalt Microstructural; Unified Continuum Damage; Micromechanics; Lattice; Aging	Hot-wet Hot-dry Cold-wet Cold-dry	Aging Permanent Deformation Fatigue Moisture Damage Low-temperature cracking	30 gallons of asphalt; 1200 lbs aggregate; 1200 pounds mix	LTPP protocol annually for 7 to 10 years if no failure; Core samples annually	5 to 6 sections at one site are probably the practical limit. Multiple sites needed for climate variation.
V1b	Compare antistrip additives in single asphalt source	Asphalt Microstructural; Unified Continuum Damage; Micromechanics; Lattice; Aging	Hot-wet Hot-dry Cold-wet Cold-dry	Aging Permanent Deformation Fatigue Moisture Damage Low-temperature cracking	30 gallons of asphalt; 1200 lbs aggregate; 1200 pounds mix	LTPP protocol annually for 7 to 10 years if no failure; Core samples annually	5 to 6 sections at one site are probably the practical limit. Multiple sites needed for climate variation.
V1b E2b	Vary RAP content in one asphalt source	Asphalt Microstructural; Unified Continuum Damage; Micromechanics; Lattice; Aging	Hot-wet Hot-dry Cold-wet Cold-dry	Aging Permanent Deformation Fatigue Moisture Damage Low-temperature cracking	30 gallons of asphalt; 1200 lbs aggregate; 1200 pounds mix	LTPP protocol annually for 7 to 10 years if no failure; Core samples annually	3 to 4 sections at one site are probably sufficient. Multiple sites needed for climate variation

Work Element/ Subtask	Major Variable	Model to be Validated	Climate Location	Validation Parameter(s)	Material Retained	Monitoring Requirement	Remarks
V1b E2b	Compare one high RAP content in different crude source asphalts	Asphalt Microstructural; Unified Continuum Damage; Micromechanics; Lattice; Aging	Hot-wet Hot-dry Cold-wet Cold-dry	Aging Permanent Deformation Fatigue Moisture Damage Low-temperature cracking	30 gallons of asphalt; 1200 lbs aggregate; 1200 pounds mix	LTPP protocol annually for 7 to 10 years if no failure; Core samples annually	4 sections at one site are probably sufficient. Multiple sites needed for climate variation.
V1b E2b	Compare two RAP contents in different crude source asphalts	Asphalt Microstructural; Unified Continuum Damage; Micromechanics; Lattice; Aging	Hot-wet Hot-dry Cold-wet Cold-dry	Aging Permanent Deformation Fatigue Moisture Damage Low-temperature cracking	30 gallons of asphalt; 1200 lbs aggregate; 1200 pounds mix	LTPP protocol annually for 7 to 10 years if no failure; Core samples annually	6 sections are probably the practical limit at one site. Multiple sites needed for climate variation.
V1b E1c	Compare Warm mix additives in one asphalt	Binder viscosity characteristics; Binder lubricity; Energy of construction effort; Energy of traffic resistance Viscosity of foamed asphalt and rate of recovery as a function of temperature	Hot-wet Hot-dry Cold-wet Cold-dry	Aging Permanent Deformation Fatigue Moisture Damage Low-temperature cracking	30 gallons of asphalt; 1200 lbs aggregate; 1200 pounds mix	LTPP protocol annually for 7 to 10 years if no failure; Core samples annually	5 to 6 sections at one site are probably the practical limit. Multiple sites needed for climate variation.
V1b E1c	Compare Warm mix additives in two different crude source asphalts	Binder viscosity characteristics; Binder lubricity; Energy of construction effort; Energy of traffic resistance Viscosity of foamed asphalt and rate of recovery as a function of temperature	Hot-wet Hot-dry Cold-wet Cold-dry	Aging Permanent Deformation Fatigue Moisture Damage Low-temperature cracking	30 gallons of asphalt; 1200 lbs aggregate; 1200 pounds mix	LTPP protocol annually for 7 to 10 years if no failure; Core samples annually	5 to 6 sections at one site are probably the practical limit. Multiple sites needed for climate variation.
V1b E1c	Compare HMA and Cold Mix using two different crude sources	Emulsion characterization; Mixture workability; Mixture compaction	Hot-wet Hot-dry Cold-wet Cold-dry	Aging Permanent Deformation Fatigue Moisture Damage Low-temperature cracking	30 gallons of asphalt; 1200 lbs aggregate; 1200 pounds mix	LTPP protocol annually for 7 to 10 years if no failure; Core samples annually	5 to 6 sections at one site are probably the practical limit. Multiple sites needed for climate variation.
V3a	Asphalt binders with various grades & modification	Binder specification parameters	All	Creep compliance for rutting; Yield energy for fatigue; Fracture energy for thermal cracking	One gallon of each binder used from various LTPP sections	None (Already obtained)	More than 25 sections have been identified where binders are at AMRL

Accelerated Pavement Testing table

Work Element/ Subtask	Major Variable	Model to be Validated	Validation Parameter(s)	Material Retained	Monitoring Requirement	Remarks
V2	Vary asphalt crude source	Asphalt Microstructural; Unified Continuum Damage; Micromechanics; Lattice	Permanent Deformation Fatigue Moisture Damage Low-temperature cracking	30 gallons of asphalt; 1200 lbs aggregate; 1200 pounds mix	LTPP protocol for distress; photos; other as appropriate; Core samples periodically	Limited influence of aging
V2	Vary High Temperature PG grade	Asphalt Microstructural; Unified Continuum Damage; Micromechanics; Lattice	Permanent Deformation Fatigue Moisture Damage	30 gallons of asphalt; 1200 lbs aggregate; 1200 pounds mix	LTPP protocol for distress; photos; other as appropriate; Core samples periodically	Limited influence of aging
V2	Vary Low Temperature PG grade	Asphalt Microstructural; Unified Continuum Damage; Micromechanics; Lattice	Fatigue Moisture Damage Low Temperature cracking	30 gallons of asphalt; 1200 lbs aggregate; 1200 pounds mix	LTPP protocol for distress; photos; other as appropriate; Core samples periodically	Limited influence of aging
V2	Compare Thick and thin structures	Asphalt Microstructural; Unified Continuum Damage; Micromechanics; Lattice	Fatigue Moisture Damage Low Temperature cracking	30 gallons of asphalt; 1200 lbs aggregate; 1200 pounds mix	LTPP protocol for distress; photos; other as appropriate; Core samples periodically	Limited influence of aging
V2	Vary aggregate mineralogy; use moisture sensitive aggregate	Asphalt Microstructural; Unified Continuum Damage; Micromechanics; Lattice	Permanent Deformation Fatigue Moisture Damage Low-temperature cracking	30 gallons of asphalt; 1200 lbs aggregate; 1200 pounds mix	LTPP protocol for distress; photos; other as appropriate; Core samples periodically	Limited influence of aging
V2	Vary gradation; to vary VMA, VFA	Asphalt Microstructural; Unified Continuum Damage; Micromechanics; Lattice	Permanent Deformation Fatigue Moisture Damage Low-temperature cracking	30 gallons of asphalt; 1200 lbs aggregate; 1200 pounds mix	LTPP protocol for distress; photos; other as appropriate; Core samples periodically	Limited influence of aging

Work Element/ Subtask	Major Variable	Model to be Validated	Validation Parameter(s)	Material Retained	Monitoring Requirement	Remarks
V2	Compare single polymer performance in different crude source asphalts	Asphalt Microstructural; Unified Continuum Damage; Micromechanics; Lattice	Permanent Deformation Fatigue Moisture Damage Low-temperature cracking	30 gallons of asphalt; 1200 lbs aggregate; 1200 pounds mix	LTPP protocol for distress; photos; other as appropriate; Core samples periodically	Limited influence of aging
V2	Compare single polymer performance in asphalts with different compatibility	Asphalt Microstructural; Unified Continuum Damage; Micromechanics; Lattice	Permanent Deformation Fatigue Moisture Damage Low-temperature cracking	30 gallons of asphalt; 1200 lbs aggregate; 1200 pounds mix	LTPP protocol for distress; photos; other as appropriate; Core samples periodically	Limited influence of aging
V2	Compare different polymers in single asphalt source	Asphalt Microstructural; Unified Continuum Damage; Micromechanics; Lattice	Permanent Deformation Fatigue Moisture Damage Low-temperature cracking	30 gallons of asphalt; 1200 lbs aggregate; 1200 pounds mix	LTPP protocol for distress; photos; other as appropriate; Core samples periodically	Limited influence of aging
V2	Compare polyphosphoric acid performance in different crude source asphalts	Asphalt Microstructural; Unified Continuum Damage; Micromechanics; Lattice	Permanent Deformation Fatigue Moisture Damage Low-temperature cracking	30 gallons of asphalt; 1200 lbs aggregate; 1200 pounds mix	LTPP protocol for distress; photos; other as appropriate; Core samples periodically	Limited influence of aging
V2	Compare polyphosphoric acid strengths/concs in single asphalt source	Asphalt Microstructural; Unified Continuum Damage; Micromechanics; Lattice	Permanent Deformation Fatigue Moisture Damage Low-temperature cracking	30 gallons of asphalt; 1200 lbs aggregate; 1200 pounds mix	LTPP protocol for distress; photos; other as appropriate; Core samples periodically	Limited influence of aging
V2	Compare antistrip additives in single asphalt source	Asphalt Microstructural; Unified Continuum Damage; Micromechanics; Lattice	Permanent Deformation Fatigue Moisture Damage Low-temperature cracking	30 gallons of asphalt; 1200 lbs aggregate; 1200 pounds mix	LTPP protocol for distress; photos; other as appropriate; Core samples periodically	Limited influence of aging
V2 E2b	Vary RAP content in one asphalt source	Asphalt Microstructural; Unified Continuum Damage; Micromechanics; Lattice	Permanent Deformation Fatigue Moisture Damage Low-temperature cracking	30 gallons of asphalt; 1200 lbs aggregate; 1200 pounds mix	LTPP protocol for distress; photos; other as appropriate; Core samples periodically	Limited influence of aging

Work Element/ Subtask	Major Variable	Model to be Validated	Validation Parameter(s)	Material Retained	Monitoring Requirement	Remarks
V2 E2b	Compare one high RAP content in different crude source asphalts	Asphalt Microstructural; Unified Continuum Damage; Micromechanics; Lattice	Permanent Deformation Fatigue Moisture Damage Low-temperature cracking	30 gallons of asphalt; 1200 lbs aggregate; 1200 pounds mix	LTPP protocol for distress; photos; other as appropriate; Core samples periodically	Limited influence of aging
V2 E2b	Compare two RAP contents in different crude source asphalts	Asphalt Microstructural; Unified Continuum Damage; Micromechanics; Lattice	Permanent Deformation Fatigue Moisture Damage Low-temperature cracking	30 gallons of asphalt; 1200 lbs aggregate; 1200 pounds mix	LTPP protocol for distress; photos; other as appropriate; Core samples periodically	Limited influence of aging
V2 E1c	Compare Warm mix additives in one asphalt	Binder viscosity characteristics; Binder lubricity; Energy of construction effort; Energy of traffic resistance Viscosity of foamed asphalt and rate of recovery as a function of temperature	Permanent Deformation Fatigue Moisture Damage Low-temperature cracking	30 gallons of asphalt; 1200 lbs aggregate; 1200 pounds mix	LTPP protocol for distress; photos; other as appropriate; Core samples periodically	Limited influence of aging
V2 E1c	Compare Warm mix additives in two different crude source asphalts	Binder viscosity characteristics; Binder lubricity; Energy of construction effort; Energy of traffic resistance Viscosity of foamed asphalt and rate of recovery as a function of temperature	Permanent Deformation Fatigue Moisture Damage Low-temperature cracking	30 gallons of asphalt; 1200 lbs aggregate; 1200 pounds mix	LTPP protocol for distress; photos; other as appropriate; Core samples periodically	Limited influence of aging
V2 E1c	Compare HMA and Cold Mix using two different crude sources	Emulsion characterization; Mixture workability; Mixture compaction	Permanent Deformation Fatigue Moisture Damage Low-temperature cracking	30 gallons of asphalt; 1200 lbs aggregate; 1200 pounds mix	LTPP protocol for distress; photos; other as appropriate; Core samples periodically	Limited influence of aging

Appendix V2

Availability of Original Materials for LTPP SPS-9 Sections

Availability of Original Materials for LTPP SPS-9 Sections
Conducted by UNR
May 14, 2008

The objective of this effort was to identify the type and amount of original materials that are available in the Material Reference Library (MRL) for the LTPP SPS-9 sections. This effort required the following steps:

- Visit the MRL facility in Reno, NV
- Discussions with the MRL personnel
- Querying the information from the DATAPAVE online database
- Querying the MRL inventory database

The following states are the participating in the LTPP SPS-9 experiment (Figure 1):
Alberta (AB), Arizona (AZ), Arkansas (AR), Connecticut (CT), Florida (FL), Indiana (IN), Kansas (KS), Maryland (MD), Michigan (MI), Minnesota (MN), Mississippi (MS), Missouri (MO), Montana (MT), Nebraska (NE), New Jersey (NJ), New Mexico (NM), North Carolina (NC), Ohio (OH), Ontario (ON), Quebec (PQ), Saskatchewan (SK), Texas (TX), and Wisconsin (WI).

Figure 2 illustrates an example layout of a generic SPS project. Each SPS project consists of multiple test sections constructed for a single project and a maintenance control zone that is extended to cover groups of adjoining sections. The LTPP DATAPAVE online was used to identify the various SPS-9 sections. Table 1 shows a list of the SPS-9 sections along with the layer where HMA has been used, their corresponding SHRP ID, and the grade of the binder that was used whenever available. Some sections include multiple HMA layers. For example, Arizona section 4-B901 includes HMA mixtures in layer 3 as original surface (4B901-3), in layer 5 as overlay (4B901-5), and in layer 6 as overlay (4B901-6).

Table 2 summarizes the inventory of materials for the various SPS-9 sections that was identified from the MRL on May 9, 2008. Again, using the Arizona section 4-B901 as an example, the MRL inventory data in Table 2 show that this section has binder, composite aggregate, and composite plant mix available in the MRL. However, what the MRL inventory does not specify is to which HMA layer these materials belong (i.e. layers 3, 5, or 6).

Table 3 summarizes the sections for which asphalt binder, aggregates, and asphalt mixes are supposedly still available in the MRL storage. The materials in the inventory were linked back to their corresponding SHRP ID that was identified in the LTPP DATAPAVE. However, the inventory does not list all the associated SHRP IDs or sometimes it refers to an ID that is not listed under the LTPP database. The sections that only aggregates are still available were not reported in Table 3. It should be noted that in some cases the inventory description of the materials involved was not clear enough to identify the type of the materials stored.

To effectively use the available SPS-9 materials by the ARC researchers, the available materials must be tied back to the specific HMA layer within the SPS-9 section. At this point, the UNR researchers believe that the only way to achieve this connection is to identify the construction date of the sections and the sampling date of the materials. Then by matching these two dates, the available materials will be tied to the specific HMA layer. For example, The DATAPAVE online reports only information for the Arizona 4-B901-6 section along with a beginning and end construction date of 3/25/96. The sampling dates for the Arizona sections are obtained from the MRL inventory (Table 2) as: 3/25/95 for both the binder and the composite aggregate. The Composite Plant Mix does not have a sampling date. Matching the construction and sampling dates of the Arizona section leads to the conclusion that the binder, aggregates, and plant mix belong to the HMA layer on the 4-B901-6 Section.

The above described process will have to be completed for every SPS-9 section listed in Table 3 of this document. It is recommended that ARC members look at the availability of the materials summarized in Table 3 and decide on which SPS-9 sections would be of interest to their work elements and then go through the process of matching the construction and sampling dates to define the HMA layer that the available materials belong to.

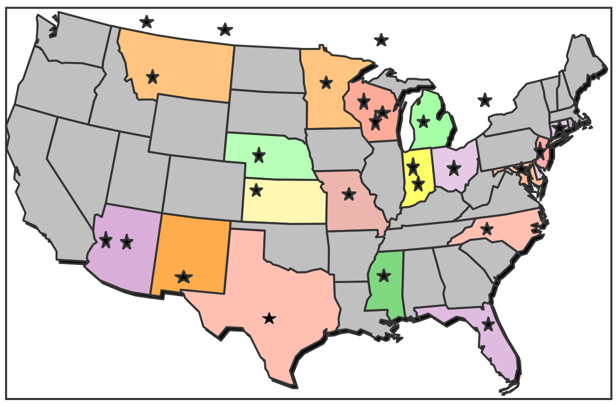


Figure 1 SPS-9 Location and Site Distribution in United States and Canada

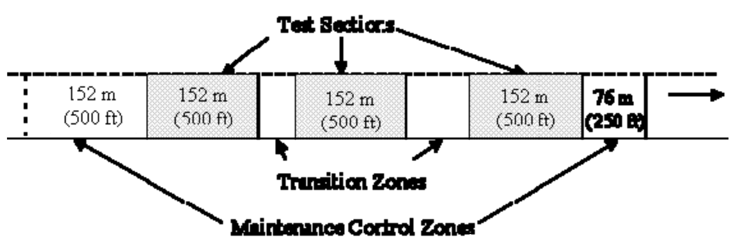


Figure 2 Example layout of a generic SPS project

Table 1 SPS-9 Sections from DATAPAVE Online.

STATE	CODE	SHRP_ID	Layer_No	ID	MATERIAL_TYPE	DESCRIPTION	PG Grade	Other Grade
Arizona	4	0902	3	4-0902-3	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer	PG64-16	
Arizona	4	0903	3	4-0903-3	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer	PG64-16	
Arizona	4	A901	3	4-A901-3	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		Asphalt Cements AC-30
Arizona	4	A902	3	4-A902-3	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer	PG64-16	
Arizona	4	A903	3	4-A903-3	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer	PG64-16	
Arizona	4	B901	3	4-B901-3	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
Arizona	4	B901	5	4-B901-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Arizona	4	B901	6	4-B901-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		Other Asphalt Cement Grade
Arizona	4	B902	3	4-B902-3	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
Arizona	4	B902	5	4-B902-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Arizona	4	B902	6	4-B902-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay	PG76-10	
Arizona	4	B903	3	4-B903-3	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
Arizona	4	B903	5	4-B903-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Arizona	4	B903	6	4-B903-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay	PG70-10	
Arizona	4	B959	3	4-B959-3	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
Arizona	4	B959	5	4-B959-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Arizona	4	B959	6	4-B959-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Arizona	4	B960	3	4-B960-3	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
Arizona	4	B960	5	4-B960-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Arizona	4	B960	6	4-B960-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Arizona	4	B961	3	4-B961-3	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
Arizona	4	B961	5	4-B961-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Arizona	4	B961	6	4-B961-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Arizona	4	B964	3	4-B964-3	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
Arizona	4	B964	5	4-B964-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Arizona	4	B964	6	4-B964-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Connecticut	9	0901	5	9-0901-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Connecticut	9	0901	6	9-0901-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
Connecticut	9	0901	7	9-0901-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		Asphalt Cements AC-20
Connecticut	9	0901	8	9-0901-8	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		Asphalt Cements AC-20
Connecticut	9	0902	5	9-0902-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Connecticut	9	0902	6	9-0902-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
Connecticut	9	0902	7	9-0902-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		Asphalt Cements AC-20
Connecticut	9	0902	8	9-0902-8	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay	PG64-28	
Connecticut	9	0903	5	9-0903-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		

STATE	CODE	SHRP_ID	Layer_No	ID	MATERIAL_TYPE	DESCRIPTION	PG Grade	Other Grade
Connecticut	9	0903	6	9-0903-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
Connecticut	9	0903	7	9-0903-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		Asphalt Cements AC-20
Connecticut	9	0903	8	9-0903-8	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay	PG64-22	
Connecticut	9	0960	5	9-0960-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Connecticut	9	0960	6	9-0960-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
Connecticut	9	0960	7	9-0960-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		Asphalt Cements AC-20
Connecticut	9	0960	8	9-0960-8	Recycled Asphalt Concrete Hot, Central Plant Mix	Overlay		Asphalt Cements AC-10
Connecticut	9	0961	5	9-0961-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Connecticut	9	0961	6	9-0961-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
Connecticut	9	0961	7	9-0961-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		Asphalt Cements AC-20
Connecticut	9	0961	8	9-0961-8	Recycled Asphalt Concrete Hot, Central Plant Mix	Overlay	PG58-34	
Connecticut	9	0962	5	9-0962-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Connecticut	9	0962	6	9-0962-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
Connecticut	9	0962	7	9-0962-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		Asphalt Cements AC-20
Connecticut	9	0962	8	9-0962-8	Recycled Asphalt Concrete Hot, Central Plant Mix	Overlay	PG58-28	
Florida	12	0901	4	12-0901-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
Florida	12	0901	7	12-0901-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay	PG64-16	Other Asphalt Cement Grade
Florida	12	0902	4	12-0902-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
Florida	12	0902	7	12-0902-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay	PG64-16	
Florida	12	0903	4	12-0903-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
Florida	12	0903	7	12-0903-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay	PG58-16	
Florida	12	0959	4	12-0959-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
Florida	12	0959	7	12-0959-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay	PG76-16	
Indiana	18	0901	6	18-0901-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Indiana	18	0901	7	18-0901-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Indiana	18	0901	8	18-0901-8	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Indiana	18	0902	5	18-0902-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Indiana	18	0902	6	18-0902-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Indiana	18	0902	7	18-0902-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Indiana	18	0904	6	18-0904-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Indiana	18	0904	7	18-0904-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Indiana	18	0904	8	18-0904-8	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Indiana	18	0905	5	18-0905-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Indiana	18	0905	6	18-0905-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Indiana	18	0905	7	18-0905-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Indiana	18	A901	4	18-A901-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)	PG64-22	Asphalt Cements AC-20

STATE	CODE	SHRP_ID	Layer_No	ID	MATERIAL_TYPE	DESCRIPTION	PG Grade	Other Grade
Indiana	18	A901	5	18-A901-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay	PG64-22	
Indiana	18	A902	4	18-A902-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)	PG64-28	
Indiana	18	A902	5	18-A902-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay	PG64-28	
Indiana	18	A903	4	18-A903-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)	PG58-28	
Indiana	18	A903	5	18-A903-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay	PG58-28	
Indiana	18	A959	4	18-A959-4	Recycled Asphalt Concrete Hot, Central Plant Mix	AC Layer Below Surface (Binder Course)	PG64-28	
Indiana	18	A959	5	18-A959-5	Recycled Asphalt Concrete Hot, Central Plant Mix	Overlay	PG64-28	
Indiana	18	A960	4	18-A960-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)	PG70-28	
Indiana	18	A960	5	18-A960-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay	PG70-28	
Indiana	18	A961	4	18-A961-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)	PG64-16	
Indiana	18	A961	5	18-A961-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay	PG64-16	
Kansas	20	0901	3	20-0901-3	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Kansas	20	0901	4	20-0901-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
Kansas	20	0902	3	20-0902-3	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		Asphalt Cements AC-5
Kansas	20	0902	4	20-0902-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		Asphalt Cements AC-5
Kansas	20	0903	3	20-0903-3	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Kansas	20	0903	4	20-0903-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		Asphalt Cements AC-20
Maryland	24	0901	4	24-0901-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Maryland	24	0901	5	24-0901-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
Maryland	24	0901	6	24-0901-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Maryland	24	0902	4	24-0902-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Maryland	24	0902	5	24-0902-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
Maryland	24	0902	6	24-0902-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Maryland	24	0903	4	24-0903-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Maryland	24	0903	5	24-0903-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
Maryland	24	0903	6	24-0903-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Maryland	24	0960	4	24-0960-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Maryland	24	0960	5	24-0960-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
Maryland	24	0960	6	24-0960-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Maryland	24	0961	4	24-0961-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Maryland	24	0961	5	24-0961-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
Maryland	24	0961	6	24-0961-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Maryland	24	0962	4	24-0962-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Maryland	24	0962	5	24-0962-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
Maryland	24	0962	6	24-0962-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Michigan	26	0901	5	26-0901-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		

STATE	CODE	SHRP_ID	Layer_No	ID	MATERIAL_TYPE	DESCRIPTION	PG Grade	Other Grade
Michigan	26	0901	6	26-0901-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Michigan	26	0901	7	26-0901-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Michigan	26	0902	5	26-0902-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Michigan	26	0902	6	26-0902-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Michigan	26	0902	7	26-0902-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Michigan	26	0903	5	26-0903-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Michigan	26	0903	6	26-0903-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Michigan	26	0903	7	26-0903-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Minnesota	27	0901	4	27-0901-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Minnesota	27	0901	5	27-0901-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Minnesota	27	0901	6	27-0901-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Minnesota	27	0902	4	27-0902-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Minnesota	27	0902	5	27-0902-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Minnesota	27	0902	6	27-0902-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Minnesota	27	0903	4	27-0903-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Minnesota	27	0903	5	27-0903-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Minnesota	27	0903	6	27-0903-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Minnesota	27	0909	4	27-0909-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Minnesota	27	0909	5	27-0909-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Minnesota	27	0909	6	27-0909-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Minnesota	27	0909	7	27-0909-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Minnesota	27	0910	4	27-0910-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Minnesota	27	0910	5	27-0910-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Minnesota	27	0910	6	27-0910-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Mississippi	28	0902	5	28-0902-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Mississippi	28	0902	6	28-0902-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Mississippi	28	0902	7	28-0902-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
Mississippi	28	0902	8	28-0902-8	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay	PG64-22	
Mississippi	28	0903	5	28-0903-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Mississippi	28	0903	6	28-0903-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Mississippi	28	0903	7	28-0903-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
Mississippi	28	0903	8	28-0903-8	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay	PG58-22	
Mississippi	28	0959	5	28-0959-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Mississippi	28	0959	6	28-0959-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Mississippi	28	0959	7	28-0959-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
Mississippi	28	0959	8	28-0959-8	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		Other Asphalt Cement Grade

STATE	CODE	SHRP_ID	Layer_No	ID	MATERIAL_TYPE	DESCRIPTION	PG Grade	Other Grade
Missouri	29	0901	4	29-0901-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)	PG64-22	Asphalt Cements AC-20
Missouri	29	0901	5	29-0901-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay	PG64-22	Asphalt Cements AC-20
Missouri	29	0902	4	29-0902-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)	PG64-28	Asphalt Cements AC-5
Missouri	29	0902	5	29-0902-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay	PG64-28	Asphalt Cements AC-5
Missouri	29	0903	4	29-0903-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)	PG64-28	Asphalt Cements AC-5
Missouri	29	0903	5	29-0903-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay	PG58-28	Asphalt Cements AC-5
Missouri	29	0959	4	29-0959-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)	PG64-22	Asphalt Cements AC-20
Missouri	29	0959	5	29-0959-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay	PG64-22	Asphalt Cements AC-20
Missouri	29	0960	4	29-0960-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)	PG64-22	Asphalt Cements AC-20
Missouri	29	0960	5	29-0960-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay	PG64-28	Asphalt Cements AC-5
Missouri	29	0961	4	29-0961-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)	PG64-22	Asphalt Cements AC-20
Missouri	29	0961	5	29-0961-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay	PG64-22	Asphalt Cements AC-20
Missouri	29	0962	4	29-0962-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)	PG64-28	Asphalt Cements AC-5
Missouri	29	0962	5	29-0962-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay	PG70-28	Asphalt Cements AC-5
Missouri	29	0963	4	29-0963-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)	PG64-28	Asphalt Cements AC-5
Missouri	29	0963	5	29-0963-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay	PG64-16	Asphalt Cements AC-20
Missouri	29	0964	4	29-0964-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)	PG64-28	Asphalt Cements AC-5
Missouri	29	0964	5	29-0964-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay	PG64-28	Asphalt Cements AC-5
Montana	30	0901	3	30-0901-3	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		Asphalt Cements AR-4000 (AR-40)
Montana	30	0902	3	30-0902-3	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer	PG64-34	
Montana	30	0903	3	30-0903-3	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer	PG64-22	
Nebraska	31	0902	3	31-0902-3	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
Nebraska	31	0903	3	31-0903-3	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
Nebraska	31	0904	3	31-0904-3	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Nebraska	31	0904	4	31-0904-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
New Jersey	34	0901	5	34-0901-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
New Jersey	34	0901	6	34-0901-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)	PG64-22	
New Jersey	34	0901	7	34-0901-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		Other Cutback Asphalt Grade
New Jersey	34	0902	5	34-0902-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
New Jersey	34	0902	6	34-0902-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)	PG64-22	
New Jersey	34	0902	7	34-0902-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay	PG58-28	
New Jersey	34	0903	5	34-0903-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
New Jersey	34	0903	6	34-0903-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)	PG64-22	
New Jersey	34	0903	7	34-0903-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay	PG52-28	
New Jersey	34	0960	5	34-0960-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
New Jersey	34	0960	6	34-0960-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)	PG64-22	

STATE	CODE	SHRP_ID	Layer_No	ID	MATERIAL_TYPE	DESCRIPTION	PG Grade	Other Grade
New Jersey	34	0960	7	34-0960-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay	PG64-22	
New Jersey	34	0961	5	34-0961-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
New Jersey	34	0961	6	34-0961-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)	PG64-22	
New Jersey	34	0961	7	34-0961-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay	PG76-28	
New Jersey	34	0962	5	34-0962-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
New Jersey	34	0962	6	34-0962-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)	PG64-22	
New Jersey	34	0962	7	34-0962-7	Recycled Asphalt Concrete Hot, Central Plant Mix	Overlay		Other Cutback Asphalt Grade
New Mexico	35	0901	3	35-0901-3	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
New Mexico	35	0901	4	35-0901-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
New Mexico	35	0901	5	35-0901-5	Recycled Asphalt Concrete Cold Laid Mixed-In-Place	Overlay		
New Mexico	35	0901	6	35-0901-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		Asphalt Cements AC-20
New Mexico	35	0902	3	35-0902-3	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
New Mexico	35	0902	4	35-0902-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
New Mexico	35	0902	5	35-0902-5	Recycled Asphalt Concrete Cold Laid Mixed-In-Place	Overlay		
New Mexico	35	0902	6	35-0902-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay	PG64-22	
New Mexico	35	0903	3	35-0903-3	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
New Mexico	35	0903	4	35-0903-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
New Mexico	35	0903	5	35-0903-5	Recycled Asphalt Concrete Cold Laid Mixed-In-Place	Overlay		
New Mexico	35	0903	6	35-0903-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay	PG58-22	
New Mexico	35	0959	3	35-0959-3	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
New Mexico	35	0959	4	35-0959-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
New Mexico	35	0959	5	35-0959-5	Recycled Asphalt Concrete Cold Laid Mixed-In-Place	Overlay		
New Mexico	35	0959	6	35-0959-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay	PG64-10	
North Carolina	37	0901	4	37-0901-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		Asphalt Cements AC-20
North Carolina	37	0901	5	37-0901-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		Asphalt Cements AC-20
North Carolina	37	0902	4	37-0902-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)	PG64-22	
North Carolina	37	0902	5	37-0902-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer	PG64-22	
North Carolina	37	0903	4	37-0903-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)	PG70-22	
North Carolina	37	0903	5	37-0903-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer	PG70-22	
North Carolina	37	0960	4	37-0960-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
North Carolina	37	0960	5	37-0960-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
North Carolina	37	0960	6	37-0960-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
North Carolina	37	0961	4	37-0961-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
North Carolina	37	0961	5	37-0961-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
North Carolina	37	0961	6	37-0961-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
North Carolina	37	0962	4	37-0962-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		

STATE	CODE	SHRP_ID	Layer_No	ID	MATERIAL_TYPE	DESCRIPTION	PG Grade	Other Grade
North Carolina	37	0962	5	37-0962-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
North Carolina	37	0962	6	37-0962-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
North Carolina	37	0963	4	37-0963-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
North Carolina	37	0963	5	37-0963-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
North Carolina	37	0963	6	37-0963-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
North Carolina	37	0964	4	37-0964-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
North Carolina	37	0964	5	37-0964-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
North Carolina	37	0964	6	37-0964-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
North Carolina	37	0965	4	37-0965-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
North Carolina	37	0965	5	37-0965-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
North Carolina	37	0965	6	37-0965-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Ohio	39	0901	6	39-0901-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		Asphalt Cements AC-20
Ohio	39	0901	7	39-0901-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		Asphalt Cements AC-20
Ohio	39	0902	5	39-0902-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Ohio	39	0902	6	39-0902-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
Ohio	39	0903	5	39-0903-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Ohio	39	0903	6	39-0903-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
Texas	48	0901	4	48-0901-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		Asphalt Cements AC-20
Texas	48	0901	5	48-0901-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		Asphalt Cements AC-20
Texas	48	0902	4	48-0902-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		Asphalt Cements AC-20
Texas	48	0903	4	48-0903-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer	PG70-22	Asphalt Cements AC-20
Wisconsin	55	0901	6	55-0901-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Wisconsin	55	0901	7	55-0901-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Wisconsin	55	0902	6	55-0902-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Wisconsin	55	0902	7	55-0902-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Wisconsin	55	0903	6	55-0903-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Wisconsin	55	0907	6	55-0907-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Wisconsin	55	0907	7	55-0907-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Wisconsin	55	0908	6	55-0908-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Wisconsin	55	0909	6	55-0909-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Wisconsin	55	0909	7	55-0909-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Wisconsin	55	A901	5	55-A901-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Wisconsin	55	A901	6	55-A901-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Wisconsin	55	A901	7	55-A901-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Wisconsin	55	A902	5	55-A902-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Wisconsin	55	A902	6	55-A902-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		

STATE	CODE	SHRP_ID	Layer_No	ID	MATERIAL_TYPE	DESCRIPTION	PG Grade	Other Grade
Wisconsin	55	A902	7	55-A902-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Wisconsin	55	A903	5	55-A903-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Wisconsin	55	A903	6	55-A903-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Wisconsin	55	A903	7	55-A903-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Wisconsin	55	A907	5	55-A907-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Wisconsin	55	A907	6	55-A907-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Wisconsin	55	A907	7	55-A907-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Wisconsin	55	A908	5	55-A908-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Wisconsin	55	A908	6	55-A908-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Wisconsin	55	A908	7	55-A908-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Wisconsin	55	A909	5	55-A909-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Wisconsin	55	A909	6	55-A909-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Wisconsin	55	A909	7	55-A909-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Wisconsin	55	B901	5	55-B901-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Wisconsin	55	B901	6	55-B901-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Wisconsin	55	B901	7	55-B901-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Wisconsin	55	B902	5	55-B902-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Wisconsin	55	B902	6	55-B902-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Wisconsin	55	B902	7	55-B902-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Wisconsin	55	B903	5	55-B903-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Wisconsin	55	B903	6	55-B903-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Wisconsin	55	B903	7	55-B903-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Wisconsin	55	B907	5	55-B907-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Wisconsin	55	B907	6	55-B907-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Wisconsin	55	B907	7	55-B907-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Wisconsin	55	B908	5	55-B908-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Wisconsin	55	B908	6	55-B908-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Wisconsin	55	B908	7	55-B908-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Wisconsin	55	B909	5	55-B909-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Wisconsin	55	B909	6	55-B909-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Wisconsin	55	B909	7	55-B909-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Overlay		
Wisconsin	55	C901	4	55-C901-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Wisconsin	55	C901	5	55-C901-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
Wisconsin	55	C902	4	55-C902-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Wisconsin	55	C902	5	55-C902-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
Wisconsin	55	C903	4	55-C903-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		

STATE	CODE	SHRP_ID	Layer_No	ID	MATERIAL_TYPE	DESCRIPTION	PG Grade	Other Grade
Wisconsin	55	C903	5	55-C903-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
Wisconsin	55	C959	4	55-C959-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Wisconsin	55	C959	5	55-C959-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
Wisconsin	55	C960	4	55-C960-4	Recycled Asphalt Concrete Hot, Central Plant Mix	AC Layer Below Surface (Binder Course)		
Wisconsin	55	C960	5	55-C960-5	Recycled Asphalt Concrete Hot, Central Plant Mix	Original Surface Layer		
Alberta	81	A901	3	81-A901-3	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		Other Asphalt Cement Grade
Alberta	81	A902	3	81-A902-3	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer	PG52-34	
Alberta	81	A903	3	81-A903-3	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer	PG46-34	
Ontario	87	0901	4	87-0901-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		Asphalt Cements 85-100 pen
Ontario	87	0901	5	87-0901-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		Asphalt Cements 85-100 pen
Ontario	87	0902	4	87-0902-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)	PG58-40	
Ontario	87	0902	5	87-0902-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer	PG58-40	
Ontario	87	0903	4	87-0903-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)	PG58-34	
Ontario	87	0903	5	87-0903-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer	PG58-34	
Ontario	87	0960	4	87-0960-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)	PG58-28	
Ontario	87	0960	5	87-0960-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer	PG58-28	
Ontario	87	0961	4	87-0961-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)	PG58-34	
Ontario	87	0961	5	87-0961-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer	PG58-34	
Ontario	87	0962	4	87-0962-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)	PG58-40	
Ontario	87	0962	5	87-0962-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer	PG58-40	
Quebec	89	0901	5	89-0901-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		Other Asphalt Cement Grade
Quebec	89	0901	6	89-0901-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		Other Asphalt Cement Grade
Quebec	89	0902	4	89-0902-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)	PG58-28	
Quebec	89	0902	5	89-0902-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer	PG52-40	
Quebec	89	0903	5	89-0903-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)	PG58-28	
Quebec	89	0903	6	89-0903-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer	PG52-34	
Quebec	89	A901	6	89-A901-6	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		Other Asphalt Cement Grade
Quebec	89	A901	7	89-A901-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		Other Asphalt Cement Grade
Quebec	89	A902	10	89-A902-10	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer	PG52-40	
Quebec	89	A902	9	89-A902-9	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)	PG58-22	
Quebec	89	A903	7	89-A903-7	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)	PG58-22	
Quebec	89	A903	8	89-A903-8	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer	PG52-34	
Saskatchewan	90	0901	4	90-0901-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Saskatchewan	90	0901	5	90-0901-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
Saskatchewan	90	0902	4	90-0902-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Saskatchewan	90	0902	5	90-0902-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		

STATE	CODE	SHRP_ID	Layer_No	ID	MATERIAL_TYPE	DESCRIPTION	PG Grade	Other Grade
Saskatchewan	90	0903	4	90-0903-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Saskatchewan	90	0903	5	90-0903-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
Saskatchewan	90	0959	4	90-0959-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Saskatchewan	90	0959	5	90-0959-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
Saskatchewan	90	0960	4	90-0960-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Saskatchewan	90	0960	5	90-0960-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
Saskatchewan	90	0961	4	90-0961-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Saskatchewan	90	0961	5	90-0961-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		
Saskatchewan	90	0962	4	90-0962-4	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	AC Layer Below Surface (Binder Course)		
Saskatchewan	90	0962	5	90-0962-5	Hot Mixed, Hot Laid Asphalt Concrete, Dense Graded	Original Surface Layer		

Table 2 MRL Materials Inventory for the SPS-9 Sections.

Agency	Exp#	Shrp_ID	Sample Type	MATERIAL TYPE	Sampled_Date	Unit Type	Qtity	Wt (lbs)	GridCoord	Description
AB	9A		A.T.d.U. PH03-08	Combined Aggregate	11/21/95	5 gal	10	737	W2-01-01	B01A03-BU01A03, TS03, PH03:08, SEC 3
AB	9A		AC 150-200	Asphalt Binder	11/22/95	5 gal	1	48	E3-05-02	B01A01, BC01A01, TS-01, 16W, 3:08, 150-200
AB	9A		AC 200/300	Asphalt Binder	11/21/95	5 gal	1	42	E3-05-02	B01A02, BC01A02, TS:02, PH 3:08
AB	9A		AC 300/400	Asphalt Binder	11/21/95	5 gal	1	48	E3-05-02	B01A03, BC01A03, TS-3, 16W, 3:08,
AB	9A		PH03:08 ATDU	Combined Aggregate	11/22/95	5 gal	10	708	W2-01-01	B01A01-BU01A01, TS01, PH03:08, SEC 1
AB	9A	81A900	BULK SAMPLE			BAG	1		23-C1-01	BULK SAMPLE
AR	9		AC SURFACE MIX	HMA Mix	12/01/93	5 gal	3	210	E6-05-02	ARKANSAS O5, FIELD SET #1 (PAVER)
AR	9	50902	PG 64-22 PLANT TANK	Asphalt Binder	10/04/96	5 gal	1	25	E6-01-02	050900, 050902
AR	9	50902	PG 64-22	Asphalt Binder		1 gal	4	38	E2-03-03	LTTP-042
AR	9	50903	PG-58-22	Asphalt Binder	10/04/96	5 gal	1	38	E6-01-02	050900, 050903, PLANT TRK
AR	9	50903	PG 58-72	Asphalt Binder		1 gal	3	21	E2-03-03	LTTP-044
AR	9	50904	PG 76-22	Asphalt Binder		1 gal	3	29	E2-03-03	LTTP-034
AR	9	50905	PG-70-22	Asphalt Binder	10/08/96	5 gal	1	38	E6-01-02	050900, 050905, TANK
AR	9	50905	PG 70-22	Asphalt Binder		1 gal	4	36	E2-03-03	LTTP-050, 282,2500
AZ	9		SUPERPAVE 3/4 MIX AGG	HMA Mix	08/03/93	55	1		F4-05-02	
AZ	9A		PG 76-10 COMPOSITE	Asphalt Binder		1 gal	2	18	E2-03-03	LTTP 034
AZ	9A	04B901	PG 76-10 BINDER	Asphalt Binder	03/25/95	1 GAL	3	23	E2-04-03	04B901
AZ	9A	04B901	AZ COMPOSITE AGGREGATE	Combined Aggregate	03/25/95	5 gal	2	143	E3-04-02	04B901
AZ	9A	04B901	COMPOSITE PLANT MIX	HMA Mix		5 gal	2	148	E3-04-02	04B901
AZ	9A	04B903	AC BINDER	Asphalt Binder	03/25/95	1 gal	1	8	E2-04-03	PG 70-10 (AC-40), 04B903
AZ	9A	04B903	AC-40 SUPERPAVE BINDER	Asphalt Binder	03/17/95	1 GAL	1	8	E2-04-03	PG-70-10 H310601C, STAKER AM PHEONIX 94A
AZ	9A	04B903	AC-40, PG 70-10 BINDER	Asphalt Binder	03/17/95	1 GAL	1	9	E2-04-03	04B903
AZ	9A	04B903	PLANT MIX	HMA Mix		5 gal	1	76	E3-04-02	PG 70-16, AC-40
AZ	9A	04B903	PLANT MIX	HMA Mix	03/18/95	5 gal	2	136	E3-04-02	LEVEL 1 (AC-40), 04B903
AZ	9A	04B903	PLANT MIX	HMA Mix	03/18/95	5 gal	1	74	E3-04-02	PG 70-10 (AC-40), 04B903
AZ	9A	04B960	PLANT MIX	HMA Mix	03/14/95	5 gal	3	210	E3-04-02	SMA POLYMER, 04B960
AZ	9A	04B964	A.R.A.C. MIX	HMA Mix		5 gal	2	131	E3-04-02	04B964
CT	9A	90901	AC-20	Asphalt Binder	06/23/97	5 gal	1	36	E3-04-01	BC01A01, 090901, ASPHALT PLANT
CT	9A	90901	COMBINED AGGREGATE SURFACE LAYER	Combined Aggregate	06/23/97	5 gal	9	585	E7-04-01	CT STANDARD, ASPHALT PLANT
CT	9A	90902	COMBINED AGG. SUPERPAVE, SURFACE	Combined Aggregate	07/15/97	5 gal	11	646	E7-04-01	ASPHALT PLANT , BU01A02, O90902
CT	9A	90960	COMBINED AGG SURFACE LAYER	Combined Aggregate	08/07/97	5 gal	8	461	E7-04-01	CT SUPERPAVE RAP , ASPHALT PLANT BU01A060, 090960
CT	9A	90960	COMBINED AGG SURFACE LAYER, RAP ONLY	RAP	08/07/97	5 gal	2	95	E7-04-01	CT SUPERPAVE RAP , ASPHALT PLANT BU01A060, 090960
CT	9A	90962	COMBINED AGG SURFACE LAYER	Combined Aggregate	08/12/97	5 gal	8	464	E7-04-01	CT SUPERPAVE RAP , ASPHALT PLANT BU01A062, 090962

Agency	Exp#	Shrp_ID	Sample Type	MATERIAL TYPE	Sampled_Date	Unit Type	Qtity	Wt (lbs)	GridCoord	Description
CT	9A	90962	COMBINED AGG SURFACE LAYER, RAP ONLY	RAP	08/12/97	5 gal	2	120	E7-04-01	CT SUPERPAVE RAP , ASPHALT PLANT BU01A062, 090962
FL	9A	120900	ASPHALT CEMENT PG 58-16	Asphalt Binder	07/23/96	5 gal	1	40	E4-04-01	PLANT 1 STORAGE TANK
FL	9A	120902	COMBINED AGG	Combined Aggregate	07/23/96	5 gal	1	60	E4-05-01	M.S.= PLANT/120902, S.L.= I-10 EB 120902
FL	9A	120902	COMBINED AGG, PG 64-16	Combined Aggregate	07/23/96	5 gal	8	524	E4-06-02	120902, I-10 EB, PLANT
FL	9A	120902	COMBINED AGG, PG 64-16	Combined Aggregate	07/23/96	5 gal	7	460	E4-06-02	I-10, EB
IN	9	180900	AC	Asphalt Binder		5 gal	1	40	E3-02-02	
IN	9	180900	AC	Asphalt Binder		5 gal	3	116	E3-03-02	
IN	9	180900	AC CEMENT IN SPS-9	Asphalt Binder		5 gal	1	38	E3-03-01	
IN	9	180900	ASPHALT CEMENT	Asphalt Binder		5 gal	1	40	E4-02-01	
IN	9	180900	ASPHALT CEMENT	Asphalt Binder		5 gal	3	116	E4-03-02	
IN	9	180900	ASPHALT CEMENT	Asphalt Binder		5 gal	1	39	E4-03-01	
IN	9	180900	BLENDED AGG. HV	Combined Aggregate		55	1		F3-02-02	
IN	9	180900	COMB. AGG + SURFACE COURSE	Combined Aggregate		55	1		F3-02-02	
IN	9	180900	COMB. AGG BINDER COURSE	Combined Aggregate		55	1		F5-01-01	
IN	9	180900	COMB. AGG BINDER COURSE	Combined Aggregate		55	1		F3-03-02	
IN	9	180900	COMB. AGG BINDER HV	Combined Aggregate		55	1		F3-04-01	
IN	9	180900	COMB. AGG SURFACE COURSE	Combined Aggregate		55	1		F4-05-01	
IN	9	180900	COMBINED AGG	Combined Aggregate		55	1		F5-03-02	
IN	9	180900	COMBINED AGG SURFACE	Combined Aggregate		55	1		F5-06-01	
IN	9	180900	COMBINED AGGREGATE	Combined Aggregate		55	1		F2-01-01	
IN	9	180900	HMAC	HMA Mix		5 gal	1	83	E3-03-01	SURFACE COURSE IN SPS-9
IN	9	180900	HMAC	HMA Mix		5 gal	1	76	E4-03-02	BIT SURFACE SAMPLE S-1
IN	9	180900	HMAC BIT BASE	HMA Mix		5 gal	1	76	E4-03-02	SAMPLE B-4
IN	9	180900	HMAC BI + BINDER	HMA Mix		5 gal	1	81	E4-03-02	BI-1
IN	9	180900	HMAC BINDER COARSE	HMA Mix		5 gal	1	82	E3-03-02	BI-4
IN	9	180900	HMAC BINDER COURSE	HMA Mix		5 gal	1	85	E4-02-01	BI-2
IN	9	180900	HMAC BITUMINOUS BASE	HMA Mix		5 gal	1	85	E4-03-02	BIT BASE SAMPLE B-5
IN	9	180900	HMAC BITUMINOUS BASE	HMA Mix		5 gal	1	80	E4-02-01	
IN	9	180900	HMAC SURFACE COURSE	HMA Mix		5 gal	1	80	E4-02-01	
IN	9	180900	HMAC SURFACE COURSE	HMA Mix		5 gal	1	78	E4-03-02	
IN	9	180900	HMAC, BINDER COURSE	HMA Mix		5 gal	1	81	E3-03-02	B1-3
IN	9	180900	HMAC, BITUMIOUS BASE	HMA Mix		5 gal	1	82	E3-03-02	SAMPLE B-4
KS	1&9		AC-20 BINDER	Asphalt Binder		1 GAL	2	17	E2-04-03	PROJECT 34-49, K-3396 KIOWA CO KS , LTPP002
KS	1&9		PATB FINE + COURSE	Combined Aggregate	08/11/93	55	1		F5-05-02	
KS	9		SMA SURFACE COURSE	HMA Mix	10/24/93	55	1		F6-02-01	

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KS	9	200900	AC 20	Asphalt Binder		1 gal	4	37	E2-03-03	54-49K3196-01
KS	9	200903	SMA (HMAC)	HMA Mix	10/24/93	5 gal	2	142	E6-03-02	200903 STA 261+00 TO 283+00 PROJECT # 54-49-K-3196-01
KS	9	200903	SMA (HMAC)	HMA Mix	10/24/93	5 gal	1	67	E6-03-02	SHRP 200903 PROJECT # 54-49-K-3196-01 STA 261+00 TO 383+00
KS	9	200903	SURFACE COURSE SUPERPAVE	HMA Mix	09/30/93	55	1		F6-02-01	FINE + COURSE AGG.
MD	9		AC	Asphalt Binder		5 gal	1	40	E3-03-02	I-70, WB
MD	9		ASPHALT CEMENT	Asphalt Binder		5 gal	7	280	E4-03-02	I-70 WB
MD	9		ASPHALT CEMENT	Asphalt Binder		5 gal	1	40	E4-02-01	I-70 WB
MD	9		MINERAL FILLER	Filler		5 gal	1	62	E3-03-02	I-70, WB
MD	9		MINERAL FILLER SMA TYPE ALL	Filler	05/01/92	5 gal	1	56	E4-02-01	FREDRICK , MD
MD	9		SHRP MIX	HMA Mix		5 gal	3	222	E4-03-02	I-70 WB
MD	9		SMA MIX	HMA Mix		5 gal	2	153	E4-03-02	I-70 WB
MD	9		SMA MIX	HMA Mix		5 gal	1	74	E4-03-01	I-70 WB
MD	9	240900				1 gal	4	32	E2-03-03	
MD	9	240900	COMBINED SHRP AGGREGATE	Combined Aggregate	10/06/92	55	1		F5-01-02	COMBINED SHRP AGGREGATE
MD	9	240900	COMBINED SHRP AGGREGATE	Combined Aggregate	10/06/92	55	1		F4-03-01	COMBINED SHRP AGGREGATE
MD	9	240900	COMBINED SHA AGGREGATE	Combined Aggregate	10/06/92	55	1		F4-01-02	COMBINED SHA AGGREGATE
MD	9	240900	COMBINED SHA AGGREGATE	Combined Aggregate	10/06/92	55	1		F4-01-02	COMBINED SHA AGGREGATE
MI	9A		SURFACE HMA	HMA Mix	08/29/96	5 gal	1		B1-01-02	
MI	9A		SURFACE HMA	HMA Mix	08/29/96	5 gal	1		B1-01-02	
MI	9A		SURFACE HMA	HMA Mix	08/29/96	5 gal	1		B1-01-02	
MI	9A		AC	Asphalt Binder	06/29/96	5 gal	6		B1-02-01	
MI	9A		AC	Asphalt Binder	06/29/96	5 gal	11		B1-02-01	
MI	9A		AC	Asphalt Binder	06/29/96	5 gal	5		B1-02-01	
MI	9A		AGG	Combined Aggregate	06/29/96	5 gal			B3-02-01	
MI	9A		RAP	RAP	06/29/96	5 gal	2		B2-01-01	
MI	9A		RAP	RAP	06/29/96	5 gal			B3-02-02	
MI	9A		VIRGIN AGG	Combined Aggregate	06/29/96	5 gal	7		B2-01-01	
MI	9A		AGG	Combined Aggregate	06/29/96	5 gal			B3-01-01	
MI	9A		AGG	Combined Aggregate	06/29/96	5 gal	10		B1-01-01	
MI	9A		AGG	Combined Aggregate	06/29/96	5 gal			B2-01-02	
MI	9A		RAP	RAP	06/29/96	5 gal			B1-01-02	
MI	9A		RAP	RAP	06/29/96	5 gal	2		B2-01-01	
MI	9A		VIRGIN AGG	Combined Aggregate	06/29/96	5 gal	8		B2-01-01	
MI	9A		AGG	Combined Aggregate	06/29/96	5 gal			B3-02-01	
MI	9A		AGG	Combined Aggregate	06/29/96	5 gal	8		B1-02-01	

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MN	9		85/100	Asphalt Binder	08/19/93	5 gal	2	112	E3-01-02	COMMERICIAL ASPHALT #9
MN	9		AGG	Combined Aggregate		55	1		F3-01-02	
MN	9		PG 58-34	Asphalt Binder	08/19/93	5 gal	1	40	E3-01-02	COMMERICIAL ASPHALT #9
MN	9		SHRP AGG. 85/100 OIL	Asphalt Binder	08/19/93	5 gal	1	67	E4-01-02	WIDROW IN FRONT OF PAVER, SECT 4B
MN	9		SHRP WEARING COURSE	HMA Mix	08/19/93	5 gal	1	68	E3-01-02	WINDROW IN FRONT OF PAVER
MN	9		SHRP WEARING COURSE SUPERPAVE	HMA Mix	08/19/93	5 gal	2	143	E4-01-01	WINDROW IN FRONT OF PAVER
MN	9		SMA AGG	Combined Aggregate		55	1		F4-01-01	
MN	9		TH169			55	1		F3-01-01	
MN	9	270900	85/100 KOCH	Asphalt Binder		1 gal	4	36	E2-03-03	PROJ TH 169, SP7007-20
MN	9	270900	PG 58-34	Asphalt Binder		1 gal	4	34	E2-03-03	SP 7007-20
MN	9	270901	2341 WEAR		08/19/93	5 gal	1	71	E4-01-01	270901 PROJECT TH169 SP 7007-20
MN	9	270901	2341 WEAR	HMA Mix	08/20/93	5 gal	2	135	E4-01-01	CONTROL WINDROW 270901
MN	9	270901	85/100	Asphalt Binder		5 gal	1	35	E4-01-01	VALLEY PAVING
MN	9	270901	85/100	Asphalt Binder	08/19/93	5 gal	1	45	E3-01-01	CONTROL SECTION 270901
MN	9	270901	GR 85/100	Asphalt Binder		1 gal	2	17	E2-03-03	PROJ # TH169, SP 7007-200, ASHLAND REFINERY
MN	9	270902	PG 58-34	Asphalt Binder		5 gal	1	41	E4-01-01	COMM. ASPHALT #9 KOCH REF
MN	9	270903	SMA ASPAHLT		08/19/93	5 gal	2	80	E4-01-01	270903 PROJECT TH169 SP 7007-20
MN	9	270903	SMA WEARING COURSE HMAC	HMA Mix	08/19/93	5 gal	1	72	E4-01-01	270903 PROJECT TH169 SP 7007-20
MN	9	270903	WEARING COURSE , HMAC	HMA Mix	08/19/93	5 gal	2	136	E4-01-01	WINDROW 270903 FRONT OF PAVER
MN	9	270910	2541 AGG AND OIL	Asphalt Binder	08/19/93	5 gal	3	220	E4-01-01	COMMERCIAL ASPHALT #9 WINDROW 270910
MN	9	270910	AGG AND 85/100	Asphalt Binder	08/19/93	5 gal	1	71	E3-01-01	COMMERCIAL ASPHALT #9 WINDROW 270910
MN	9A	27A901	31 B BASE			5 gal	2	122	E4-06-02	307+50-312+50
MN	9A	27A901	47 B AC MIX BNDER & WEARING COURSE	HMA Mix		5 gal	6	371	E4-06-02	27A901, 307+50 TO 312+50
MN	9A	27A901	AC MIX WEARING BINDER COURSE	HMA Mix		5 gal	4	255	E4-06-02	SL -47B
MN	9A	27A901	BASE COURSE 31 B			5 gal	7	440	E4-06-02	27A901, BIMIDJI MN
MO	9A		PG 64-28	Asphalt Binder		5 gal	1	43	E6-03-01	
MO	9A	290901	AC-20	Asphalt Binder	09/12/96	5 gal	1	33	E6-03-01	BC51A01
MO	9A	290901	IC-1, IC-2, IC-3, IC-4, IC-5, IC-6		07/24/96	5 gal	6	465	W2-01-01	BU02A01
MO	9A	290901	IB MIX-1, 2, 3, 4, 5, 6		07/24/96	5 gal	6	463	E7-01-01	BU51A01, #5
MO	9A	290902	SP 125,#1,#2,#3,#4,#5,#6		09/12/96	5 gal	6	435	E7-01-01	BU02A02, SPS-125, #1
MO	9A	290902	SPS-190, #1,#2,#3,#4,#5,#6		09/12/96	5 gal	4	277	E7-01-01	BU51A02, SPS-190, #1
MO	9A	290903	SP 125,#1,#2,#3,#4,#5,#6			5 gal	5	369	E7-01-01	BU02A03, SPS-125, #1-5
MO	9A	290903	SP 190,#1,#2,#3,#4,#5,#6		09/12/96	5 gal	6	407	E7-01-01	SPS-190, #1-6
MO	9A	290959	SMA,#1,#2,#3,#4,#5,#6		09/12/96	5 gal	6	466	E7-01-01	BU02A59

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MS	9A		PG 64-22 COMBINED AGG	Combined Aggregate	08/23/95	5 gal	10	613	E7-02-02	MISSISSIPPI 2809 #7, BELT, FIELD SET #2
MS	9A	280200	BINDER PG 58-22	Asphalt Binder	08/25/95	5 gal	1	38	E6-02-02	MISSISSIPPI, 2802, MISS PROJ #59-0055-04-061-10, PLANT/TANK, FIELD SET #2
MS	9A	280900	AC-30 BINDER	Asphalt Binder	11/11/92	1 GAL	2	17	E2-04-03	MS STATE HIGHWAY DEPT LTPP003
MS	9A	280900	BINDER PG 76-22	Asphalt Binder	08/30/95	5 gal	1	38	E6-02-02	MISSISSIPPI, 2809, MISS PROJ #59-0055-04-061-10, PLANT, FIELD SET #4
MS	9A	280900	BINDER#1, PG 64-22	Asphalt Binder	08/23/95	5 gal	1	38	E6-02-02	MISSISSIPPI, 2809, MISS PROJ #59-0055-04-061-10, FIELD SET #2
MS	9A	280900	PG SA22		08/23/94	5 gal	1	38	W4-01-01	STATE PROJECT NO. 59-0055-04-061-10, PLANT, FIELD SET 2
MS	9A	280900	PG64-22 BINDER	Asphalt Binder		5 gal	1	38	W4-01-01	
MT	9		GRADE D	Combined Aggregate		5 gal	0	0	E2-02-01	
MT	9		GRADE D COARSE PMBS	Combined Aggregate		5 gal	1	54	E2-01-02	
MT	9		GRADE D CR-FINES PMBS	Combined Aggregate		5 gal	1	54	E2-01-02	74489-16
MT	9		GRADE D CR-FINES PMBS	Combined Aggregate		5 gal	2	103	E2-01-02	744809-16
MT	9		GRADE D FOR PMAC	Combined Aggregate	10/28/98	5 gal	3	129	E3-05-01	I 15
MT	9		GRADE D GYRO COARSE	Combined Aggregate		5 gal	1	52	E2-01-02	
MT	9		PMAC		10/26/98	5 gal	2	88	E3-05-01	I 15
MT	9	300902				BAG	1	60	E2-02-04	300902 STA 629+00
MT	9	300902	GRADE "S" AGGREGATE	Combined Aggregate		5 gal	4	300	E4-05-01	300902
MT	9	300902	GRADE "S" AGGREGATE	Combined Aggregate		5 gal	5	384	E4-05-01	300902
MT	9	300902	GRADE "S" AGGREGATE	Combined Aggregate		5 gal	1	78	E4-05-02	300902
MT	9	300902	GRADE D FOR GYRO-CR FINES PMBS	Combined Aggregate	10/28/98	BAG	3	180	E2-02-03	IM15-5(93)256[2273]
MT	9	300902	GRADE S 64-34	Combined Aggregate	10/23/98	BAG	1	60	E2-02-02	IM15-5(93)256[2273]
MT	9	300902	GRADE S FOR MIX DESIGN COARSE PMBS	Combined Aggregate	02/19/98	BAG	1	60	E2-02-03	IM15-5(93)256[2273]
MT	9	300902	GRADE S FOR MIX DESIGN COARSE PMBS	Combined Aggregate	02/19/98	BAG	2	120	E2-02-02	IM15-5(93)256[2273]
MT	9	300902	GRADE S FOR MIX DESIGN CR-FINES PMBS	Combined Aggregate	02/19/98	BAG	1	66	E2-02-04	IM15-5(93)256[2273]
MT	9	300902	GRADE S FOR MIX DESIGN CR-FINES PMBS	Combined Aggregate	02/19/98	BAG	1	60	E2-02-03	IM15-5(93)256[2273]
MT	9	300902	GRADE S FOR MIX DESIGN PMBS COARSE	Combined Aggregate	02/19/98	BAG	1	60	E2-02-04	IM15-5(93)256[2273]
MT	9	300902	GRADE S FOR MIX DESIGN PMBS COARSE	Combined Aggregate	02/19/98	BAG	1	60	E2-02-04	IM15-5(93)256[2273]
MT	9	300902	64-34	Asphalt Binder		5 gal	1	42	E2-01-02	IM15-5(93)256[2273]
MT	9	300902	GRADE S AGG HARDY CREEK UIM N.B.	Combined Aggregate		BAG	2	120	E2-02-02	SEC. 300902 IM15-5(93)256[2273]
MT	9	300902	GRADE S HARDY CREEK	Combined Aggregate		5 gal	1	67	E2-01-02	A99

Agency	Exp#	Shrp_ID	Sample Type	MATERIAL TYPE	Sampled_Date	Unit Type	Qtity	Wt (lbs)	GridCoord	Description
MT	9	300903	GRADE D MATERIAL FOR GYRATORY SPECIMENS	Combined Aggregate	10/30/98	BAG	1	60	E2-02-03	SEC. 15 300901 STA 651+00 TO 655+00 IM15-5(93)256[2273]
MT	9	300903	PG 64-22 AC	Asphalt Binder		5 gal	1	42	E2-01-02	
MT	9	300903	PG 64-22 AC	Asphalt Binder		5 gal	1	52	E2-01-02	
MT	9	300903	CTS			BAG	1	60	E2-02-04	
MT	9	300907	PMAC GRADE D	Combined Aggregate		5 gal	1	52	E2-01-02	
NC	9A	370963	COMBINED & GRADED AGG	Combined Aggregate	09/18/98	5 gal	10	678	E5-01-02	LEE PAVING SANFORD PLANT, FRONT END LOADER (PLANT HOT), STOCKPILE (PLANT)
NC	9A	370965	COMBINED & GRADED AGG	Combined Aggregate	09/30/98	5 gal	9	556	E5-01-02	LEE PAVING SANFORD PLANT, FRONT END LOADER (PLANT HOT), STOCKPILE (PLANT)
NE	9	310902	SUPERPAVE COMBINED AGG	Combined Aggregate		5 gal	11	772	E7-03-01	310902 NEB SPS-9
NJ	9A		AC-20	Asphalt Binder		5 gal	1	40	E6-01-01	
NJ	9A		PG 58-28	Asphalt Binder		5 gal	1	37	E6-01-01	
NJ	9A		PG 64-16 AMI	Asphalt Binder	05/15/97	5 gal	1	30	E6-01-01	
NJ	9A		PG 64-28	Asphalt Binder		5 gal	1	38	E6-01-01	
NJ	9A		PG 70-28	Asphalt Binder	08/29/96	5 gal	1	36	E6-01-01	T-9
NJ	9A	340902	COMBINED AGG SUPERPAVE	Combined Aggregate	06/16/98	5 gal	10	705	E2-06-01	PG 58-28, 19 MM SEC 2
NJ	9A	340963	AC-PG 52-28	Asphalt Binder	06/17/98	5 gal	1	26	E2-06-02	FLORENCE, NJ
NM	9	350901	AC CEMENT (BINDER) AC 10 (IA)	Asphalt Binder	09/11/96	5 gal	1	43	E6-01-02	PLANT 2nd LIFT, 350901, SPS-9
NM	9	350901	AC CEMENT BINDER	Asphalt Binder	09/09/96	5 gal	1	37	E6-01-02	PLANT 1ST LIFT
NM	9	350902	AC CEMENT BINDER PG 64-22	Asphalt Binder	09/11/96	5 gal	2	83	E6-01-02	350902, PLANT, 2nd LIFT
NM	9	350903	PG 58-22, AC BINDER	Asphalt Binder	09/09/96	5 gal	1	42	E6-01-02	PLANT 1ST LIFT
NM	9	350904	PG 64-10 AC CEMENT BINDER	Asphalt Binder	09/09/96	5 gal	1	40	E6-01-02	PLANT 2nd LIFT, 350904, SPS-9
OH	9	390900	TYPE I HOT MIX	HMA Mix	07/01/95	5 gal	3	190	E3-05-02	SUMMER 1995 / 390900, BA01A01
OH	9	390900	TYPE II HOT MIX	HMA Mix	07/01/95	5 gal	1	65	E3-05-02	SUMMER 1995 / 390900, BA02A01
OH	9	390903	TYPE I HOT MIX	HMA Mix		5 gal	2	137	E4-06-01	390903, BA01A03
OH	9	390903	TYPE II HOT MIX	HMA Mix		5 gal	2	143	E4-06-01	390903, BA02A03, FIELD SET #1
ON	9	870902			10/03/96	5 gal	10	366	E7-06-02	870902, BG01A02, BO1A02
ON	9	870902			06/10/97	5 gal	10	708	E7-06-02	870902, BU0A02
ON	9	870902	AC SURFACE , GSC			CYL	19		21-C1-01	GRYO SAMPLE
ON	9	870902	AC BULK, GCS		10/24/01	CYL	12		20-C1-01	AC BULK, GCS
ON	9	870902	AC SURFACE , GSC			CYL	20		21-C1-01	GRYO SAMPLE
ON	9	870903			06/11/97	5 gal	1		E3-06-02	870903, BC01A03
ON	9	870960			06/12/97	5 gal	1		E3-06-02	870960, BC01A60
ON	9	870961			06/16/97	5 gal	1		E3-06-02	870961, BC01A61
ON	9	870962	AGGREGATE	Combined Aggregate	06/17/97	5 gal	10	810	E7-06-02	870962, BU01A62
PQ	9	890900	AC BULK			BOX	1		23-C2-01	AC BULK

Agency	Exp#	Shrp_ID	Sample Type	MATERIAL TYPE	Sampled_Date	Unit Type	Qtity	Wt (lbs)	GridCoord	Description
PQ	9	890900	AC BULK			BOX	1		23-C2-01	AC BULK
PQ	9	890900	AC BULK			BOX	1		23-C2-01	AC BULK
PQ	9	890900	AC BULK			BOX	1		23-C2-01	AC BULK
PQ	9	890900	AC BULK			BOX	1		23-C2-01	AC BULK
PQ	9	890900	AC BULK			BOX	1		23-C2-01	AC BULK
PQ	9	890900	AC BULK			BOX	1		23-C2-01	AC BULK
PQ	9	890900	AC BULK			BOX	1		23-C2-01	AC BULK
PQ	9	890900	AC BULK			BOX	1		23-C2-01	AC BULK
PQ	9	890900	AC BULK			BOX	1		23-C2-01	AC BULK
PQ	9	890900	AC BULK			BOX	1		23-C2-01	AC BULK
PQ	9	890900	AC BULK			BOX	1		23-C2-01	AC BULK
PQ	9	890902	SUPERPAVE SURFACE COURSE, COMBINED AGG	Combined Aggregate	09/24/96	5 gal	5	300	E7-02-01	BU01A02, 890902
PQ	9A	89A900	AC BULK			BOX	1		23-C2-01	AC BULK
PQ	9A	89A900	AC BULK, 1/6			BOX	1		23-C2-01	AC BULK
PQ	9A	89A900	AC BULK, 2/6			BOX	1		23-C2-01	AC BULK
PQ	9A	89A900	AC BULK, 3/6			BOX	1		23-C2-01	AC BULK
PQ	9A	89A900	AC BULK, 5/6			BOX	1		23-C2-01	AC BULK
PQ	9A	89A900	AC BULK, 6/6			BOX	1		23-C2-01	AC BULK
PQ	9A	89A900	ASPHALT & CONCRETE , GCS		09/18/96	CYL	38		22-B1-01	GRYO SAMPLE, 170 EB FIELD SET #1
PQ	9A	89A901	AGENCY SURFACE COURSE, COMBINED AGG.	Combined Aggregate	09/17/96	5 gal	5	287	E7-02-01	BU01A01, 89A901
PQ	9A	89A902	SUPERPAVE SURFACE COURSE, COMBINED AGG	Combined Aggregate	09/18/96	5 gal	5	289	E7-02-01	BU01A02, 89A902
SK	9	900902	AGG	Combined Aggregate		5 gal	1	69	W1-01-01	
SK	9	900902	SPS-119			5 gal	1		E6-03-02	900902 DEPT. OF HIGHWAY REPAIRS, SASKATCHEWAN, CANADA SAMPLE #BU05A02
SK	9A	900901	AC, BULK		09/04/96	5 gal	1	42	E6-03-02	AC BULK
SK	9A	900902	COMPACTED AC, GCS		11/21/96	CYL	26		22-B2-01	GRYO COMPACTED AC , HIGHWAY 16-24A WB
SK	9A	900902	AC, BULK		11/21/96	5 gal	1	42	E6-03-02	HIGHWAY 16-24A
SK	9A	900902	BULK AGG	Combined Aggregate	11/21/96	5 gal	1	72	E6-03-02	HIGHWAY 16-24A
SK	9A	900902	BULK AGG	Combined Aggregate	11/21/96	5 gal	1	68	E6-03-02	HIGHWAY 16-24A
SK	9A	900902	BULK AGG	Combined Aggregate	11/21/96	5 gal	1	70	E6-03-02	HIGHWAY 16-24A
SK	9A	900902	BULK AGG	Combined Aggregate	11/21/96	5 gal	1	71	E6-03-02	HIGHWAY 16-24A
SK	9A	900902	BULK AGG	Combined Aggregate	11/21/96	5 gal	1	72	E6-03-02	HIGHWAY 16-24A
SK	9A	900902	BULK AGG	Combined Aggregate	11/21/96	5 gal	1	74	E6-03-02	HIGHWAY 16-24A

Agency	Exp#	Shrp_ID	Sample Type	MATERIAL TYPE	Sampled_Date	Unit Type	Qtity	Wt (lbs)	GridCoord	Description
SK	9A	900902	BULK AGG	Combined Aggregate	11/21/96	5 gal	1	72	E6-03-02	HIGHWAY 16-24A
SK	9A	900902	BULK AGG	Combined Aggregate	11/21/96	5 gal	1	74	E6-03-02	HIGHWAY 16-24A
SK	9A	900902	BULK AGG	Combined Aggregate	11/21/96	5 gal	1	70	E6-03-02	HIGHWAY 16-24A
SK	9A	900902	BULK AGG	Combined Aggregate	11/21/96	5 gal	1		E6-03-02	HIGHWAY 16-24A
SK	9A	900902	COMPACTED AC, GCS		11/21/96	CYL	27		22-B2-01	GRYO COMPACTED AC , HIGHWAY 16-24A WB
SK	9A	900902	LIME	Lime	11/21/96	5 gal	1	14	E6-03-02	HIGHWAY 16-24A
SK	9A	900903	AC BULK	Asphalt Binder	09/04/96	5 gal	1	43	E6-03-02	HIGHWAY 16-24A
TX	9		AC-20 WITH LATEX BINDER	Asphalt Binder		5 gal	1	46	E4-04-01	PG 70-22, BUCKET # 24
WI	9		(PG 3-4), AC ELF ASPHALT MAC-10	Asphalt Binder	07/29/92	5 gal	3	121	E4-01-02	
WI	9		6% AC 85/100 W/ANTISTRIP ON WEARING	Asphalt Binder	07/23/92	5 gal	1	85	E3-03-01	IH 94 EB+WB, TRK 94 LOAD 24
WI	9		85/100 AMACO OIL	Asphalt Binder	07/29/92	5 gal	1	75	E4-01-02	I 43, NB+SB SAMP 5
WI	9		85/100 AMACO OIL	Asphalt Binder	07/29/92	5 gal	2	154	E4-01-02	I 43, NB+SB SAMP 3
WI	9		AC (PG 3-4)	Asphalt Binder	07/29/97	5 gal	3	123	E3-02-01	I-43 NB + SB, ELF ALSPHALT - MAC-10
WI	9		AC 20 EVA , SHRP SURFACE	Asphalt Binder	07/10/92	5 gal	3	227	E3-03-01	I-94, EB & WB,
WI	9		AC 28 EVA SHRP SURFACE	Asphalt Binder	07/10/92	5 gal	1		E3-03-01	I-94, EB & WB,
WI	9		AC 85/100 ANTISTRIP	Asphalt Binder	07/29/92	5 gal	1	42	E3-01-01	TRK E17, TR T17, AC USED ON WISE DOT MIX
WI	9		AC 85/100 ANTI-STRIP	Asphalt Binder	07/29/92	5 gal	1	43	E3-03-01	I-94, EB & WB, E-17, T-17
WI	9		AC 85/100 ANTI-STRIP, SAMP#6	Asphalt Binder	07/28/92	5 gal	1	44	E3-03-01	I-94, EB & WB, E-17, T-17
WI	9		AC 85/100 W/ ANTI - STRIP ON BINDER COURSE	Asphalt Binder	07/28/92	5 gal	1	80	E3-03-01	I-94, EB & WB, TRK-93, LOAD 34
WI	9		AC 85/100 W/ANTISTRIP	Asphalt Binder	07/28/92	5 gal	1	42	E4-01-02	I 94 TRK E9, TRL T7
WI	9		AC 85/100 W/ANTI-STRIP	Asphalt Binder	07/29/92	5 gal	1	43	E3-03-01	I-94, EB & WB, E-17, T-17
WI	9		AC 85/100 W/ANTISTRIP ON SURFACE OR WEARING MIX GRD 3	Asphalt Binder	07/23/92	5 gal	1	76	E3-03-01	TRK 93, LOAD 40
WI	9		AC 85/100, W/ANTISTRIP	Asphalt Binder	07/28/92	5 gal	1	43	E3-03-01	I-94, EB & WB, TRUCK E9, TRAILER T17
WI	9		AC 85/100,W/ANTISTRIP ON WEARING	Asphalt Binder	07/23/92	5 gal	1		E3-03-01	I-94, EB & WB, SAMPLE 2
WI	9		AC BINDER MIX	Asphalt Binder	07/08/92	5 gal	1	75	E3-03-01	I-94, EB & WB, TRK #93, LOAD 44
WI	9		AC MIX 85/100, ANTI STRIP	Asphalt Binder	07/28/92	5 gal	1	40	E3-03-01	I-94 E.B., SA#3, TRUCK E9, TRAILER T7
WI	9		AC MIX 85/100, ANTI STRIP	Asphalt Binder	07/28/92	5 gal	1		E3-03-01	I-94 E.B., SA # 6, TRUCK E17, TRAILER T17
WI	9		AC/85/100 ANTI-STRIP , WEARING SURFACE	Asphalt Binder	07/23/92	5 gal	1	78	E3-03-01	I-94, EB & WB, TRK-93, LOAD 48
WI	9		AC/85/100 ANTI-STRIP , WEARING SURFACE	Asphalt Binder	07/23/92	5 gal	1	85	E3-03-01	I-94, EB & WB, TRK-93, LOAD 96

Agency	Exp#	Shrp_ID	Sample Type	MATERIAL TYPE	Sampled_Date	Unit Type	Qtity	Wt (lbs)	GridCoord	Description
WI	9		AGG	Combined Aggregate		55	1		F5-06-02	
WI	9		AGGREGATE	Combined Aggregate		5 gal	1	50	E6-01-01	8 BINDER HV 973 MD
WI	9		AMACO 85/100 AC	Asphalt Binder	07/28/92	5 gal	5	190	E4-01-02	I-43 NB+SB
WI	9		AMAOC 85/100, AC	Asphalt Binder	07/28/92	5 gal	4	156	E4-01-02	I-43 NB+SB
WI	9		BINDER COURSE, AC/85/100 , W/ANTI-STRIP		07/28/92	5 gal	2	170	E3-03-01	I-94, EB & WB, LOAD 44
WI	9		BINDER MAC-15		07/29/92	5 gal	2		E4-01-02	I-43 NB+SB, FIELD SET #1 (P63-4) OIL
WI	9		HV BINDER			5 gal	1		E7-01-01	
WI	9		MINERAL FILLER	Filler	07/28/92	5 gal	1	66	E3-03-01	I-94, EB & WB MATERIAL, PLANT 10, PROJECT # 0624-32-41
WI	9		MINERAL FILLER FOR SNIA	Filler	07/03/92	5 gal	1	56	E3-01-01	I-43 NB+SB
WI	9		MIX OF FINE+COURSE AGG	Combined Aggregate	07/23/92	55	1		F4-03-01	
WI	9		MIX OF FINE+COURSE AGG	Combined Aggregate	07/23/92	55	1		F4-06-01	
WI	9		MOD. AC GRADE, BINDER MIX, SAMP 93		07/08/92	5 gal	1	80	E3-03-01	I-94, EB & WB
WI	9		SHRP AC20 EVA	Asphalt Binder	07/10/92	5 gal	1	76	E3-03-01	I 94 EB 8TH TRUCK
WI	9		SHRP BINDER 85/100 OIL	Asphalt Binder	07/10/92	5 gal	1	78	E3-03-01	I 94 EB 2ND TRUCK
WI	9		SHRP BINDER 85/100 OIL AMACO AC	Asphalt Binder	07/31/92	5 gal	4	258	E4-01-02	I 43, NB+SB
WI	9		SHRP BINDER 85/100, SAMP #5	Asphalt Binder	07/29/92	5 gal	1	69	E4-01-02	FIELD 85/100 AMACO OIL
WI	9		SHRP BINDER MAC 10 MIX PG 3-4-OIL	Asphalt Binder	07/29/92	5 gal	4	275	E4-01-02	I 43 NB-SB
WI	9		SHRP BINDER MAC-10, (FIELD SET) EIF ASPHALT	Asphalt Binder	07/29/92	5 gal	4	241	E4-01-02	I-43 NB+SB, PG 3-4-AC
WI	9		SHRP BINDER MIX, SAMPLE #3	Asphalt Binder	07/08/92	5 gal	1	76	E3-03-01	I-94, EB & WB,
WI	9		SHRP BINDER, AC 85/100 OIL	Asphalt Binder	07/10/92	5 gal	1	74	E3-03-01	I- 94 E.B., 3rd TRUCK
WI	9		SHRP BINDER, AC 85/100 OIL	Asphalt Binder	07/10/92	5 gal	1	75	E3-03-01	I- 94 E.B., 1st TRUCK
WI	9		SHRP SURF. MAC-10 ELF ASPHALT		07/31/92	5 gal	4	288	E4-01-02	
WI	9		W.S TYPE A1 GRADE 3		08/12/92	5 gal	1		E4-03-02	W.S TYPE A1 GRADE 3,
WI	9	550900	85/100 W/ANTISTRIP	Asphalt Binder		1 GAL	4	37	E2-03-03	I-94 EB, 1021-09-82, 1021-09-83
WI	9	550900	85/100 W/ANTISTRIP	Asphalt Binder		1 GAL	5	45	E2-03-03	I-94 EB
WI	9A		CONVENTIONAL BINDER, ANOCO 85-100	Asphalt Binder	08/26/92	5 gal	1	70	E4-03-02	A1 GRADE 1 W.S. CONVENTIONAL BINDER, ANOCO 85-100 , 0.1, 55, I-43
WI	9A		PG 58-22	Asphalt Binder	10/02/97	5 gal	1	37	E6-03-01	STH-29 MIDWEST IND. FUELS, TANK
WI	9A		PG 58-28	Asphalt Binder	10/02/97	5 gal	1	38	E6-03-01	STH-29 MIDWEST IND. FUELS, TANK
WI	9A		PG 58-34	Asphalt Binder	10/02/97	5 gal	1	27	E6-03-01	STH-29 MIDWEST IND. FUELS, TANK
WI	9A		STATE MIX HV BINDER AGG		10/03/97	5 gal	3	204	E7-01-02	AMERICAN ASPHALT, BELT & PLANT, STH-29, SPS 9A, WISCONSIN
WI	9A		STATE MIX HV BINDER AGG		10/03/97	5 gal	2	135	E7-01-02	M.S.=AMERICAN ASPHALT; S.L.=BELT @ PLANT
WI	9A		STATE MIX HV BINDER AGG		10/03/97	5 gal	4	257	E7-01-02	M.S.=AMERICAN ASPHALT; S.L.=BELT @ PLANT

Agency	Exp#	Shrp_ID	Sample Type	MATERIAL TYPE	Sampled_Date	Unit Type	Qtity	Wt (lbs)	GridCoord	Description
WI	9A		SUPERPAVE AGG	Combined Aggregate	10/03/97	5 gal	4	271	E7-01-02	M.S.=AMERICAN ASPHALT; S.L.=BELT @ PLANT
WI	9A		SUPERPAVE AGG	Combined Aggregate	10/03/97	5 gal	2	136	E7-01-02	AMERICAN ASPHALT, BELT & PLANT, STH-29, SPS 9A, WISCONSIN
WI	9A		SUPERPAVE AGG	Combined Aggregate	10/03/97	5 gal	3	209	E7-01-01	AMERICAN ASPHALT / BELT&PLANT
WI	9A		SUPERPAVE AGGREGATES	Combined Aggregate	10/03/97	5 gal	1	72	E7-02-01	STH-29 AMERICAN ASPHALT BELT @ PLANT
WI	9A		SUPERPAVE RAP	RAP	10/03/97	5 gal	1	65	E7-01-01	AMERICAN ASPHALT / BELT&PLANT
WI	9A		SUPERPAVE RAP AGG	RAP	10/03/97	5 gal	1	71	E7-01-02	M.S.=AMERICAN ASPHALT; S.L.=BELT @ PLANT
WI	9A		SUPERPAVE RAP AGG	RAP	10/03/97	5 gal	7	477	E7-01-02	AMERICAN ASPHALT, BELT & PLANT, STH-29, SPS 9A, WISCONSIN
WI	9A		SUPERPAVE RAP AGGREGATES	RAP	10/03/97	5 gal	1	66	E7-02-01	STH-29 AMERICAN ASPHALT BELT @ PLANT
WI	9A	55A901	A1 GRADE 1 BINDER, AMERO , 85/100 OIL		08/26/92	5 gal	3	213	E3-02-01	55A901, CONTROL SURFACE , I-43 , 55A90, 155B901, WAUKESHA CO.
WI	9A	55A901	A1, GRADE 3		08/18/92	5 gal	2	125	E3-02-01	55A901, CONTROL SURFACE , I-43 , WAUKESHA CO.
WI	9A	55A901	A1-GRADE 3		08/18/92	5 gal	1	60	E3-02-02	55A901-CONTROL SURFACE, I43 WAUKESHA CO.
WI	9A	55A901	STATE MIX HV BINDER AGG.		10/03/97	5 gal	1	70	E7-01-01	AMERICAN ASPHALT BELT + PLANT STH 29

Table 3 Materials Inventory for the SPS-9 Sites that have Asphalt Binder and Virgin Aggregate in MRL.

Site	Exp No.	SHRP ID	AGG.	RAP	Binder	HMA Loose Mix
Arizona (AZ) (2 Sites)	9	04B901	Composite (2 x 5 gal = 143 lbs)	0	PG76-10 (3 x 1 gal = 23 lbs & 1 x 5 gal = 34 lbs)	Composite (2 x 5 gal = 148 lbs)
	9	04B903	0	0	PG70-10 (1 x 1 gal = 8 lbs) PG70-10 (1 x 1 gal = 8 lbs) PG70-10 (1 x 1 gal = 9 lbs)	Plant mix (1 x 5 gal = 76 lbs) Plant Mix (2 x 5 gal = 136 lbs) Plant Mix (1 x 5 gal = 74 lbs)
Arkansas (AR)	9	500902	0	0	PG64-22 (1 x 5 gal = 25 lbs) PG64-22 (4 x 1 gal = 38 lbs)	0
	9	500903	0	0	PG58-22 (1 x 5 gal = 38 lbs) PG58-22 (3 x 1 gal = 21 lbs)	0
	9	500904	0	0	PG76-22 (3 x 1 gal = 29 lbs)	0
	9	500905	0	0	PG70-22 (1 x 5 gal = 38 lbs) PG70-22 (4 x 1 gal = 36 lbs)	0
Connecticut (CT)	9A	090901	Combined (9 x 5 gal = 585 lbs)	0	AC-20 (1 x 5 gal = 36 lbs)	0
	9A	090902	Combined (11 x 5 gal = 646 lbs)	0	0	0
	9A	090960	Combined (8 x 5 gal = 461 lbs)	RAP (2 x 5 gal = 95 lbs)	0	0
	9A	090962	Combined (8 x 5 gal = 464 lbs)	RAP (2 x 5 gal = 120 lbs)	0	0
Florida (FL)	9A	120900	0	0	PG58-16 (1 x 5 gal = 40 lbs)	0
	9A	120902	Combined (7 x 5 gal = 460 lbs) Combined (1 x 5 gal = 60 lbs) Combined (8 x 5 gal = 524 lbs)	0	0	0
Indiana (IN) (2 Sites)	9	180900	Combined Aggregate Surface (3 x 55) Combined Aggregate Binder (3 x 55) Combined Aggregate (2 x 55)		AC (1 x 5 gal = 40 lbs) AC (3 x 5 gal = 116 lbs) AC (1 x 5 gal = 38 lbs) AC (1 x 5 gal = 40 lbs) AC (3 x 5 gal = 116 lbs) AC (1 x 5 gal = 39 lbs)	HMA Surface (1 x 5 gal = 80 lbs) HMA Surface (1 x 5 gal = 78 lbs) HMA Binder (1 x 5 gal = 82 lbs) HMA Binder (1 x 5 gal = 85 lbs) HMA Binder (1 x 5 gal = 85 lbs) HMA Bit. Base (1x5 gal = 76 lbs) HMA Bit. Base (1x5 gal = 85 lbs) HMA Bit. Base (1x5 gal = 80 lbs) HMA Bit. Base (1x5 gal = 82 lbs)
Kansas	9	200902	0	0	0	HMA Binder? HMA Surface?
	9	200903	Fine + Coarse Agg. (1 x 55)	0	0	SMA (1 x 5 gal =67 lbs) SMA (2 x 5 gal = 142 lbs)
Maryland (MD)	9	24xxxx	Mineral Filler (1 x 5 gal =62 lbs) Mineral Filler SMA Type All (1 x 5 gal = 56 lbs)	0	AC (1 x 5 gal = 40 lbs) AC (1 x 5 gal = 40 lbs) AC (7 x 5 gal = 280 lbs)	SHRP Mix (3 x 5 gal = 222 lbs) SMA Mix (1 x 5 gal = 74 lbs) SMA Mix (2 x 5 gal = 153 lbs)
	9	240900	Combined SHRP Agg (2 x 55) Combined SHA Agg (2 x 55)	0	0	0
Michigan (MI)	9	26xxxx	Combined Agg.	RAP	AC (6 x 5 gal) AC (11 x 5 gal) AC (5 x 5 gal)	0

Site	Exp No.	SHRP ID	AGG.	RAP	Binder	HMA Loose Mix
Minnesota (MN)	9	27xxxx	Combined Agg (1 x 55) SMA Agg (1 x 55)	0	85/100 (2 x 5 gal = 112 lbs) PG58-34 (1 x 5 gal = 40 lbs)	Wearing Course (1x5 gal =68 lbs) Wearing Course (2x5gal =143lbs)
	9	270900	0	0	85/100 Koch (4 x 1 gal = 36 lbs) PG58-34 (4 x 1 gal = 34 lbs)	0
	9	270901	85/100 (1 x 5 gal = 35 lbs) 85/100 (1 x 5 gal = 45 lbs) GR 85/100 (2 x 1 gal = 17 lbs)	0	0	0
	9	270902	0	0	PG58-34 (1 x 5 gal = 41 lbs)	0
Mississippi (MS)	9A	280900	PG64-22 Combined Agg (10 x 5 gal = 613 lbs)	0	PG58-22 (1 x 5 gal = 38 lbs) AC-30 (2 x 1 gal = 17 lbs) PG76-22 (1 x 5 gal = 38 lbs) PG64-22 (1 x 5 gal = 38 lbs) PG SA22 (1 x 5 f=gal = 38 lbs) PG64-22 (1 x 5 gal = 38 lbs)	0
Missouri (MO)	9	290901	IC-1, IC-2, IC-3, IC-4, IC-5, IC-6 (6 x 5 gal = 465 lbs) SP 125 #1, #2, #3, #4, #5, #6 (6 x 5 gal = 435 lbs)	0	PG64-28 (1 x 5 gal = 43 lbs) AC20 (1 x 5 gal = 33 lbs)	IB Mix (6 x 5 gal = 463 lbs)
Montana (MT)	9	300902	Grade S Agg. (4 x 5 gal = 300 lbs) Grade S Agg. (5 x 5 gal = 384 lbs) Grade S Agg. (1 x 5 gal = 78 lbs) Grade D (3 x Bag = 180 lbs) Others	0	PG64-34 (1 x 5 gal = 42 lbs)	0
	9	300903	Grade D Mat For Gyratory S (1 x Bag = 60 lbs)	0	PG64-22 (1 x 5 gal = 52 lbs) PG64-22 (1 x 5 gal = 42 lbs)	0
Nebraska (NE)	9	310902	SP Combined Aggregate (11 x 5 gal = 772 lbs)	0	0	0
New Jersey (NJ)	9A	34xxxx	0	0	AC-20 (1 x 5 gal = 40 lbs) PG58-28 (1 x 5 gal = 37 lbs) PG64-16 AMI (1 x 5gal = 30 lbs) PG64-28 (1 x 5 gal = 38 lbs) PG70-28 (1 x 5 gal = 36 lbs)	0
	9A	340902	Combined Aggregate SP (10 x 5 gal = 705 lbs)	0	0	0
	9A	340963	0	0	AC-PG52-28 (1 x 5 gal = 26 lbs)	0
New Mexico (NM)	9	350901	0	0	AC-10 (1 x 5 gal = 43 lbs) AC (1 x 5 gal = 37 lbs)	0
	9	350902	0	0	PG64-22 (2 x 5 gal = 83 lbs)	0
	9	350903	0	0	PG58-22 (1 x 5 gal = 42 lbs)	0
	9	350904	0	0	PG64-10 (1 x 5 gal = 40 lbs)	0
North Carolina (NC)	9A	370963	Combined & Graded Agg (10 x 5 gal = 678 lbs)	0	0	0
	9A	370965	Combined & Graded Agg (9 x 5 gal = 556 lbs)	0	0	0
Ohio (OH)	9	390900/3	0	0	0	Type I and II Hot mix
Texas(TX)	9	48xxxx	0	0	AC-20 with Latex (1 x 5 gal = 46 lbs)	0
Wisconsin (3 Sites)	9-9A	55xxxx	Combined Aggregate Mineral Filler	RAP	Asphalt Binder	HMA Mix
Alberta (AB)	9A	81xxxx	A T. D. U. PH03-08 (10 x 5 gal = 737 lbs) PH03:08 ATDU (10 x 5 gal = 708 lbs)	0	AC 150-200 (1 x 5 gal = 48 lbs) AC 200/300 (1 x 5 gal = 42 lbs) AC 300/400 (1 x 5 gal = 48 lbs)	0

Site	Exp No.	SHRP ID	AGG.	RAP	Binder	HMA Loose Mix
Ontario (ON)	9	870902	0	0	0	0
Quebec (PQ)	9	89xxxx	0	0	0	Yes
Saskatchewan (SK)	9A	900902	Combined AGG (1 x 5 gal = 69 lbs) Bulk Agg Lime (1 x 5 gal = 14 lbs)	0	0	0

PROGRAM AREA: TECHNOLOGY DEVELOPMENT

Program Area Lead: Dr. Ramon Bonaquist, P.E.

Introduction

A major criticism of past fundamental research efforts in flexible pavements and asphalt materials is they did not produced products that were directly useable by practicing engineers and technologists. Historically, fundamental research studies have produced promising, new approaches that require substantial follow-on research, development, and training efforts before useable products are available to the profession. Even the products from the highly focused, goal oriented Strategic Highway Research Program required substantial additional effort for further development and training before being successfully implemented into design and construction practice.

The Technology Development program area has been included in the research program of the Asphalt Research Consortium to address this concern. The purpose of this program is to begin the process of refining selected products from the Fatigue, Moisture Damage, Engineered Pavement Materials, and Vehicle Pavement Interaction research programs into useful tools for engineers and technologists involved in the design, construction, and maintenance of flexible pavement systems. These tools may take the form of new or improved standard test methods, improved specifications, improved performance models, or specific design guidance for improving the performance of flexible pavements. The Technology Development program area will be closely coordinated with the Technology Transfer program area.

Relationship to FHWA Focus Area

The Technology Development Program Area supports the FHWA Focus Areas of Optimizing Pavement Performance, Advanced Quality Systems, and Technical Capability Building.

Hypothesis

Early identification of implementable research products and further development of those products by Consortium partners will lead to more rapid acceptance of these products by practicing engineers and technicians.

Objective

The objective of this program is to begin the process of refining selected products from the Consortium research programs into useful tools for engineers and technologists involved in the design, construction, and maintenance of flexible pavement systems

Approach

The work in the Technology Development Program Area has been organized to provide early, mid-term, and long-term products. Early efforts will focus on products developed in past FHWA research studies completed by WRI. Promising products from this past work will be developed into useable tools within the first two years of the Agreement. Mid-term and long-term efforts will focus on research being performed in the Fatigue, Moisture Damage, Engineered Pavement Materials, and Vehicle Pavement Interaction program areas and in the current FHWA/WRI Fundamental Asphalt Research contract. Mid-term products will be available in Years 3 and 4, and long-term products will be available at the end of the contract or later.

Work element TD1: Prioritize and Select Products for Early Development

A number of test procedures, analysis methods, and models were developed by Consortium partners using funding provided by previous FHWA/WRI Fundamental Asphalt Research contracts or other federal sources. This work element will consist of prioritizing and selecting the most promising of these for development into early Asphalt Research Consortium products. For each potential early product, the developing Consortium member will prepare a brief summary of the product. This summary will describe the product, the potential user of the product, and how the product can be used to improve asphalt pavement technology. As agreed to at the July, 2007 ETG meeting, these product descriptions will be submitted to the FHWA, then to the ETG chairs, and finally to the appropriate ETG membership for rating. Products receiving the highest ratings from the ETG membership will be recommended for further development.

Work element TD2: Develop Early Products

It is envisioned that several early products will be identified by Work Element TD1. In Work Element TD2, these products will be further developed as needed. The general approach will be for the Consortium to prepare a detailed product development plan and budget for review by the FHWA AOTR. Once agreement is reached on the scope and budget, the assigned Consortium partner will undertake the development effort. It is envisioned that these early product development efforts will require one year or less to complete.

Work element TD3: Identify Products for Mid-Term and Long-Term Development

As research by the Consortium progresses, it is envisioned that potential mid-term and long-term products will emerge. These potential products will be identified in the Quarterly Progress Reports submitted to the AOTR. When the AOTR concurs that a viable mid-term or long-term product has been identified, the potential product will be presented to the appropriate ETG (s) for consideration. The ETG membership may recommend one of the following specific actions for the potential product:

1. Proceed to development.
2. Reassess after completion of additional research.
3. Eliminate from further consideration.

Work element TD4: Develop Mid-Term and Long-Term Products

It is envisioned that several products will be identified by Work Element TD3. In Work Element TD4, these products will be further developed as needed. The general approach will be for the Consortium to prepare a detailed product development plan and budget for review by the FHWA AOTR. Once agreement is reached on the scope and budget, the assigned Consortium partner will undertake the development effort.

Major Findings from Year 1

Six potential early technology delivery projects were identified by the members of the Asphalt Research Consortium (ARC) in Work Element TD1. Table TD1.1 presents a summary listing of the projects, the anticipated product, and the Expert Task Group(s) (ETG) that would have major interest in the project. All of these projects deal with further development of test methods that were conceived during research under Federal Highway Administration (FHWA) project "Fundamental Properties of Asphalt and Modified Asphalts." Each of these projects will provide a product that addressed a current need of the highway industry.

Table TD1.1. Summary Listing of Early Technology Delivery Projects.

Project	Product	ETG
Automated Flocculation Titrimetric Analysis	Draft AASHTO Standard Test Method for evaluation the propensity of an asphalt or mixture of asphalts to exhibit phase separation	Binder
Determination of Polymer in Asphalt	Draft AASHTO Standard Test Method to determine the quantity of polymer and the nature of the polymer(s) in asphalt	Binder Mixture and Construction
Dynamic Mechanical Analysis	Draft AASHTO Standard Test Method for torsional fatigue testing of the fine aggregate matrix of asphalt concrete	Mixture and Construction Binder Fundamental Properties and Advanced Modeling
Simplified Continuum Damage Fatigue Test	Draft AASHTO Standard Method of Test for fatigue testing of asphalt concrete that can be used with the Simple Performance Test System	Mixture and Construction Fundamental Properties and Advanced Modeling
Universal Sorption Device	Draft AASHTO Standard Method of Test for measuring the surface free energy components of aggregates	Binder Mixture and Construction Fundamental Properties and Advanced Modeling
Wilhelmy Plate Test	Draft AASHTO Standard Method of Test for measuring the surface free energy components of the asphalt binder	Binder Mixture and Construction Fundamental Properties and Advanced Modeling

The project descriptions will be circulated to the ETG Chairs then the appropriate ETG membership in January, 2008 to determine if there is sufficient interest within highway industry for the proposed product. Those projects receiving the support of the ETG membership will proceed to develop in Year 2.

Year 2 Work Plan

It is anticipated that all six projects listed in table TD1.1 will receive sufficient support to warrant development. This development work will be initiated in Year 2 in Work Element TD2. Table TD2.1 lists the Consortium partner that will undertake the development effort for each project in Work Element TD2. For each project, the responsible Consortium partner will prepare a detailed product development plan and budget for review and approval by the FHWA AOTR. The specific tasks that will be included in the development plan will vary depending on the current state of development, but may include the following:

1. Prepare a Draft AASHTO Standard Method of Test.
2. Encourage equipment manufacturers to develop commercial equipment.
3. Perform additional testing to provide characterization of a additional materials.
4. Perform ruggedness testing and revise the Draft AASHTO Standard as needed.
5. Provide technical support for adoption of the procedure as a Provisional Standard.

Upon approval of the product development plan by the FHWA AOTR, development work will be initiated in accordance with the approved product development plan.

Table TD2.1. Responsible Consortium partner for the early technology development projects.

Project	Responsible Consortium Partner
Automated Flocculation Titrimetric Analysis	WRI
Determination of Polymer in Asphalt	WRI
Dynamic Mechanical Analysis	TTI
Simplified Continuum Damage Fatigue Test	AAT
Universal Sorption Device	TTI
Wilhelmy Plate Test	TTI

Year 2 Milestones

No.	Description	Planned Date
1.	Submit Detailed Product Development Plans	6/30/08
2.	AOTR Approval of Product Development Plans	7/31/08
3.	Initiate Early Development Projects	8/1/08

Overall Schedule

Work Element	Year 1	Year 2	Year 3	Year 4	Year 5
TD1: Prioritize and Select Products for Early Development	X				
TD2: Develop Early Products		X	X		
TD3: Identify Products for Mid-Term and Long-Term Development		X	X	X	
TD4: Develop Mid-Term and Long-Term Products			X	X	X

Year 2 Schedule

Work Element	Qtr 1	Qtr 2	Qtr 3	Qtr 4
TD1: Prioritize and Select Products for Early Development	This task was completed in Year 1			
TD2: Develop Early Products	X	X	X	X
TD3: Identify Products for Mid-Term and Long-Term Development				
TD4: Develop Mid-Term and Long-Term Products				

Budget

The budget for the Technology Development Program area is estimated to initially be $1.12M over the five years of the project. However, it is expected that as procedures, methods, and models are developed, the Technology Development area will be increased.

PROGRAM AREA: TECHNOLOGY TRANSFER

Technology transfer is a very critical step in the overall process of research-technology development-implementation. The ultimate goal of research is to develop sound techniques that can be implemented by the industry to design and build more durable and long-lasting pavements. If the research can not be transferred to the industry in the form of implementable material selection, design, analysis, and construction techniques, then its overall value will be highly questionable. The technology transfer task is a crucial part of every research and development program that is aimed at improving the state of the practice of the asphalt pavements/materials engineering community. This has been highly recognized by the FHWA through its technology transfer centers throughout the country as part of the national Local Technology Assistance Program (LTAP).

The overall objective of the technology transfer effort is to transfer the technology from the various research activities into practical applications for the asphalt pavement community, including both public agencies and private industry. The research findings will be communicated to the highway community using presentations at conferences, publication of results in a variety of journals, presentations at Expert Task Group (ETG) meetings, development and frequent updates of a website, development of training materials, and conducting of workshops. The technology transfer effort will attempt to close the loop between research and practice by translating research findings into standard test methods (some of which may be useful as specification tests), training materials, and training workshops and courses.

The Consortium will work on two areas of technology transfer: (1) Outreach and Databases and (2) Training. The Outreach and Databases effort will start in the first year of the Consortium while the training effort will start in the later years of the Consortium.

Category TT1: Outreach and Databases

BACKGROUND

The two critical aspects of outreach are: communication and accessibility. There is a great need to keep the stakeholders informed of the various Consortium activities. The stakeholders should also be able to have unobstructed and easy access to the various components of the research and development. They should be able to view and follow the progress of the various activities of the Consortium on their own time schedule. The stakeholders should also be kept informed of all the locations, dates, and deadlines for any training activities.

Accessibility is defined as the ability of the stakeholders to access valuable materials and research data that may help their programs. There may be some intermediate findings that the industry will use to improve a certain aspect of their operations. Accessibility to such information will be provided through electronic databases that incorporate the technical information on the various materials that are being researched by the Consortium.

HYPOTHESIS

All activities of the Consortium should be communicated and accessible to the stakeholders in a timely manner.

OBJECTIVES

The objectives of this effort are to provide venues for the transfer of the various activities of the Consortium to the asphalt pavement community in a highly effective and organized manner.

EXPERIMENTAL DESIGN

The following work elements will be completed in order to achieve the objectives of this research effort.

Work Element TT1a: Development and Maintenance of Consortium Website

Work Element lead: Elie Hajj (UNR)

Introduction

There is a great need to keep the stakeholders informed of the various Consortium activities. The stakeholders should also be able to have unobstructed and easy access to the various components of the research and development. They should be able to view and follow the progress of the various activities of the Consortium on their own time schedule. The stakeholders should also be kept informed of all the locations, dates, and deadlines for any training activities.

Relationship to FHWA Focus Areas

This effort supports the FHWA Focus Area of Technical Capabilities Building.

Hypothesis

All activities of the Consortium should be communicated and accessible to the stakeholders in a timely manner.

Objectives

The objective of this effort is to provide venues for the transfer of the various activities of the Consortium to the asphalt pavement community in a highly effective and organized manner.

Experimental Design

A Consortium Website will be developed using Micromedia Dreamweaver. The Website will announce workshops and training courses, provide links to partners research activities, federal and asphalt paving related association websites. The Consortium website will have a comment submission page. The Website will be developed within the first six-month of the contract and will be routinely updated to stay current with the various activities.

Major Findings from Year 1

During Year 1, the Consortium website was developed. It can be accessed on www.ARC.unr.edu

Year 2 Work Plan

During Year 2, the team will continue to maintain and update the Consortium Website.

Work Element TT1b: Communications

Work Element lead: Peter Sebaaly (UNR)

Introduction

Communication is a very important part of the Asphalt Research Consortium (ARC). The ARC team will make every effort to provide open communications with the entire asphalt industry including stakeholders and producers. Timely updates on the ARC activities will be provided in written electronic formats that will be distributed to all interested parties.

Relationship to FHWA Focus Areas

This effort supports the FHWA Focus Area of Technical Capabilities Building.

Hypothesis

All activities of the Consortium should communicated and accessible to the stakeholders in a timely manner.

Objectives

The objective of this effort is to provide venues for the transfer of the various activities of the Consortium to the asphalt pavement community in a highly effective and organized manner.

Experimental Design

The Consortium will produce and distribute flyers and newsletters on the progress of the various research activities. Brochures of the scheduled workshops and training courses will be produced and distributed to the industry. Newsletters will be produced three times annually which will highlight the activities of the Consortium with technical write-ups on the various research activities.

Major Findings from Year 1

During Year 1, the first Consortium newsletter was produced and delivered to the asphalt industry. It can be accessed from: www.ARC.unr.edu

Year 2 Work Plan

During Year 2, the team will produce three Newsletters.

Work Element TT1c: Prepare presentations and publications

The Consortium members will prepare presentations and publications on the results and progress of the research. The presentations may be made at forums such as, but not limited to, Expert Task Group (ETG) meetings, Association of Asphalt Paving Technologists (AAPT), Transportation Research Board (TRB), Petersen Asphalt Research Conference, Association of Modified Asphalt Producers, Regional Asphalt User-Producer Groups, and many others.

Work Element TT1d: Development of Materials Database

Work Element Lead: Elie Hajj (UNR) and Amit Bhasin (A&M)

Introduction

The goal of selecting a suite of materials (asphalt, aggregates, modifiers) for all Asphalt Research Consortium (ARC) members to use in their research studies is to assure that a wide range of variation in properties is considered and also to provide for the integration and commonality of the research results among the various subtasks and work elements. This type of material selection planning has occurred in the highway material industry since at least the 1950's with the most recent and perhaps the most prominent one being the Strategic Highway Research Program (SHRP) Material Reference Library.

The SHRP Material Reference Library contained eight "core" asphalts (unmodified) that had wide-ranging geologic and chemical properties, represented a range of different production (refining) processes, and also represented major supply sources. In addition to the "core" asphalts, the SHRP Library contained a large array of "non-core" asphalts (unmodified) with other variations and from other sources. The SHRP Material Reference Library also contained a set of 11 different aggregates, four of which were designated "core" aggregates. The goal of the SHRP Materials Reference Library was to provide a common set of materials for all of the researchers that had sufficient diversity in order to investigate whether newly developed test methods could be applied to all unmodified asphalts and aggregates. At this point in time, it is probably universally agreed that the SHRP Asphalt Materials provided an excellent source of variability for unmodified asphalts and aggregates. Although some of the "core" asphalts have been depleted from the SHRP Materials Library, many of the "non-core" asphalts are still available for use and provide a source of asphalts that have unique properties. Similarly, many of the aggregates have been depleted to the point where only a relatively small amount of material remains. However, some of the aggregate sources have a useable supply. The SHRP Materials Reference Library, now called the FHWA-LTPP Materials Reference Library (MRL), is currently managed by Sierra Transportation Engineers located in Reno/Sparks, Nevada.

Core versus Non-core Materials

The selection of materials for each work element or task will depend on the hypothesis and objectives of that particular task. However, ARC partners will try to maximize the benefits of findings from each work element or task by utilizing a common set of materials wherever possible. To achieve this, ARC partners propose to develop a library of core materials. The core materials will be selected to represent a diverse range of properties as well as to span across the various geographic regions that fairly represent the U.S. The experiment design for various work elements or tasks by different ARC partners will incorporate (but will not be limited to) applicable core materials. Most of the work elements and tasks in years 1 and 2 are related to development of test methods. Therefore, the materials used at this stage may or may not be the core materials. In fact sound scientific reasons may require the use of "non-core" materials in the development and sensitivity evaluation of certain test protocols. However, after the development of test or analytical methods, the core materials will be included in various tasks to obtain relevant properties / data and in validation and verification testing.

Because of the geographic diversity of the ARC members, they each have familiarity and knowledge of locally and regionally available materials. It is expected that each ARC partner will use locally and regionally available materials that represent different properties in much of the development research and then use the ARC core materials to confirm research results when methods, tests, and models have progressed toward the application stage. The rational for proceeding in this way is to minimize the costs associated with large volume sampling and transporting asphalt over long distances. Each ARC member will be responsible for obtaining their own supply of locally and regionally available materials. Additionally, it is important to recall that the FHWA-LTPP MRL "non-core" asphalts and some aggregates have reasonable availability and can be used in the ARC research.

Adequate quantities of the core materials will be procured and stored for use during the duration of the ARC research in order to reduce the effect of production and batch variability on the material properties. Quantities of core materials in excess of the requirements of the ARC partners are proposed to be shipped to the FHWA-LTPP MRL in Reno/Sparks, Nevada. All samples will be uniquely labeled prior to shipment in accordance with the procedures developed for the ARC materials database.

All materials, core as well as non-core, used by the ARC researchers will be listed in a comprehensive and common database. There will be two levels of information in the database. The first level includes the properties and characteristics of the materials that have been finalized by the ARC researchers. The second level includes information and data for use by ARC researchers only during the conduct of the various work elements. The information in this level (level 2) will be subject to refinement and changes as the research progress is made. This information will be propagated to level 1 after it has been finalized by the ARC researchers and presented in a final technical report. More details on this database are provided at the end of this document. Figure TT1d.1 summarizes the differences in the management and use of core vs. non-core materials.

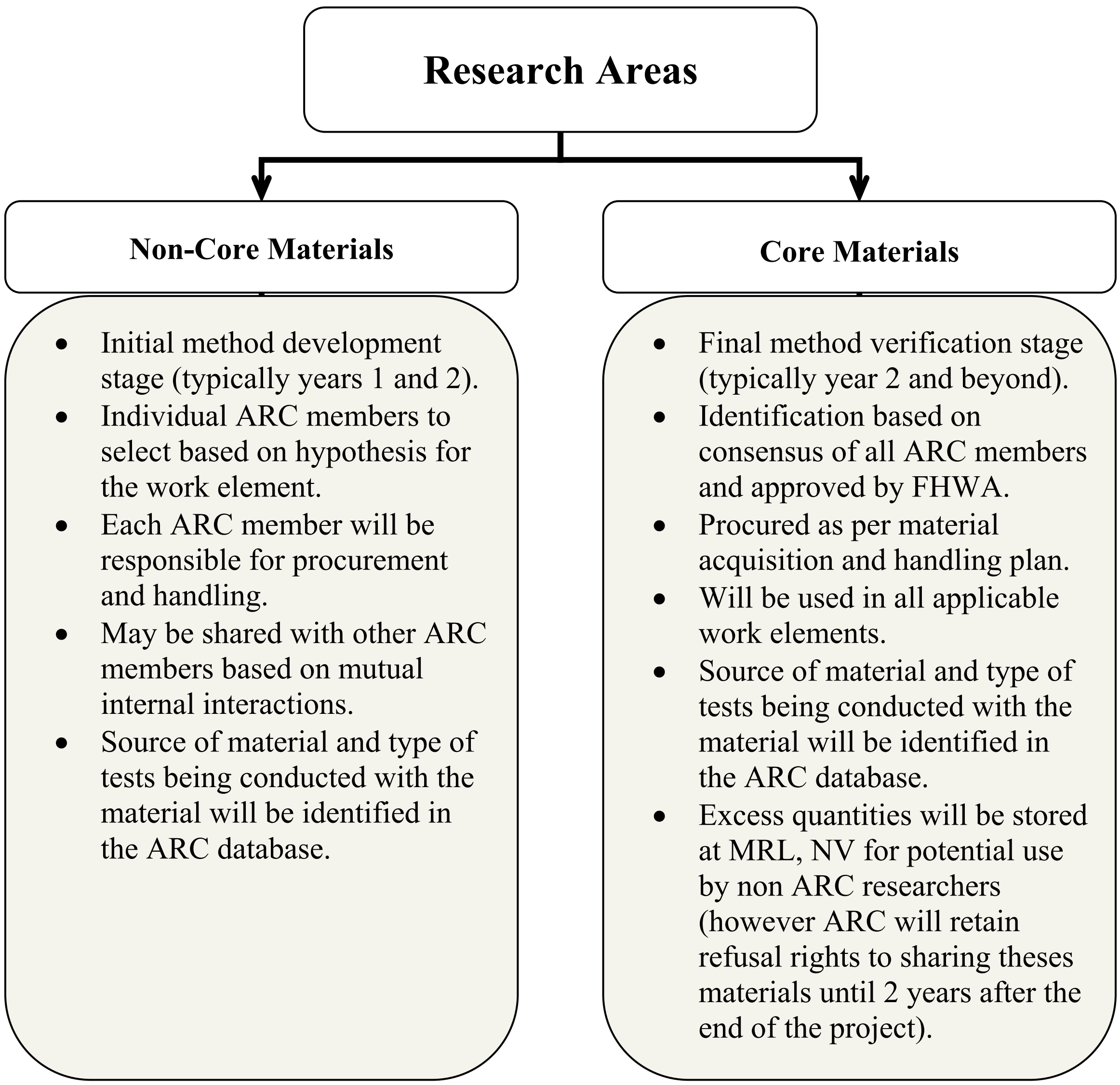


Figure TT1d.1. Core vs. non-core materials.

Identification of Core Materials

Core Asphalts

The Asphalt Research Consortium (ARC) plan for asphalt selection is similar in some ways to the plan used for the SHRP program. It is planned that the ARC will obtain four unmodified asphalts that will be used by the Consortium members. The selection of the four asphalts will be based upon the following criteria:

- geologic/chemical properties
- production volume
- geographic area of use
- potential for significant use in the future

The goal of the selection of the four asphalts is to obtain asphalts that have significantly different geologic/chemical properties, represent large supply lines in different areas of the U.S., and are expected to continue to be significant sources of supply.

After the four ARC core asphalts are selected, it is anticipated that the refiners/suppliers will want to provide their own personnel for sampling because of safety and insurance issues. It is hoped that the refiners/suppliers will donate the cost of the asphalt and also the labor cost to sample the asphalts, but if not, the ARC can pay these costs. The ARC will obtain five-gallon sample containers and ship them to each of the four sites. After sampling, each refiner/supplier will be given a list of the quantity of asphalt to ship to each ARC member. It is proposed to ship the remainder of the sample containers to the Materials Reference Library in Reno/Sparks, Nevada.

Core Aggregates

As described earlier, the list of core materials is not an exhaustive list of materials applicable for every work element or task. Instead, it is a minimum list of materials that are proposed to be incorporated in the applicable experiment designs of various tasks by ARC partners. We propose to identify at least four different types of aggregates for the core materials library. Table TT1d.1 presents a list of the identified four core aggregates.

The responsibility for sampling and shipping the four core aggregates will be divided among ARC members Texas A&M, University of Wisconsin-Madison, University of Nevada Reno, and Western Research Institute. Texas A&M personnel will be responsible for the gravel aggregate source from Arkansas. The University of Wisconsin-Madison personnel will be responsible for the limestone aggregate source from Wisconsin. The University of Nevada personnel will be responsible for the andesite aggregate source from Nevada. Western Research Institute personnel will be responsible for the gravel source from Wyoming.

Table TT1d.1. Proposed list of core aggregates for ARC.

Aggregate Description and Source	Mineralogy	Surface Characteristics	Remarks
Limestone (from WI)	(detailed mineralogical characteristics will be determined)	(detailed surface characteristics will be determined)	This aggregate has poor moisture damage resistance
Gravel (from WY)	(detailed mineralogical characteristics will be determined)	(detailed surface characteristics will be determined)	The proposed source is from the same area as SHRP designation RJ; regarded as susceptible to moisture damage;
Gravel (from AR) (also used in TX)	Gravel (detailed mineralogical characteristics will be determined)	Will be determined	Used in NCHRP 9-34; aggregate has poor moisture damage resistance as reported by field and 9-34 protocols but it has very high TSR (AASHTO T283); no field or lab problems were reported with the same aggregate after changing the binder[3]
Andesite (from NV)	Andesite (detailed mineralogical characteristics will be determined)	Will be determined	Highly moisture sensitive aggregate; presents challenge in establishing the Superpave mix design

Modifiers

For the ARC projects, it is proposed to include a core set of modifiers that are widely used and are known to have significant impact on performance. In addition, modifiers that are used in other countries or show a significant promise will be included. The modifiers are divided into 3 groups: Modifiers for pavement sustainability (to enhance resistance to traffic and climatic conditions); Modifiers for green pavements (to reduce heat energy during construction and/or allow increased use of RAP); and Emulsifiers. The following points describe the selection and sampling plan for each group:

1. Modifiers for Sustainability Mixtures (Target enhancement of resistance to traffic and environment):

    a. Polymers: A wide range of polymers are used today in the global paving market. The three that appear to be used widely are SBS, Elvaloy, and EVA. These will be collected as the core polymer modifiers. Although there are multiple producers of these polymers, the chemical composition however appears to be very consistent. A number of suppliers in North America and Europe will be contacted and asked to supply 500 pounds of each of the additives. For the non-core polymers, SBR, low density poly-ethylene, and SEBS will be collected. The amount of 200 pounds of each of the non-core polymers will be requested from suppliers. The opportunity to supply new types of polymers to be included in the project will be kept open with no promise to test these materials and each request from any supplier will be reviewed by the Consortium Advisory Board.

b. Poly-phosphoric Acid: There are a few grades of this acid used today. Based on initial testing and communication with suppliers, PPA with 105 % and 115 % concentration will be collected for the material library. Suppliers will be contacted to provide 100 gallons of each of the grades.

c. Anti-strip additives: Three core additives will be collected. Amine-based, phosphate esters, and lime. Depending on the storage stability of the liquid additives, the amount that will be stored will be determined. For the lime, a total of 500 pounds will be requested from suppliers. The non-core materials will vary depending on what is being used and the interest of suppliers to include there additives in the study.

2. Modifiers for Green Mixtures (Target reducing heat energy required for production and increase use of RAP)

   a. Warm Mix Additives: The core modifiers will include wax-based and mineral-based additives. Similar to polymers, 500 pounds of each of these additives will be requested.

   b. Emulsifiers (Cold Mix Additives): It is well known that emulsified asphalts are not very stable and thus selecting emulsifiers to be stored in the material library will require some research and understanding of these additives. The target will be to select the most widely used surfactants and additives used in production of cationic, anionic, nonionic, and polymer emulsions. The selection of the specific additives will be completed during the first half of Year 2 of the project and sufficient amounts of these additives will be collected and stored. The plan is to produce emulsions at the time of research. The team has already contacted suppliers and is in the process of finalizing commitments for production of emulsions in a laboratory setting when needed for research. It is well recognized that the laboratory produced samples may not be the same as the field produced samples. It is however assumed that for the purpose of work plans, these laboratory produced samples are sufficient for meeting objectives and defining the performance of cold applied asphalt products.

In addition to the above modifiers/additives, ARC members could use in their research ready-made modified asphalts and ready-made emulsified asphalts. These materials will not be considered "core" materials. They are non-core materials and will be used for development of tests methods and validation of certain concepts. For the "core" additives, the UW-Madison team will be responsible for collecting the materials and help in producing the modified asphalts. For the non-core materials, each member of the ARC will be responsible for obtaining their own supply of locally and regionally available modified asphalts or emulsions.

After the ARC modifiers are selected, it is hoped that the suppliers will donate the cost of the additives and also the labor cost to sample, but if not, the ARC can pay these costs. It is proposed that a reasonable amount of modifiers be stored at UW-Madison and to ship the remainder of the sample containers to the Materials Reference Library in Reno/Sparks, Nevada.

Validation Site Materials

Validation sites consist of field sections that will be constructed during the duration of the ARC to validate the methodologies and concepts that will be developed during the ARC contract. It is anticipated that validation sites will be constructed throughout the U.S. to cover the various environmental zones, materials sources, and traffic distributions. Depending on the methodology that is being validated, some of the sites may include a single test section while others may include multiple field sections. A project ID will be developed for each validation site.

The involvement of the ARC researchers in the validation sites is expected at all stages of design, construction, and performance monitoring. At the design stage, the ARC researchers will develop the experimental plan and assist the owner agency in the structural and mix design of the test sections. During construction, the ARC researchers will obtain samples from the sites to be tested in the appropriate parts of the ARC research. After construction, the ARC researchers will monitor the performance of the validation sites for the duration of the ARC contract. It is expected that the owner agencies will continue the monitoring of the long-term performance of the validation sites according to the plans developed by the ARC researchers.

Materials samples from the validation sites may be obtained in the following categories:

- Raw Materials
    - Binder
    - Aggregate
    - RAP
    - Additives
- Loose mixtures during construction
    - Plant samples
    - Site samples
- Compacted field samples
    - Cores
    - Slabs

The raw materials samples will be used in the mix design of the validation sites. These materials will be characterized by the appropriate ARC researchers according to the mix design procedure that is being used.

In addition, the samples from all three categories of raw materials, loose mixtures, and compacted samples will also be subjected to additional testing as needed for the validation of the various ARC methodologies and processes. Therefore, the samples from the three categories will be shared among the ARC partners as needed.

The results of the various testing programs on samples from the validation sites and the long-term performance of the sites will be stored in the ARC Materials Database. A very efficient tracking and data checking system will be developed to insure the consistency and integrity of the data from the materials testing programs and performance monitoring. This effort will follow as closely as possible the system that has been established and implemented by the Long Term Pavement Performance (LTPP) program, i.e. DataPave.

Materials Acquisition and Storage

As illustrated in figure TT1d.1, each ARC member will be individually responsible for acquisition and storage of non-core materials. If there is a mutual interest between more than one ARC member to use the same non-core material for a particular work element, the individual members shall mutually coordinate the sharing and usage of such materials. Figure TT1d.2 illustrates the process that will be followed to acquire the core materials from different suppliers for this project.

Each ARC member will be responsible for the storage of their portion of core and non-core materials after receipt from the supplier. A general and tentative guideline for storage of each material type is provided below. These guidelines will be refined and revised by ARC members so as to ensure that the storage conditions used by different ARC members are consistent.

Asphalt Binders

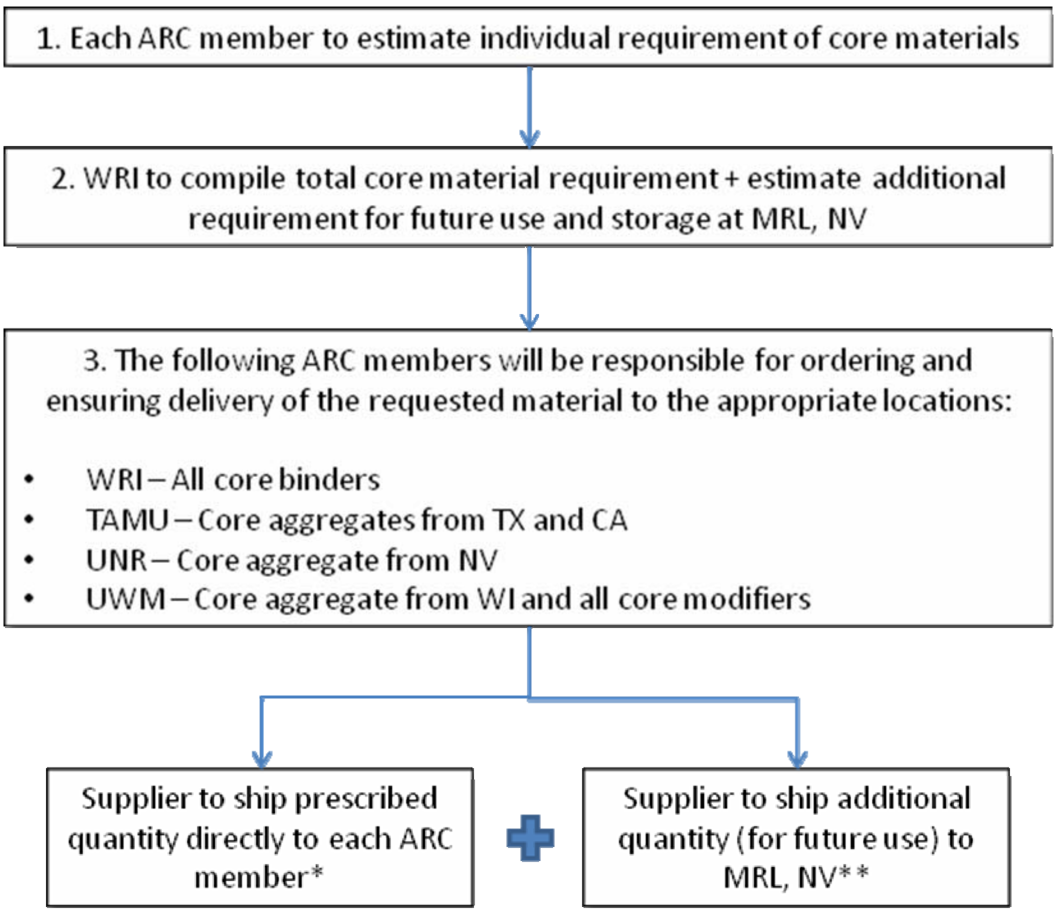
All asphalt binders will be obtained in 5 gallon containers and shipped to individual ARC members. Each ARC member will ensure that the binder is reheated not more than two times before being used for any type of test. The binder will be stored in air tight containers at a temperature between 4 to 8°C prior to being used for the test.

Aggregates and Fillers

Aggregates received by each ARC member will be processed and stored in air tight containers.

Modifiers

Modifiers will be stored as per the recommendations of the manufacturer.



NOTE:

* Each ARC member will directly receive their requirement of the core material from the supplier and will be individually responsible for storing these materials in consistent conditions. This will greatly reduce the shipping costs and prevent double handling.

** Materials at MRL, NV, is for future use by ARC and non-ARC members with permission from FHWA. However, ARC members will retain refusal rights for requests made by non-members until 2 years from the end of the project.

Figure TT1d.2. Acquisition and distribution of core materials for ARC.

Labeling and Tracking

An ARC member will be assigned as the responsible party for every core material, non-core material and validation site. The assignments for the core material are summarized in figure TT1d.2. For the non-core material, the assigned party will be the ARC member that is using the specific source in their work elements. For the validation site, the assigned part will be the ARC member that is responsible for the design and construction of the validation site.

The responsible ARC member will generate the appropriate materials labels as described in table TT1d.2. It is anticipated that initially the labels will be generated manually until the materials database is fully operational at which time the responsible party will generate the labels through the ARC materials database. It is anticipated that the ARC materials database will reach the operational stage toward the end of year 2. The suppliers of the core and non-core materials will be provided with these labels for shipping materials to ARC members or MRL, NV.

Once a material request is made, the ARC responsible party will generate the appropriate label (either manually or through the database) and ensure that the requested materials are sampled, shipped, and delivered to the requesting party. To facilitate this process a tracking system will be developed which includes the date of sampling, date of shipping, amount of materials shipped, and date of receipt at the requesting party facility. Again, currently the tracking process will have to be completed manually until the ARC materials database is fully operational at which time the responsible party will complete the tracking process through the ARC materials database.

MRL Requirements

In general, MRL will receive, handle, inventory, and disseminate materials using their existing protocols and management system with the following exceptions:

1. MRL shall use the material identification that will be provided by ARC as described in section 5 of this document.
2. MRL shall use material storage protocols as described in sections 4.1 through 4.3.
3. Prior to dissemination of materials to non ARC agencies, MRL shall obtain the consensus of FHWA and ARC.

Table TT1d.2. Labeling system for ARC materials.

Material	Labeling Format	Comments
Aggregate	ARC AG xxxx ttt	1. xxxx = 0001 through 0010 are reserved for core aggregates 2. xxxx = 0011 through 0030 are reserved for aggregates from validation sections 3. xxxx = 0031 through 0050 are reserved for RAP materials 4. xxxx = 0051 and above are for non-core aggregates* 5. ttt = where to ship the material to = WRI, TTI, UNR, UWM, AAT, MRL
Asphalt Binder	ARC BI xxxx ttt	1. xxxx = 0001 through 0010 are reserved for core binders 2. xxxx = 0011 through 0030 are reserved for binders from validation sections 3. xxxx = 0051 and above are for non-core binders including binders polymer or chemically modified by manufacturer* 4. ttt = where to ship the material to = WRI, TTI, UNR, UWM, AAT, MRL
Filler	ARC FI xxxx ttt	1. xxxx = 0001 through 0010 are reserved for core fillers 2. xxxx = 0011 through 0030 are reserved for fillers from validation sections 3. xxxx = 0051 and above are for non-core fillers* 4. ttt = where to ship the material to = WRI, TTI, UNR, UWM, AAT, MRL
Antistrip	ARC AS xxxx ttt	1. xxxx = 0001 through 0010 are reserved for core antistrip additives 2. xxxx = 0011 through 0030 are reserved for antistrip additives from validation sections 3. xxxx = 0051 and above are for non-core antistrip additives* 4. ttt = where to ship the material to = WRI, TTI, UNR, UWM, AAT, MRL
Polymer	ARC PM xxxx ttt	xxxx = 0001 and above for all polymer modifiers (these are just polymers used for modifying binders in the lab for engineered materials and not polymer modified binders supplied by the manufacturer which are covered in the binder list) ttt = where to ship the material to = WRI, TTI, UNR, UWM, AAT, MRL
Chemical Additive	ARC AM xxxx ttt	xxxx = 0001 and above for all acids or chemical modifiers (these are just modifiers used for engineered materials and not modified binders supplied by the manufacturer which are covered in the binder list) ttt = where to ship the material to = WRI, TTI, UNR, UWM, AAT, MRL
Warm Mix Additive	ARC WM xxxx ttt	xxxx = 0001 and above for all warm mix additives ttt = where to ship the material to = WRI, TTI, UNR, UWM, AAT, MRL
Emulsifier	ARC EM xxxx ttt	xxxx = 0001 and above for all emulsifiers ttt = where to ship the material to = WRI, TTI, UNR, UWM, AAT, MRL
Field Core (Validation)	ARC VC xx yy zz ttt	xx = Project ID, yy = section in the validation site, and zz = 01 and above for each core, ttt = where to ship the material to = WRI, TTI, UNR, UWM, AAT, MRL
Field Mix (Validation)	ARC VM xx yy zz ttt	xx = Project ID, yy = section in the validation site, and zz=01 and above for each sample collected, ttt = where to ship the material to = WRI, TTI, UNR, UWM, AAT, MRL

* ARC members can assign these labels using a centralized database (see section 5)

Central Database of Measured Properties

A central database of materials being used by ARC members (core and non-core) will be maintained. The proposed database consists of four components namely, the Material Database files, Data Access, Data Utility, and a User Interface as shown in figure TT1d.3.

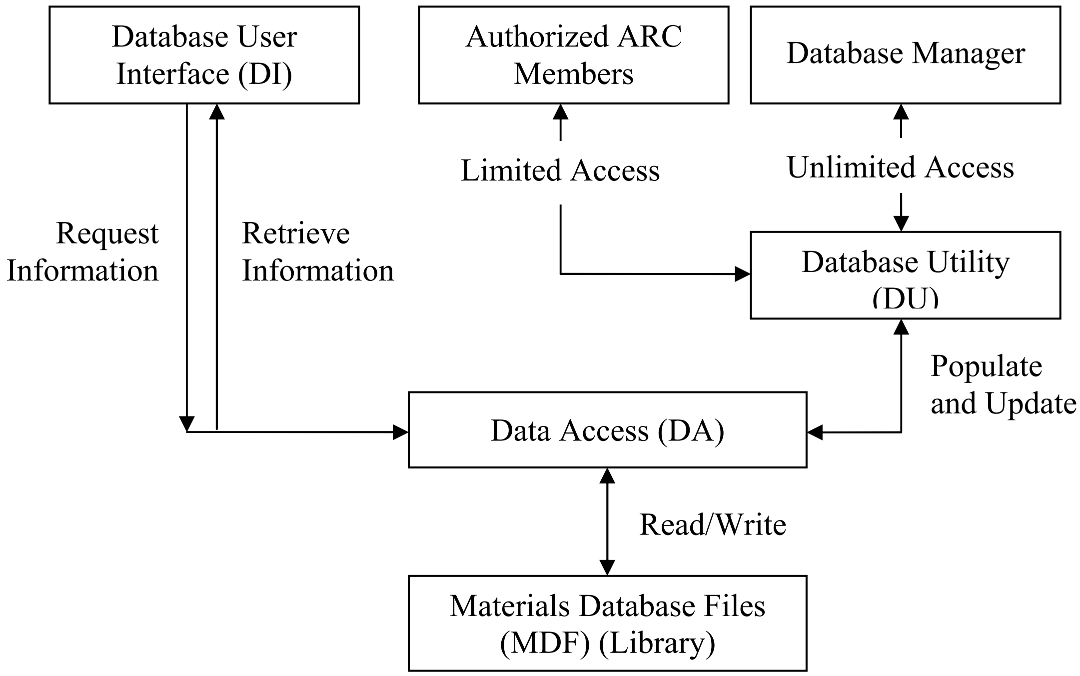
Material Database Files (MDF): the MDF will house the following information. The relationship among the various entities is shown in figures TT1d.4-TT1d.6.

- MDF-1: List of all core and non-core constitutive materials used in the ARC research including, aggregates, binders (neat and modified by supplier), fillers, antistrip agents, polymers for lab modification, chemical additives for lab modification, warm mix additives, and emulsifiers. The materials will follow the labeling format as shown in table TT1d.2.
- MDF-2: List of validation sites/sections with labeling format as shown in table TT1d.2.
- MDF-3: List of all composite materials that are produced from at least one of the constitutive materials listed in MDF-1or MDF-2. The composite materials categories include, binders, mastic, fine aggregate matrix (FAM), laboratory produced mixes, validation site mixes, and validation sites cores and slabs.
- MDF-4: List of material properties including binder properties, mastic properties, fine aggregate matrix properties, and mixture properties that will be measured as a part of various work elements.
- MDF-5: Database of measured composite materials properties including binders (unmodified, modified by supplier, and modified in the lab), mastics, fine aggregate matrix, and mixtures.

Data access (DA): This is a dynamic link library containing procedures that a program can call upon to retrieve data from the database using specialized procedures. It provides users with the ability to retrieve as well as update the data and at the same time preserve the data integrity. It contains all queries needed to retrieve information from the database.

Database Utility (DU): Using this utility, a Database Manager can directly work with the data stored in the *Material Database Files*. It allows the manager to find, update, add and delete records as well as display database information. The database will be initially uploaded with the information lists on materials and made available to all ARC members for updating with other area specific information and material properties. Consequently, it is anticipated that the database manager will create and generate the lists in MDF-1, MDF-2, MDF-3, and MDF-4 upon a request submitted electronically by other authorized ARC research members. This component also includes facilities to allow authorized users from ARC members to connect to the database to populate and update the database information in MDF-5. Additionally, the DU encompasses data management capabilities such as data cleaning, quality checks and formatting.

Database User Interface (DI): It allows a user to retrieve information from the database. It allows the user to see, print information retrieved from the database. The user will identify the information needed from the database. The input focuses the search on locating specific materials corresponding to the information entered by the user.



FigureTT1d.3. Materials Database structure.

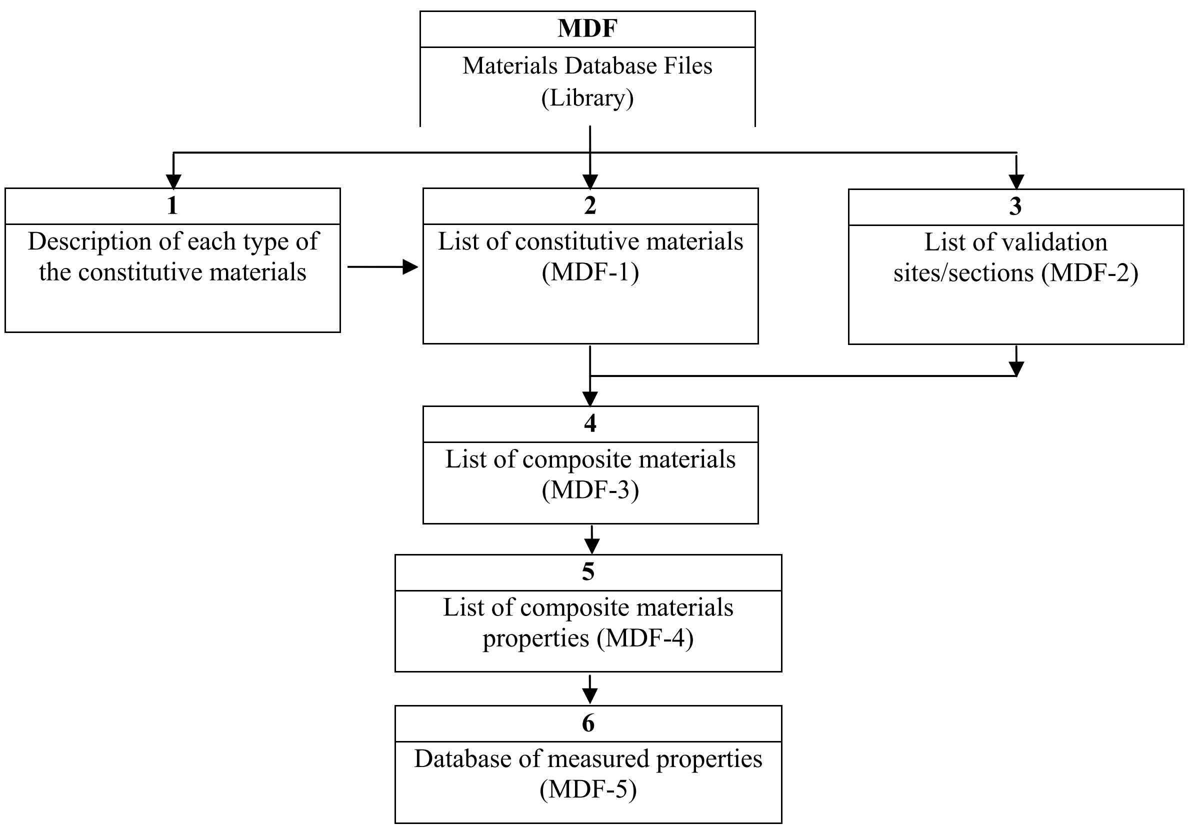


Figure TT1d.4. Flow chart for Materials Database files showing different information blocks.

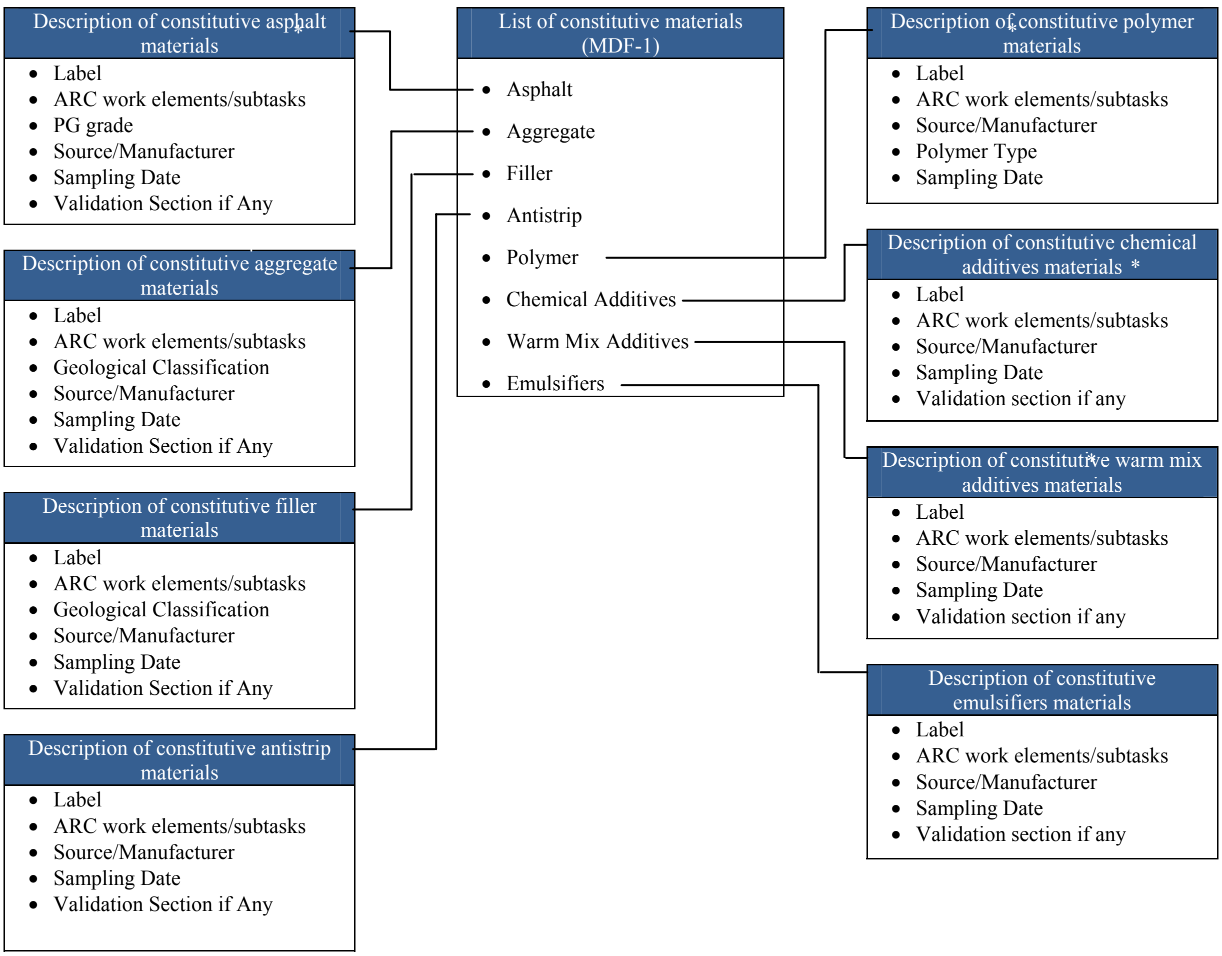


Figure TT1d.5. Relationship between block 1 (Description of each type of constitutive material) and block 2 (list of constitutive materials – MDF-1)

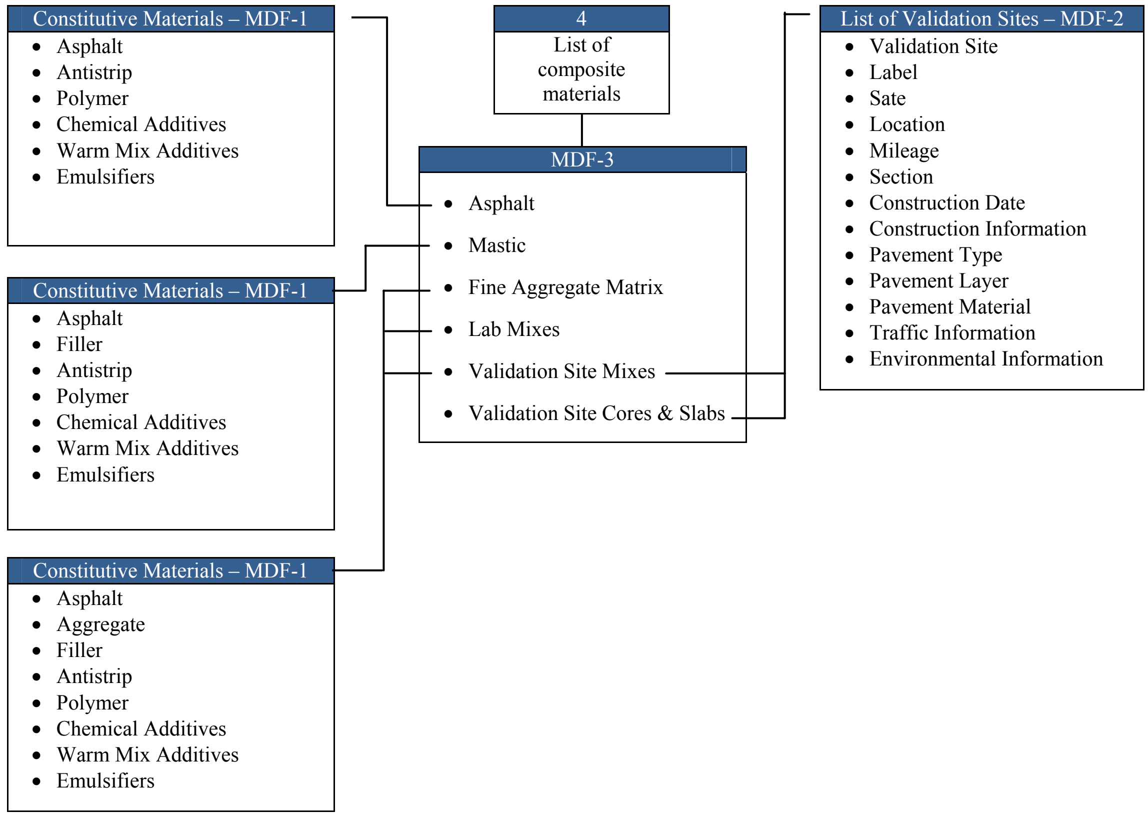


Figure TT1d.6. Relationship between block 2 (list of constitutive materials – MDF-1), block 3 (list of validation sites/sections – MDF-2) and block 4 (list of composite materials – MDF-3)

The generated database will compile all ARC materials along with their related information and properties. It is anticipated that the user will also have the capability of retrieving information from the database by the ARC work elements and subtasks. Table TT1d.3 shows an example indicating which materials are related to which work elements and subtasks. This table is only an illustration and eventually will be generated by querying the database as the database is populated.

Table TT1d.3. Materials used under Subtask E2d-3.

Work Element	Subtask	Materials Used
E2d: Thermal Cracking Resistant Mixes for Intermountain States	E2d-3: Identify an Evaluation and Testing System	Binders: • PG64-22 • PG64-22+3% SBS • PG64-28PM Aggregates: • Nevada: Andesite • California: Granite • Colorado: • Utah:

References

Howson, J. E., E. Masad, A. Bhasin, V. C. Branco, E. Arambula, R. L. Lytton, and D. N. Little, 2007, "System for the Evaluation of Moisture Damage Using Fundamental Material Properties." *Research Report 0-4524-1*, Texas Transportation Institute, College Station.

Little, D. N., and A. Bhasin, 2006, "Using Surface Energy Measurements to Select Materials for Asphalt Pavement. " *Final Report for Project 9-37*, Texas Transportation Institute.

Masad, E., C. Zollinger, R. Bulut, D. N. Little, and R. L. Lytton, 2006, Characterization of HMA Moisture Damage Using Surface Energy and Fracture Properties. *Proc. Association of Asphalt Paving Technologists*, 75, 713-754.

Robl, T. L., D. Milburn, G. Thomas, J. Groppo, and K. O'Hara, 1991, *The SHRP Materials Reference Library Aggregates: Chemical, Mineralogical, and Sorption Analyses*, Report No. SHRP-A/UIR-91-509. Strategic Highway Research Program, National Research Council, Washington, DC.

Solaimanian, M., R. F. Bonaquist, and V. Tandon, 2007, "Improved Conditioning and Testing Procedures for HMA Moisture Susceptibility." Transportation Research Board, Washington D.C.

Western Research Institute, 2001, *Fundamental Properties of Asphalts and Modified Asphalts, Volume I: Interpretive Report*, *FHWA-RD-99-212*, U. S. Department of Transportation, Federal Highway Administration, McLean, VA.

Work Element TT1e: Development of Research Database

Work Element Lead: Elie Hajj (UNR)

Introduction

Accessibility is defined as the ability of the stakeholders to access valuable materials and research data that may help their programs. There may be some intermediate findings that the industry will use to improve a certain aspect of their operations. Accessibility to such information will be provided through an electronic database that incorporates the technical information on the various materials that are being researched by the Consortium.

Relationship to FHWA Focus Areas

This effort supports the FHWA Focus Area of Technical Capabilities Building.

Hypothesis

All activities of the Consortium should be communicated and accessible to the stakeholders in a timely manner.

Objectives

The objective of this effort is to provide venues for the transfer of the various activities of the Consortium to the asphalt pavement community in a highly effective and organized manner.

Experimental Design

A research database is important to keep Consortium partners and the asphalt pavement community current with the on-going and completed researches. The research database will cover the Consortium's recent, ongoing, and planned research studies. The Consortium website developed in Task 1.0 will serve as a medium to access the research database. It is anticipated that the University of Nevada will develop and maintain the Research Database and the other Consortium partners will populate the databases through a secured access with information pertinent to their activities. A dynamic database-driven web application will be developed allowing data users to present information retrieved from the research database on the web pages. The subsequent steps will be followed to design the materials database system.

Subtask TT1e-1: Identify the Information to Include in the Research Database

This subtask will identify the information in the research database that needs to be included. It is anticipated at this point the research database will include the following information for each research task: problem statement, budget, timeline of activities, results update in form of reports, white papers or any other type of documents, contacts information, and relationship to other studies.

UNR will send the Consortium partners a list of the anticipated information that needs to be included in the research database for inputs and modifications.

Subtask TT1e-2: Define the Structure of the Database

After defining the type of information that needs to go into the research database the structure of the database will be defined. All data will be stored in a simple row/column format in tables (rows referred as records and columns referred to as fields). The first step consists of choosing the tables in the database. A relational database format will most probably be used. A relational database is a database containing separate tables, with the tables sharing data. Each table will describe a collection of related entities. The next step will be choosing, in each table, the columns describing the properties of each entity in the table and the *primary key* column(s). Each row of data will be uniquely identified by the values in a *primary key* column or a combination of columns allowing users to zero in on the exact row requested when searching the database. After defining the basic columns and *primary keys* in the tables, relationships between the various tables will be defined. Once the relationships are defined, Structured Query

Language (SQL) statements to combine data from two tables will be written in Dreamweaver. SQL is the standard language for controlling and interacting with relational databases. SQL allows retrieving, adding, and deleting data to and from a database.

Subtask TT1e-3: Create and Populate the Database

The final design step is to create the database using a database system like Microsoft Access, SQL Server, or Oracle9i.

Major Findings from Year 1

This work element will start in year 2.

Year 2 Work Plan

During Year 2, the researchers will work on Subtasks TT1e-1 and TT1e-2.

Budget

The initial estimated budget for the website and database portion of the Technology Transfer area is $650,000 for the five year period. The budget may be revised as the project progresses.

Work Element TT1f: Workshops and Training

Work Element lead: Peter Sebaaly **(**UNR)

Introduction

Technology transfer is a very critical step in the overall process of research-technology development-implementation. The task of workshops development and training is a crucial part of every research and development program that is aimed at improving the state of the practice of the asphalt pavements/materials engineering community. This has been highly recognized by the FHWA through its technology transfer centers throughout the country as part of the national Local Technology Assistance Program (LTAP).

Relationship to FHWA Focus Areas

This effort fits under the FHWA Focus Area of Technical Capabilities Building.

Hypothesis

The findings of the research and development activities of the Consortium should be transferred to the asphalt pavements/materials engineering community through workshop developments and hands-on training.

Objectives

The objective of this effort is to develop workshop and training materials that can be delivered to the pavements/materials engineering community at various locations and time intervals throughout the country.

Experimental Design

As the research and development activities of the Consortium progresses, workshops and training materials maybe developed and delivered to the pavements/materials engineering community at various locations and time intervals throughout the country. The subjects of the workshops and training materials will be submitted for approval by the AOTR prior to their development. Appropriate budgets will be developed for each individual workshop and training activity.

Budget

Specific budgets for workshop and training activities will be developed as they occur.

Technology Transfer Year 2

	Year 2 (4/2008-3/2009)												Team
	4	5	6	7	8	9	10	11	12	1	2	3	
(1) Outreach and Databases													
TT1a: Development and Maintenance of Consortium Website													UNR
TT1b: Communications													UNR
TT1c: Prepare presentations and publications													UNR
TT1d: Development of Materials Database													UNR
TT1d-1: Identify the overall Features of the Web Application TT1d-2: Identify Materials Properties to Include in the Materials Database TT1d-3: Define the Structure of the Database TT1d-4: Create and Populate the Database													
TT1e: Development of Research Database													UNR
TT1e-1: Identify the Information to Include in the Research Database TT1e-2: Define the Structure of the Database TT1e-3: Create and Populate the Database													
TT1f: Workshops and Training													UNR

Deliverable codes	Deliverable Description
D: Draft Report	Report delivered to FHWA for 3 week review period.
F: Final Report	Final report delivered in compliance with FHWA publication standards
M&A: Model and algorithm	Mathematical model and sample code
SW: Software	Executable software, code and user manual
JP: Journal paper	Paper submitted to conference or journal
P: Presentation	Presentation for symposium, conference or other
DP: Decision Point	Time to make a decision on two parallel paths as to which is most promising to follow througjh

Work planned
Work completed
Parallel topic

Technology Transfer Year 2 - 5

	Year 2 (4/08-3/09)				Year 3 (4/09-3/10)				Year 4 (04/10-03/11)				Year 5 (04/11-03/12)				Team
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	
(1) Outreach and Databases																	
TT1a: Development and Maintenance of Consortium Website																	UNR
TT1b: Communications																	UNR
TT1c: Prepare presentations and publications																	ALL
TT1d: Development of Materials Database																	UNR
TT1d-1: Identify the overall Features of the Web Application TT1d-2: Identify Materials Properties to Include in the Materials Database TT1d-3: Define the Structure of the Database TT1d-4: Create and Populate the Database																	
TT1e: Development of Research Database																	UNR
TT1e-1: Identify the Information to Include in the Research Database TT1e-2: Define the Structure of the Database TT1e-3: Create and Populate the Database																	
TT1f: Workshops and Training																	UNR

Deliverable codes	Deliverable Description
D: Draft Report	Report delivered to FHWA for 3 week review period.
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DP: Decision Point	Time to make a decision on two parallel paths as to which is most promising to follow througjh

Work planned
Work completed
Parallel topic

APPENDIX A

EXTERNAL COORDINATION TABLE

ARC Coordination
Efforts

	Research Area	Related Effort	Similarities	Differences	Contact
1	F1c Aging	TxDOT 0-6009: Evaluation of Binder Aging and Its Influence of Aging in Hot Mix Asphalt Concrete	Both are assessing the extent and rate of binder oxidation in pavements and effect of binder oxidation on mixture and pavement fatigue performance. Both projects contribute to developing a model of binder oxidation in pavements as a means of enhancing pvement design and predicting pavement performance.	The TxDOT project also addresses 1) aging test development for binders to predict binder aging in production and field service, 2) the effectiveness of maintenance treatments in retarding binder aging in pavements, 3) development of an HMA fatigue mix design and analysis system to optimize resistance to binder aging. The TxDOT project focuses on Texas materials, sites, and climate, whereas the ARC project focuses on nationwide materials, sites, and climates. Additionally, the ARC project coordinates closely with the ARC models development effort, recognizing that binder aging, to the extent it occurs in pavements, changes the binder in a fundamental and profound way that leads to different pavement performance. Thus, the ARC work is directed at developing a fundamental understanding of binder aging and its impact on pavement fatigue including continuum damage and crack growth, whereas the TxDOT project is addressing the problem from a much more applied methodology and perspective. The two projects are very complementary.	Charles Glover 979-845-3389, c-glover@tamu.edu; Amy Epps Martin, 979-862-1750, a-eppsmartin@tamu.edu

ARC Coordination Efforts

Work Element E1c-1: Warm Mix

Related Effort	Work Plan Task	Similarities	Differences		Contact
			ARC	NCHRP	
NCHRP 09-43. Mix Design Practices for Warm Mix Asphalt.	Objectives of Project	Define impact of WAM additives on binder and mixture performance. Verify mix design recommendations with field trials and performance monitoring. Work Plans aim to develop/revise AASHTO specification language.	Focused on defining mechanisms of how WAM additives lower mixing temperature. Hypotheses verified through lab and field testing. Plans to evaluate effects of WAM Additives on mixture workability through mechanical measures. Free to select additives for	Developing a mix design guide catered to DOT and industry. Evaluates mixture workability through SuperPave criteria. Mix Design methods must be applicable to any WMA technology used. Workshop: Project includes a half day work shop to explain the mix	Ramon Bonaquist 703-444-4200, aatt@erols.com. Full work plan and latest quarterly report received 5/3/08
	Materials Selection	**Addtives:** Both projects plan to evaluate four of five types of Warm Mix Additives: Water bearing zeolites, Viscosity Reducers, Foaming, and Emulsions **Binder:** Projects will consider a range of binder grades both modifed and unmodified.	**Additives:** ARC is not considering multi-component binder coating processes (WAM Foam and LEA) **Recycled Materials:** At this stage ARC is not including evaluation of RAP. Incorporation under consideration after year 2 results.	**Additives:** NCHRP includes multi component binder coating processes. **Recycled Materials:** NCHRP is incorporating the use of RAP into the mix design process.	
	Experimental Plan	**Binder Testing**: Projects evaluate binders using standard SuperPave Binder Grading Tests. Also will evalute effects on short and long term aging and physical hardening. **Mixture Testing:** Evaluate rutting, fatigue, moisture sensitivity, and thermal cracking	**Binder Testing:** Includes more advanced binder testing: MSCR, Monotonic Fatigue Test, SENB, thin film rheology. **Mixture Testing:** Flexibility to incorporate tests/methodologies developed in other ARC work elements. **Mix Design Recommendations:** Plans to u	**Binder Testing:** Specifies only PG Grading tests, unless differences between WAM and HMA create need for more detailed binder evaluation. **Mixture Testing:** Will use efforts developed through other NCHRP projects or other research efforts.	
NCHRP 09-47: Engineering Properties, Emissions, and Field Performance of Warm Mix Asphalt Technologies*	Objectives of Project	Define impact of WAM additives on binder and mixture performance with laboratory generated data compared to performance of field sections. Comparison of production and laydown practices. Recommend modifications to NCHRP 9-43 protocols.	Focused on defining mechanisms of how WAM additives lower mixing temperature. Hypotheses verified through lab and field testing. Plans to evaluate effects of WAM Additives on mixture workability through mechanical measures. Free to select additives for	Focus is to define engineering properties and quantify reduced emissions and energy consumption from Warm Mix. Tasked with defining relative performance measures for WAM mixes and conventional HMA. Unclear how performance measurement will differ for warm	Michael Anderson Asphalt Institute manderson@asphaltinstitute.org 859-288-4984 **Contacted PI 5/5/08** **Waiting for response**
	Materials Selection	**Addtives:** Both projects plan to evaluate four of five types of Warm Mix Additives: Water bearing zeolites, Viscosity Reducers, Foaming, and Emulsions **Binder:** Projects will consider a range of binder grades both modifed and unmodified. **Mix Design:** Proj	Includes evaluation of both materials and mixes solely prepared in the laboratory and those linked to field sections.	Considers only mix designs and materials that have been used in a field trial. Unclear of solely laboratory mixes will be included in evaluation.	
	Experimental Plan	**Binder Testing**: Projects evaluate binders using standard SuperPave Binder Grading Tests. Also include any other binder properties related to warm mix. Both workplans expect to use tests to relate to pavement performance. **Mixture Testing:** Evaluate mixtur	**Binder Testing:** Includes more advanced binder testing: MSCR, Monotonic Fatigue Test, SENB, thin film rheology. **Mixture Testing:** Flexibility to incorporate tests/methodologies developed in other ARC work elements. Performance evaluation not tied to MEP	**Binder Testing:** Tests used beyond SuperPave protocols not defined in RFP. **Mixture Testing:** Must use mechanical tests specified in the MEPDG at a minimum. **Field Evaluation**: Technologies and required quantities clearly defined for pavement sections and e	

ARC Coordination Efforts					
Work Element E1c-1: Warm Mix					
			Differences		Contact
Related Effort	Work Plan Task	Similarities	ARC	Other Efforts	
NCHRP 09-40: Optimization of Tack Coat for HMA Placement	Objectives of Project	Projects focus on development of test procedures to predict field performance of emulsified asphalt materials. Specifically, both studies evaluate the bonding characteristics of emulsified asphalts in terms the time dependence on development of adhesive	ARC includes evaluation of emulsified asphalts used in a variety of surface treatments as well as in cold mix applications. The diverse applications will necessitate definition and evaluation of a wider range of performance criteria.	Project is specifically focused on tack coats. Certain aspects of the project relate well to the ARC effort, specifically in the development of performance tests and field performance criteria.	Louay Mohammad Contacted PI 5/7/08 Waiting for Response
NCHRP 14-17: Manual for Emulsion-Based Chip Seals for Pavement Preservation	Objectives of Project	Focus on chip seals in terms of construction properties of emulsion, performance of residual asphalt, and aggregate properites. Definition of residue recovery method. Define distresses and performance of chip seals and use to define testing procedures. Pr	Project is evaluating other surface treatments and cold mix applications. Overall goal is to define a framework of common performance properties for surface treatments with different performance thresholds based on the application. Application specific t	Project is focused specifically on developing guidance for design and construction of chip seals. The applicability of the tests recommended in this study to other surface treatments won't be investigated. Project is more focused on construction guideline	Scott Schuler - Contact Amy Epps-Martin and Scott Schuler, was directed to Amir Hanna, contacted 5/15/08 Waiting for Response
Federal Lands Study: Best Practices for the use of Polymer Modifiers in Asphalt Emulsions**	Objectives of Project	Studies are both aimed at advancing specification for polymer modified emulsions in the use of surface treatments (chip seals, slurry seals, microsurfacing, etc.) Recommedations will be made in terms of desired emulsion properties, aggregate properties.	Focused on both emulsions prepared with neat binder and polymer modified emulsions. Also will address the differences in performance between latex modified and polymer modified emulsions. Emulsion performance testing will relate to construction and in-se	Focus is on specification for polymer modified emulsions, no mention of latex modified or neat emulsions. Testing focus seems to be on properties of the emulsion residue, no considerations of construction properties (breaking, setting, viscosity, etc.) In	Gayle King Contacted PI 5/5/08. Will send work plan when it becomes available (mid - May to June)

* Work Plan unavailable comparison made based on RFP posted on NCHRP website

** Work Plan unavailable project information taken from a request for survey participation sent by Dr. King on January 8th, 2008

ARC Coordination Efforts					
Work Element E2b: Design System for HMA Containing a High Percentage of RAP Material					
Related Effort	Work Plan Task	Similarities	Differences		Contact
			ARC	NCHRP	
NCHRP 09-46: Improved Mix Design, Evaluation, and Materials Management Practices for Hot Mix Asphalt with High Reclaimed Asphalt Pavement Content	Objectives of Project	Develop a mix design and analysis procedure for HMA containing high-RAP contents that provide satisfactory long-term performance.	Develop a system to evaluate the properties of RAP aggregates and binders. Incorporate ARC developed technologies to evaluate the performance of HMA mixtures containing RAP materials.	Recommend changes to AASHTO R35 Propose changes to existing specifications to account for HMA containing high-RAP contents.	Dr. Randy West (westran@auburn.edu) Dr. Andrea Kvasnak (ank0004@auburn.edu) 334-844-6228
	Materials Selection	Both projects will evaluate multiple HMA mixtures, multiple RAP sources, and multiple virgin binders. RAP containing neat and polymer-modified binders will be evaluated in both projects.	**RAP sources:** Four different RAP sources will be included. **Virgin Aggregate:** one virgin aggregate source will be included. *Virgin Binders:* three virgin binder grades will be included.	**RAP Sources:** low and high stiffness, neat and modified binders, and different RAP processing techniques – 2 fractionated and 2 non-fractionated. **RAP Percent:** three RAP percentages will be used. *Virgin Binders:* two virgin binders – neat and modified.	
	Experimental Plan	Both projects will cooperate to evaluate the impact of extraction method on the properties of RAP aggregates. Both projects will cooperate to simulate the plant mixing of HMA mixtures containing RAP. Both projects will monitor field performance of RAP co	**RAP Binders:** RAP binders will be evaluated through a non-solvent process using the bending beam rheometer or the dynamic shear rheometer or a combination of the two equipments. **Mixtures Aging:** a fundamental procedure for the long-term aging of HMA mixtur	Twenty-four mixes will be designed. Eight mixes each will contain no RAP, 25% RAP, 55% RAP. The mix designs within each RAP percentage will vary in NMAS, virgin binder, RAP processing technique, and RAP binder stiffness. The designed mixes will then un	

ARC Coordination Efforts					
Work Element E2d: Thermal Cracking Resistant Mixes for Intermountain States					
Related Effort	Work Plan Task	Similarities	Differences		Contact
			ARC	NCHRP	
National Pool Fund Study: Investigation of Low Temperature Cracking in Asphalt Pavements - Phase II	Objectives of Project	Development of mixtures test to evaluate the thermal cracking resistance of HMA mixtures	Develop a binder/mix evaluation system that can effectively simulate the long term properties of HMA mixtures in the intermountain region and to assess the impact of such properties on the resistance of HMA mixtures to thermal cracking.	Develop test methods and specification criteria that will allow the selection of fracture resistant asphalt mixtures and binders at low temperatures.	Mihai Marasteanu 612-625-5558 Maras002@umn.edu
	Materials Selection	Both projects will evaluate multiple HMA mixtures	**Aggregates:** four different aggregate sources from the intermountain region	**HMA mixtures:** nine field mixtures will be tested - seven mixtures from MnROAD, one mixture from Wisconsin, and one mix from New York. Three mixtures will include acid modified binders and three mixtures will include 30% RAP.	
	Experimental Plan	Both projects will evaluate the thermal cracking resistance of HMA mixtures in the laboratory.	**Temperature Profiles:** obtain typical temperature profiles from LTPP sections in the Intermountain region and Westrack **Performance:** collect thermal cracking performance of LTPP sites in the intermountain region and Westrack **Binder aging:** conduct long-term	**Aging:** short term oven aging of loose mixtures **Thermal cracking tests:** IDT creep and strength, Semi circular Bending (SCB), and Disc Compact Tension (DCT) will be evaluated. **Field performance:** the thermal cracking of the field sections will be used to as	

APPENDIX B

MASTER REFERENCE LIST

Section	Reference
MSP	Howson, J. E., E. Masad, A. Bhasin, V. C. Branco, E. Arambula, R. L. Lytton, and D. N. Little, 2007, "System for the Evaluation of Moisture Damage Using Fundamental Material Properties." Research Report 0-4524-1, Texas Transportation Institute, College Station, Texas.
MSP	Little, D. N., and A. Bhasin, 2006, "Using Surface Energy Measurements to Select Materials for Asphalt Pavement." Final Report for Project 9-37, Texas Transportation Institute, College Station, Texas.
MSP	Masad, E., C. Zollinger, R. Bulut, D. N. Little, and R. L. Lytton, 2006, "Characterization of HMA Moisture Damage Using Surface Energy and Fracture Properties." *Proc.*, Association of Asphalt Paving Technologists, 75: 713-754.
MSP	Robl, T. L., D. Milburn, G. Thomas, J. Groppo, and K. O'Hara, 1991, "The SHRP Materials Reference Library Aggregates: Chemical, Mineralogical, and Sorption Analyses." Report No. SHRP-A/UIR-91-509. Strategic Highway Research Program.
MSP	Solaimanian, M., R. F. Bonaquist, and V. Tandon, 2007, "Improved Conditioning and Testing Procedures for HMA Moisture Susceptibility." NCHRP Report 589, National Research Council, Washington D.C. http://onlinepubs.trb.org/onlinepubs/nchrp/ncrhp_rpt_589.pdf. ISBN: 9780309099066.
MSP	Western Research Institute, 2001, *Fundamental Properties of Asphalts and Modified Asphalts, Volume I: Interpretive Report*, FHWA-RD-99-212. U. S. Department of Transportation, Federal Highway Administration, McLean, VA.
M1a	Cho, D. W. and H. U. Bahia, 1998, Effects of Aggregate Surface and Water on Rheology of Asphalt Films. *Transportation Research Record 2007*, (-1), 10-17.
M1a-3	ASTM, 2002, D 4541 – 02 Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers. *American Society of Testing and Materials*. 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959, United States.
M1a-3	Bahia, H., and K. Kanitpong, 2003, Role of Adhesion and Thin Film Tackiness of Asphalt Binders in Moisture Damage of HMA. *Journal of the Association of Asphalt Paving Technologists*, 72: 502-528.
M1a-3	Cho, D.-W., and H. Bahia, 2007, Effects of Aggregates' Surface and Water on Rheology of Asphalt Film, Accepted to the T*ransportation Research Record*, 2007.
M1a-3	Kanitpong, K., 2005, Evaluation of the Roles of Adhesion and Cohesion Properties of Asphalt Binders in Moisture Damage of HMA. Ph.D. Thesis. University of Wisconsin-Madison.
M1a-3	Youtcheff, J. and V. Aurilio, 1997, Moisture Sensitivity of asphalt Binders: Evaluation and Modeling of the Pneumatic Adhesion test Results. *Canadian Technical Asphalt Association proceedings*.

M1b Bhasin, A., and D. N. Little, 2006, Application of Micro-Calorimeter to Characterize Adhesion Between Asphalt Binders and Aggregates. *Journal of Materials in Civil Engineering*, in review.

M1b-2 Boatto, S., L. P. Kadanoff, and P. Olla, 1993, Traveling-wave Solutions to Thin-film Equations. *Physical Review E*, 48(6): 4423-4431.

M1b-2 Brenner, M., 1993, Spreading of Droplets on a Solid Surface. *Physical Review Letters*, 71(4); 593-596.

M1b-2 Carpick, R. W., D. F. Ogletree, and M. Salmeron, 1999, A General Equation for Fitting Contact Area and Friction vs Load Measurements. *Journal of Colloid and Interface Science*, 211: 395-400.

M1b-2 Dandapat, B. S., P. Daripa, and P. C. Ray, 2003, Asymptotic Study of Film Thinning Process on a Spinning Annular Disk. *Journal of Applied Physics*, 94(6): 4144-4151.

M1b-2 Danov, K. D., N. Alleborn, H. Raszillier, and F. Durst, 1998, The Stability of Evaporating Thin Liquid Films in the Presence of Surfactant. I. Lubrication Approximation and Linear Analysis. *Physics of Fluids*, 10(1): 131-143.

M1b-2 David, M. B., Y. Zvirin, and Y. Zimmels, 1999, Determination of the Quench Velocity and Rewetting Temperature of Hot Surfaces: Formulation of a Nonisothermal Microscale Hydrodynamic Model. *Physical Review E*, 59(6): 6687-6698.

M1b-2 Derjaguin, B. V., V. M. Muller, and Y. P. Toporov, 1975, Effect of Contact Deformations on the Adhesion of Particles. *Journal of Colloid Interface Science*, 50: 314-326.

M1b-2 Diez, J. A., L. Kondic, and A. Bertozzi, 2000, Global Models for Moving Contact Lines. *Physical Review E*, 63(011208): 1-13.

M1b-2 Emslie, A. G., F. T. Bonner, and L. G. Peck, 1958, Flow of a Viscous Liquid on a Rotating Disk. *Journal of Applied Physics*, 29(5): 858-861.

M1b-2 Eres, M. H., L. W. Schwartz, and R. V. Roy, 2000, Fingering Phenomena for Driven Coating Films. *Physics of Fluids*, 12(6): 1278-1295.

M1b-2 Fraysse, N., and G. M. Homsy, 1994, An Experimental Study of Rivulet Instabilities in Centrifugal Spin Coating of Viscous Newtonian and Non-Newtonian Fluids. *Physics of Fluids*, 6(4), 1491-1504.

M1b-2 Hocking, L. M., 1992, The Influence of Intermolecular Forces on Thin Fluid Layers. *Physics of Fluids A*, 5(4): 793-799.

M1b-2 Hui, C. Y., and J. M. Baney, 1998, Contact Mechanics and Adhesion of Viscoelastic Spheres. *Langmuir*, 14: 6570-6578.

M1b-2 Hwang, J. H., and F. Ma, 1989, On the Flow of a Thin Liquid Film over a Rough Rotating Disk. *Journal of Applied Physics*, 66(1): 388-394.

M1b-2 Israelachvili, J., 1992, *Intermolecular & Surface Forces*, 2nd Ed., Academic Press Limited, Academic Press Inc., San Diego, CA.

M1b-2 Johnson, K. L., K. Kendall, and A. D. Roberts, 1971, Surface Energy and the Contact of Elastic Solids. *Proceedings of the Royal Society of London A.*, 324: 301-313.

M1b-2 Khomenko, A. V., and O. V. Yushchenko, 2003, Solid-Liquid Transition of Ultrathin Lubricant Film. *Physical Review E*, 68(036110): 1-6.

M1b-2 Kim, S., J. S. Kim, and F. Ma, 1990, On the Flow of a Thin Liquid Film Over a Rotating Disk. *Journal of Applied Physics*, 69(4): 2593-2601.

M1b-2 Kim, S., J. S. Kim, and F. Ma, 1992, Topographic Effect of Surface Roughness on Thin-Film Flow. *Journal of Applied Physics*, 72(1): 422-428.

M1b-2 Kinloch, A. J., 1987, *Adhesion and Adhesives Science and Technology*, Chapman and Hall, New York, NY, p. 339-400.

M1b-2 Kitamura, A., 2001, Thermal Effects on Liquid Film Flow During Spin Coating. *Physics of Fluids*, 13(10): 2788-2794.

M1b-2 Meyerhofer, D., 1978, Characteristics of Resist Films Produced by Spinning. *Journal of Applied Physics*, 49(7): 3993-3997.

M1b-2 Middleman, S., 1987, The Effect of Induced Air-Flow on the Spin Coating of Viscous Liquids. *Journal of Applied Physics*, 62(6): 2530-2532.

M1b-2 Moriarty, J. A., L. W. Schwartz, and E. O. Tuck, 1991, Unsteady Spreading of Thin Liquid Films with Small Surface Tension. *Physics of Fluids A*, 3(5): 733-742.

M1b-2 Neto, C., K. Jacobs, R. Seemann, R. Blossey, J. Becker, and G. Grün, 2003, Correlated Dewetting Patterns in Thin Polystyrene Films. *Journal of Physics: Condensed Matter*, 15: S421-S426.

M1b-2 Oron, A., S. H. Davis, and S. G. Bankoff, 1997, Long-Scale Evolution of Thin Liquid Films. *Reviews of Modern Physics*, 69(3): 931-980.

M1b-2 Pollock, H. M., D. Maugis, and M. Barquins, 1978, The Force of Adhesion Between Solid Surfaces in Contact. *Applied Physics Letters*, 33(9): 798-799.

M1b-2 Schwartz, L. W., 1989, Viscous Flows Down an Inclined Plane: Instability and Fingering Formation. *Physics of Fluids A* 1(3): 443-445.

M1b-2 Schwartz, L. W., and R. V. Roy, 2004, Theoretical and Numerical Results for Spin Coating of Viscous Liquids. *Physics of Fluids*, 16(3): 569-584.

M1b-2 Shull, K. R., 2002, Contact Mechanics and the Adhesion of Soft Solids. *Materials Science and Engineering R.*, 36: 1.

M1b-2 Spaid, M. A., and G. M. Homsy, 1996, Stability of Newtonian and Viscoelastic Dynamic Contact Lines. *Physics of Fluids*, 8(2): 460-478.

M1b-2 Spaid, M. A., and G. M. Homsy, 1997, Stability of Viscoelastic Dynamic Contact Lines: An Experimental Study. *Physics of Fluids*, 9(4): 823-832.

M1b-2 Stillwagon, L. E., and R. G. Larson, 1990, Leveling of Thin Films Over Uneven Substrates During Spin Coating. *Physics of Fluids A* 2(11): 1937-1944.

M1b-2 Wilson, S. K., R. Hunt, and B. R. Duffy, 2000, The Rate of Spreading in Spin Coating. *Journal of Fluid Mechanics*, 413: 65-88.

M1b-2 Yanagisawa, M., 1987, Slip Effect for Thin Liquid Film on a Rotating Disk. *Journal of Applied Physics*, 61(3): 1034-1037.

M1b-2 Zhang, W. W., and J. R. Lister, 1999, Similarity Solutions for van der Waals Rupture of a Thin Film on a Solid Substrate. *Physics of Fluids*, 11(9): 2454-2462.

M1c Caro, S., E. Masad, G. Airey, A. Bhasin, and D. N. Little. "Probabilistic Analysis of Fracture in Asphalt Mixtures Caused by Moisture Damage." Submitted for consideration in the Transportation Research Record, TRB, National Research Council, Washington D.C.

M2a Creton, C., and H. Lakrout, 2000, Micromechanics of Flat Probe Adhesion Tests of Soft Visocelastic Polymer Films. *Journal of Polymer Science: Part B: Polymer Physics*, 38: 965-979.

M2a Kawashita, L. F., D. R. Moore, and J. G. Williams, 2006, Protocols for the Measurement of Adhesive Fracture Toughness by Peel Tests. *Journal of Adhesion*, 82(10), 973-995.

M2a Shull, K. R., 2002, Contact Mechanics and the Adhesion of Soft Solids. *Material Science and Engineering, R.*, 36(1), 1-45.

M2a-2 Adamson, A. W., and A. P. Gast, 1997, *Physical Chemistry of Surfaces*, 6th Ed., A Wiley-Interscience Publication, John Wiley & Sons, Inc., New York, 534-535.

M2a-2 Robertson, R. E., J. F. Branthaver, P. M. Harnsberger, J. C. Petersen, S. M. Dorrence, J. F. McKay, T. F. Turner, A. T. Pauli, S.-C. Huang, J.-D. Huh, J. E. Tauer, K. P. Thomas, D. A. Netzel, F. P. Miknis, T. Williams, J. J. Duvall, F. A. Barbour, C. Wright, 2001, *Fundamental Properties of Asphalts and Modified Asphalts, Volume I: Interpretive Report*, FHWA-RD-99-212. U. S. Department of Transportation, Federal Highway Administration, McLean, VA.

M2a-2 Robertson, R. E., K. P. Thomas, P. M. Harnsberger, F. P. Miknis, T. F. Turner, J. F. Branthaver, S-C. Huang, A. T. Pauli, D. A. Netzel, T. M. Bomstad, M. J. Farrar, J. F. McKay, and M. McCann. "Fundamental Properties of Asphalts and Modified Asphalts II, Final Report, Volume I: Interpretive Report," Federal Highway Administration, Contract No. DTFH61-99C-00022, Chapters 1-4 submitted for publication, November 2005.

M2a-2 Tiller, W. A., 1991, *The Science of Crystallization: Macroscopic Phenomena and Defect Generation*, Cambridge University Press, Great Britain, New York, NY.

M2b Nguyen, T., E. Byrd, D. Bentz, and J. Seiler, 1996, *Development of a Method for Measuring Water-Stripping Resistance of Asphalt/Siliceous Aggregate Mixtures*. NISTIR 5865, National Institute of Standards and Technology, Gaithersburg, MD.

M2b-1 Crank, J., 1975, *The Mathematics of Diffusion*, 2nd ed., Oxford University Press, NY.

M2b-1 Vogt, B.D., 2008, Moisture Distribution and Transport in Polymers in Confined Spaces. *Proc.*, 2nd International Workshop on Moisture Damage, College Station, Texas, September 2008.

M2b-2 Linossier, I., F. Gaillard, M. Romand, and T. Nguyen, 1999, A Spectroscopic Technique for Studies of Water Transport Along the Interface and Hydrolytic Stability of Polymer/Substrate Systems. *Journal of Adhesion*, 70: 221-239.

M2c Al-Omari, A., and E. Masad, 2004, Three Dimensional Simulation of Fluid Flow in X-ray CT Images of Porous Media. *International Journal for Numerical and Analytical Methods in Geomechanics*, 28: 1327-1360.

M2c ASTM, 2002, "D 4541 – 02 Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers." *American Society of Testing and Materials*. 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959, United States.

M2c Bahia, H., and C. Dong-Woo, 2007, Effects of Aggregate Surface and Water on Rheology of Asphalt Films. *Transportation Research Record 1998*.

M2c Bhasin, A., and D. N. Little, 2006, Application of Micro-Calorimeter to Characterize Adhesion Between Asphalt Binders and Aggregates. *Journal of Materials in Civil Engineering*, In Review.

M2c Cho, D.-W., and H. Bahia, 2007, Effects of Aggregates' Surface and Water on Rheology of Asphalt Film. Accepted to the *Transportation Research Record*, 2007.

M2c Hueckel, T., 2002, Reactive Plasticity for Clays during Dehydration and Rehydration. Part I: Concepts and Options. *International Journal of Plasticity*, 18(3): 281-312.

M2c Kanitpong, K, and H. Bahia, 2003, Role of Adhesion and Thin Film Tackiness of Asphalt Binders in Moisture Damage of HMA. *Journal of the Association of Asphalt Paving Technologists*, 72: 502-528.

M2c Kringos, N., and A. Scarpas, 2006, Numerical Simulation of the Physical Processes Inducing Moisture Damage in Asphaltic Mixtures. *Proc.*, 10th International Conference on Asphalt Pavements (ICAP), Quebec, Canada, 732-741.

M2c Kringos, N., and N. Scarpas, 2005a, Raveling of Asphaltic Mixes Due to Water Damage: Computational Identification of Controlling Parameters. *Transportation Research Record, 1929*, 79-87.

M2c Kutay, E. M., M. Aydilek, E. Masad, and T. Harman, 2007, Evaluation of Hydraulic Conductivity Anisotropy in Asphalt Specimens. *International Journal of Pavement Engineering*, 8(1): 29-43.

M2c Youtcheff, J., and V. Aurilio, 1997, Moisture Sensitivity of asphalt Binders: Evaluation and Modeling of the Pneumatic Adhesion test Results. *Proc.*, Canadian Technical Asphalt Association.

M3a Little, D. N., and A. Bhasin, 2006, Using Surface Energy Measurements to Select Materials for Asphalt Pavement. *Final Report for NCHRP Project 9-37*, Transportation Research Board, Washington D.C.

M4a Allen, K. W., 1993, Some Reflections on Contemporary Views of Theories of Adhesion. *International Journal of Adhesion and Adhesives*, 13(2): 67-73.

M4a Bhasin, A., E. Masad, D. Little, and R. Lytton, 2006, Limits on Adhesive Bond Energy for Improved Resistance of Hot Mix Asphalt to Moisture Damage. *Transportation Research Record: Journal of the Transportation Research Board*, 1970: 3-13.

M4a Clint, J. H., and A. C. Wicks, 2001, Adhesion under Water: Surface Energy Considerations. *International Journal of Adhesion and Adhesives*, 21: 267-273.

M4a Crocombre, A. D., 1997, Durability modeling concepts and tools for the cohesive environmental degradation of bonded structures. *International Journal of Adhesion and Adhesives*, 17: 229-238.

M4a Ferguson, T. P, and J. Qu, 2006, Predictive Model for Adhesion Loss of Molding Compounds from Exposure to Humid Environments, in IEEE 2006 Electronic Components and Technology Conference, pp. 1408-1414.

M4a Fernando, M., W. W. Harjoprayitno, and A. J. Kinloch, 1996, A fracture mechanics study of the influence of moisture on the fatigue behavior of adhesively bonded aluminum-alloy joints. *International Journal of Adhesion and Adhesives*, 16(2): 113-119.

M4a Gdoutos, E. E., 2005, *Fracture Mechanics: An Introduction*, Second edition. Springer, The Netherlands.

M4a Gledhill, R. A., A. J. Kinloch, S. J. Shaw, 1980, A Model for Predicting Joint Durability. *Journal of Adhesion*, 11: 3-15.

M4a Hefer, A. W., D. N. Little, and R. L. Lytton, 2005, A synthesis of theories and mechanisms of bitumen-aggregate adhesion including recent advances in quantifying the effects of water. *Journal of the Association of Asphalt Paving Technologists*, vol. 74.

M4a Hua, Y., A. D. Crocombre, M. A. Wahab, and I. A. Ashcroft, 2006, Modelling Environmental Degradation in EA9321-Bonded Joints using a Progressive Damage Failure Model. *Journal of Adhesion*, 82: 135–160.

M4a Kinloch, A. J., 1980, The Science of Adhesion, Part 1: Surface and Interfacial Aspects. *Journal of Materials Science*, 15: 2141-2166.

M4a Kinloch, A. J., 1982, The Science of Adhesion, Part 2, Mechanics and mechanisms of failure. Journal of Materials Science, 17: 617-651.

M4a Kinloch, A. J., M. S. G. Little, and J. F. Watts, 2000, The Role of the Interphase in the Environmental Failure of Adhesive Joints. *Acta Materialia*, 48: 4543-4553.

M4a Kook, S., and R. H. Dauskardt, 2002, Moisture-assisted subcritical debonding of a polymer/metal interface. *Journal of Applied Physics*, 91(3): 1293-1303.

M4a Lam, D. C. C. and J. Wang, 2007, Hygrothermal Delaminations in Lead-Free Solder Reflow of Electronic Packages. *The Journal of Electronic Materials*, 36(3): 226-231.

M4a Lam, D. C. C., F. Yang, and P. Tong, 1999, Chemical Kinetic Model of Interfacial Degradation of Adhesive Joints. *IEEE Transactions of Components and packaging Technology*, 22(2): 215-220.

M4a Lane, M. W., X. H. Liu, and T. M. Shaw, 2004, Environmental Effects on Cracking and Delamination of Dielectric Films. *IEEE Transactions pn device and materials reliability*, 4(2): 142-147.

M4a Leung, S. Y. Y., D. C. C. Lam, S. Luo, and C. P. Wong, 2004, The Role of Water in Delamination in Electronic Packages: Degradation of Interfacial Adhesion. *Journal of Adhesion Science Technology*, 18(10): 1103-1121.

M4a Liljedahl, C. D. M., A. D. Crocombe, M. A. Wahab, and I. A. Ashcroft, 2006, Modelling the Environmental Degradation of the Interface in Adhesively Bonded Joints using a Cohesive Zone Approach. *The Journal of Adhesion*, 82: 1061–1089.

M4a Mostovoy, S., and E. J. Ripling, 1969, Influence of Water on Stress Corrosion Cracking of Epoxy Bonds. Vol. 13, pp. 1083-1111.

M4a O'Brien, E. P., C. C. White, and B. D. Vogt, 2006, Content and Adhesive Fracture Energy of Polymer Coatings on Different Surfaces. *Advanced Engineering Materials*, 8(1–2):114-118.

M4a Ritter, J. E., and K. Conley, 1992, Moisture-assisted Crack Propagation at Polymer/glass Interfaces. *International Journal of Adhesion and Adhesives*, 12(4): 245-250.

M4a Weiderhorn, S. M., E. R. Fuller, and R. Thomson, 1980, Micromechanisms of crack growth in ceramics and glasses in corrosive environments. *Metal Science*, 14: 450-458.

M4a Zewi, I. G., F. Flashner, H. Dodiuk, and L. Drori, 1984, Durability of Structural Adhesive Joints. *International Journal of Adhesion and Adhesives*, 4(3): 137-140.

M4b Masad, E., C. Zollinger, R. Bulut, D. Little, and R. Lytton, 2006, Characterization of HMA Moisture Damage Using Surface Energy and Fracture Properties. *Journal of the Association of Asphalt Paving Technologists*, 75: 713-748.

M4c Abaqus, 2006. Version 6.5, Habbitt, Karlsson and Sorensen, Inc: Providence, RI.

M4c Abu Al-Rub, R. K., and G. Z. Voyiadjis, 2003, On the coupling of anisotropic damage and plasticity models for ductile materials. *Int. J. Solids Struct.*, 40: 2611-2643.

M4c Al-Omari, A., and E. Masad, 2004, Three Dimensional Simulation of Fluid Flow in X-ray CT Images of Porous Media. *International Journal for Numerical and Analytical Methods in Geomechanics*, 28: 1327-1360.

M4c Caro, S., E. Masad, A. Bhasin, and D. N. Little, 2008a, Moisture susceptibility of asphalt mixtures, Part 1: mechanisms. *International Journal of Pavement Engineering*, 9: 81-98.

M4c Caro, S., E. Masad, A. Bhasin, and D. N. Little, 2008b, Moisture susceptibility of asphalt mixtures, Part 2: characterization and modeling. *International Journal of Pavement Engineering*, 9: 99-114.

M4c Hueckel, T., 2002, Reactive Plasticity for Clays during Dehydration and Rehydration. Part I: Concepts and Options. *International Journal of Plasticity*, 18(3): 281-312.

M4c Kringos, N., 2007. *Modeling of Combinded Physical-Mechanical Moisture Induced Damage in Asphaltic Mixes*. Ph.D. Dissertation, Delft University, The Netherlands.

M4c Kringos, N., and A. Scarpas, 2005, Raveling of Asphaltic Mixes Due to Water Damage: Computational Identification of Controlling Parameters. *Transportation Research Record*, 1929, 79-87.

M4c Kringos, N., and A. Scarpas, 2006, Numerical Simulation of the Physical Processes Inducing Moisture Damage in Asphaltic Mixtures. *Proc.*, 10th International Conference on Asphalt Pavements (ICAP), Quebec, Canada, 732-741.

M4c Kutay, E. M., M. Aydilek, E. Masad, and T. Harman, 2007, Evaluation of Hydraulic Conductivity Anisotropy in Asphalt Specimens. *International Journal of Pavement Engineering*, 8(1), 29-43.

M4c Lemaitre, J., 1992, *A Short Course in Damage Mechanics*. Springer-Verlag, New York.

M4c Voyiadjis, G.Z. and P. I. Kattan, 1999, *Advances in Damage Mechanics: Metals and Metals Matrix Composites*. Elsvier, Oxford.

F1a Bhasin, A., and D. N. Little, 2006, Characterization of aggregate surface energy using the universal sorption device. *Journal of Materials in Civil Engineering (ASCE)*, Accepted for publication.

F1a Della Volpe, C., and S. Siboni, 2000, Acid base surface free energies of solids and the definition of scales in the Good van Oss Chaudhury theory. *Journal of Adhesion Science and Technology*, 14(2): 235-272.

F1a Hefer, A. W., A. Bhasin, and D. L. Little, 2006, Bitumen surface energy characterization using a contact angle approach. *Journal of Materials in Civil Engineering (ASCE)*, 18(6): 759-767.

F1a Little, D. N., and A. Bhasin, 2006, Using Surface Energy Measurements to Select Materials for Asphalt Pavement. Final Report for Project 9-37, Texas Transportation Institute.

F1a Sharon, E., S. P. Gross, and J. Fineberg, 1996, Energy Dissipation in Dynamic Fracture. *Physical Review Letters*, 76(12): 2117-2120.

F1b Huang, C. W., E. Masad, A. Muliana, and H. Bahia, 2007, Development and Numerical Implementation of a Nonlinear Viscoelastic Model for Hot Mix Asphalt. *Mechanics of Time Dependent Materials*, in review.

F1b-1 Golden, H. J., T. W. Strganac, and R. A. Schapery, 1996, A Test and Analysis Protocol to Rapidly Characterize Nonlinear Viscoelastic Properties of Ballon Materials. American Institute of Aeronautics (AIAA) Meeting, Paper 96-0572.

F1b-1 Park, S. W., and Y. R. Kim, 1999, Interconversion Between Relaxation Modulus and Creep Compliance for Viscoelastic Solids. *Journal of Materials in Civil Engineering*, 11(1): 76-82.

F1b-1 Schapery, R. A., 1969, On the Characterization of Nonlinear Viscoelastic Materials. *Polymer Engineering and Science*, 9: 295-310.

F1b-2 Ashby, M. F., and D. R. H. Jones, 1995, *Engineering Materials 1*. Butterworth-Heinemann, 306 pp.

F1b-2 Beake, B., 2006, Modelling indentation creep of polymers: a phenomenological approach. *J. Phys. D: Appl. Phys.*, 39: 4478–4485.

F1b-2 Li, X., and B. Bhushan, 2002, A review of nanoindentation continuous stiffness measurement technique and its applications. *Materials Characterization*, 48(5): 11–36.

F1b-2 Lin, D. C., E. K. Dimitriadis, and F. Horkay, F., 2006, Advances in the mechanical characterization of soft materials by nanoindentation. *Recent Res. Devel. Biophys.*, 5(2006): ISBN: 81-7895-215-7.

F1b-2 McGennis, R. B., S. Shuler, and H. U. Bahia, 1994, *Background of SUPERPAVE Asphalt Binder Test Methods*. Federal Highway Administration Report No. FHWA-SA-94-069.

F1b-2 Pichler, C., A. Jager, R. Lackner, and J. Eberhardsteiner, 2005, Identification of Material Properties from Nanoindentation: Application to Bitumen and Cement Paste. *Proc.*, 22nd Danubia-Adria Symposium on Experimental Methods in Solid Mechanics, Sept. 28-Oct. 1, 2005, Moniticellu Terme, Parma, Italy.

F1b-2 Roberts, F. L., P. S. Kandhal, E. R. Brown, D.-T. Lee, and T. W. Kennedy, 1996, *Hot Mix Asphalt Materials, Mixtures, and Construction*. National Asphalt Pavement Association – Research and Education Foundation, Lanham, MD, 585 pp.

F1c-1 Bosscher, Peter J., et al., 1998, Relationship between Pavement Temperature and Weather Data: Wisconsin Field Study to Verify Superpave Algorithm. *Transportation Research Record 1609*, Paper No. 98-0944.

F1c-1 Dickinson, E. J., and J. H. Nicholas, 1949, The Reaction of Oxygen with Tar Oils, Road Research Technical Paper, No. 16.

F1c-1 Diefenderfer, B.K., A.M. ASCE, I.L. AL-Qadi, and S.D Diefenderfer, 2006, Model to predict pavement temperature profile: development and validation. *Journal of Transportation Engineering*, 132: 162-167.

F1c-1 Fromont, G. F., and K. B. Bischoff, 1979, *Chemical Reactor Analysis and Design*, John Wiley and Sons, New York, NY.

F1c-1 Gui, Jooseng Gavin, et al., 2007, Impact of Pavement Thermophysical Properties on Surface Temperatures. *Journal of Materials in Civil Engineering*, August 2007, 683-690.

F1c-1 Hermansson, Ake, 2001, Mathematical Model for Calculation of Pavement Temperatures. Comparison of Calculated and Measured Temperatures, *Transportation Research Record 1764*, Paper No. 01-3543.

F1c-1 Hermansson, Ake, 2004, Mathematical model for paved surface summer and winter temperature: comparison of calculated and measured temperatures, *Cold Regions Science and Technology*, 40.

F1c-1 Herrington, P. R., 1998, Oxidation of Bitumen in the Presence of a Constant Concentration of Oxygen. *Petroleum Science and Technology*, 16 (9&10): 1061-1084.

F1c-1 Lau, C.K., K.M. Lunsford, C.J. Glover, R.R. Davison, and J.A. Bullin, 1992, Reaction Rates and Hardening Susceptibilities as Determined from POV Aging of Asphalt. *Transportation Research Record 1342*, 50.

F1c-1 Martin, K.L., C.J. Glover, R.R. Davison, and J.A. Bullin, 1990, Asphalt Aging in Texas Roads and Test Sections. *Transportation Research Record 1269*, 9.

F1c-1 Minhoto, Manuel J.C., et al., 2005, Predicting Asphalt Pavement Temperature with a Three-Dimensional Finite Element Method, Journal of the Transportation Research Board, *Transportation Research Record 1919*, 96–110.

F1c-1 Reid, R.C., J.M. Prausnitz, and T.K. Sherwood, 1983, *The Properties of Gases and Liquids*, McGraw-Hill, 4th ed., New York, NY.

F1c-1 Van Oort, W. P., 1956, Durability of Asphalt. *Industrial and Engineering Chemistry*, 1196-1201.

F1c-1 Woo, W.J., E. Ofori-Abebresse, A. Chowdhury, J. Hilbrich, Z. Kraus, A. Epps Martin, and C.J. Glover, 2007, Polymer Modified Asphalt Durability in Pavements. Report FHWA/TX-07/0-4688-1, Texas Transportation Institute, College Station, TX.

F1c-3 Bosscher, Peter J., et al., 1998, Relationship between Pavement Temperature and Weather Data: Wisconsin Field Study to Verify Superpave Algorithm, Transportation Research Record 1609, Paper No. 98-0944.

F1c-3 Diefenderfer, Brian K., et al., February 2006, Model to Predict Pavement Temperature Profile: Development and Validation. *Journal of Transportation Engineering*, 162-167.

F1c-3 Fromont, G.F., and K.B. Bischoff, 1979, *Chemical Reactor Analysis and Design*, John Wiley and sons, New York, NY.

F1c-3 Gui, Jooseng Gavin, et al., August 2007, Impact of Pavement Thermophysical Properties on Surface Temperatures. *Journal of Materials in Civil Engineering*, 683-690.

F1c-3 Hermansson, Ake, 2001, Mathematical Model for Calculation of Pavement Temperatures Comparison of Calculated and Measured Temperatures. Transportation Research Record 1764, Paper No. 01-3543.

F1c-3 Hermansson, Ake, 2004, Mathematical model for paved surface summer and winter temperature: comparison of calculated and measured temperatures. *Cold Regions Science and Technology*, 40.

F1c-3 Lau, C. K., K. M. Lunsford, C. J. Glover, R. R. Davison, and J. A. Bullin, 1992, Reaction Rates and Hardening Susceptibilities as Determined from POV Aging of Asphalt. *Trans. Res. Rec.*, 1342, 50.

F1c-3 Martin, K. L., C. J. Glover, R. R. Davison, and J. A. Bullin, 1990, Asphalt Aging in Texas Roads and Test Sections. *Trans. Res. Rec.*, 1269, 9.

F1c-3 Minhoto, Manuel J. C., et al., 2005, Predicting Asphalt Pavement Temperature with a Three-Dimensional Finite Element Method. Transportation Research Record: *Journal of the Transportation Research Board, No. 1919*, Transportation Research Board of the National Academies, Washington, D.C., 96–110.

F1c-3 Reid, R. C., J. M. Prausnitz, and T. K. Sherwood, 1983, *The Properties of Gases and Liquids*, McGraw-Hill, 4th, ed., New York, NY.

F1c-3 Won Jun Woo, et al., November 2006, Polymer Modified Asphalt Durability in Pavements, Chapter 5, Report No. FHWA/TX-07/0-4688-1.

F1d Baglieri, O., 2007, Preliminary investigation on healing of bituminous binders, Internal Report, UW-Madison.

F1d Bhasin, A., D. N. Little, R. Bommavaram, and K. L. Vasconcelos, 2008, A Framework to Quantify the Effect of Healing in Bituminous Materials Using Material Properties. *International Journal of Road Materials and Pavement Design*, in review.

F1d Carpenter, S. H., and S. Shen (2006). A Dissipated Energy Approach to Study HMA Healing in Fatigue. 85th Annual Meeting of the Transportation Research Board, Washington D.C.

F1d Kim, B., and R. Roque, 2006, Evaluation of Healing Property of Asphalt Mixture. 85th Annual Meeting of the Transportation Research Board, Washington, D.C.

F1d Little, D. N., A. Letton, S. Prapnnachari, and Y. R. Kim, 1994, Rheological and Rheo-Optical Characterization of Asphalt Cement and Evaluation of Relaxation Properties. Transportation Research Record: *Journal of the Transportation Research Board*, 1436: 71-82.

F1d Little, D. N., and A. Bhasin, 2007, Exploring Mechanisms of Healing in Asphalt Mixtures and Quantifying its Impact, in *Self Healing Materials*, S. van der Zwaag, ed., Springer, Dordrecht, The Netherlands, 205-218.

F1d Wool, R. P., and K. M. O'Connor, 1981, A Theory of Crack Healing in Polymers. *Journal of Applied Physics*, 52(10): 5923-5963.

F1d-1 Berger, L. L., and E. J. Kramer, 1987, Chain Disentanglement during High Temperature Crazing of Polystyrene. *Macromolecules*, 20: 1980-1985.

F1d-1 Bhairampally, R. K., R. L. Lytton, and D. N. Little, 2000, Numerical and Graphical Method to Assess Permanent Deformation Potential for Repeated Compressive Loading of Asphalt Mixtures. *Transportation Research Record: Journal of the Transportation Research Board*, 1723: 150-158.

F1d-1 Carpenter, S. H., and S. Shen. A Dissipated Energy Approach to Study HMA Healing in Fatigue. 85th Annual Meeting of the Transportation Research Board, Washington D.C.

F1d-1 de Gennes, P. G., 1971, Reptation of a Polymer Chain in the Presence of Fixed Obstacles. *The Journal of Chemical Physics*, 55(2): 572-579.

F1d-1 Kim, B., and R. Roque, Evaluation of Healing Property of Asphalt Mixture. 85th Annual Meeting of the Transportation Research Board, Washington, D.C.

F1d-1 Kim, Y. R., D. N. Little, and F. C. Benson, 1990, Chemical and Mechanical Evaluation on Healing Mechanism of Asphalt Concrete. *Proc. Association of Asphalt Paving Technologists*, 59: 240275.

F1d-1 Kim, Y. R., D. N. Little, and R. L. Lytton, 2003, Fatigue and Healing Characterization of Asphalt Mixes. *Journal of Materials in Civil Engineering (ASCE)*, 15: 75-83.

F1d-1 Kim, Y. R., H. Lee, and D. N. Little, 2001, Microdamage Healing in Asphalt and Asphalt Concrete, Volume IV: A Viscoelastic Continum Damage Fatigue Model of Asphalt Concrete with Microdamage Healing. Texas Transportation Institute, College Station, Texas.

F1d-1 Little, D. N., A. and Bhasin, 2006, Using Surface Energy Measurements to Select Materials for Asphalt Pavement. Final Report for Project 9-37, Texas Transportation Institute, Texas.

F1d-1 Little, D. N., R. L. Lytton, A. D. Williams, and C. W. Chen, 2001, *Microdamage Healing in Asphalt and Asphalt Concrete, Volume I: Microdamage and Microdamage Healing, Project Summary Report*. *FHWA-RD-98-141*, Texas Transportation Institution, College Station, Texas.

F1d-1 Maillard, S., C. de La Roche, F. Hammoum, L. Gaillet, and C. Such. Experimental Investigation of Fracture and Healing at Pseudo-Contact of Two Aggregates. 3rd Euroasphalt and Eurobitume Congress, Vienna.

F1d-1 Nishizawa, T., S. Shimeno, and M. Sekiguchi, Fatigue Analysis of Asphalt Pavements with Thick Asphalt Mixture, Layer. 8th International Conference on Asphalt Pavements, Seattle, Washington, 969-976.

F1d-1 Schapery, R. A., 1981, Non linear fracture analysis of viscoelastic composite materials based on a generalized J integral theory.

F1d-1 Williams, A. D., D. N. Little, R. L. Lytton, Y. R. Kim, and Y. Kim, 2001, *Microdamage Healing in Asphalt and Asphalt Concrete, Volume II: Laboratory and Field Testing to Assess and Evaluate Microdamage and Microdamage Healing*. FHWA-RD-98-142, Texas Transportation Institution, College Station, Texas.

F1d-1 Wool, R. P., and K. M. O'Connor, 1981, A theory of crack healing in polymers. *Journal of Applied Physics*, 52(10): 5953-5963.

F1d-2 Greenfield, M. L., 2006, Modeling for Nanoengineering: Molecular Simulation of Asphalt-like Materials. Presented at NSF Workshop on Nanomodification of Cementitious Materials.

F1d-2 Jennings, P. W., J. A. Pribanic, M. A. Desando, and M. F. Raub, 1993, *Binder Characterization and Evaluation by Nuclear Magnetic Resonance Spectroscopy*. *SHRP-A-355*, Strategic Highway Research Program, National Research Council, Washington, DC.

F1d-2 Kim, Y. R., D. N. Little, and F. C. Benson, 1990, Chemical and Mechanical Evaluation on Healing Mechanism of Asphalt Concrete. *Proc.*, Association of Asphalt Paving Technologists, 59: 240-275.

F1d-2 Prathab, B., V. Subramanian, and T. M. Aminabhavi, 2007, Computation of surface energy and surface segregation phenomena of perfluorinated copolymers and blends - A molecular modeling approach. *Polymer*, 48(1): 417-424.

F1d-4 Karlsson, R., U. Isacsson, and J. Ekblad, 2007, Rheological Characterisation of Bitumen Diffusion. *Journal of Materials Science*, 42: 101-108.

F1d-4 Qiu, H., and M. Bousmina, 1999, New technique allowing the quantification of diffusion at polymer/polymer interfaces using rheological analysis: Theoretical and experimental results. *Journal of Rheology*, 43(3): 551-568.

F1d-6 Baglieri, O., 2007, Preliminary investigation on healing of bituminous binders, *Internal Report*, *UW-Madison*.

F1d-6 Bhasin, A., D. N. Little, R. Bommavaram, and K. L. Vasconcelos, 2008, A framework to quantify the effect of healing in bituminous materials using material properties. *Road Materials and Pavement Design*, 219-242.

F1d-6 Bonnetti, Karen S., 2001, *Fatigue behavior of modified asphalt binders*. Master's thesis, University of Wisconsin-Madison.

F1d-6 Carpenter, S. H., and S. Shen, 2006, A Dissipated Energy Approach to Study HMA Healing in Fatigue. *Transportation Research Record*, no. 1970, 178-185.

F1d-6 Kim, B., and R. Roque, Evaluation of Healing Property of Asphalt Mixture. 85th Annual Meeting of the Transportation Research Board, Washington, D.C.

F1d-6 Kim, Y. R., D. N. Little, and R. L. Lytton, 2003, Fatigue and Healing Characterization of Asphalt Mixes. *Journal of Materials in Civil Engineering (ASCE)*, 15: 75-83.

F1d-6 Kim, Y-R., D. N. Little, and R. L. Lytton, 2002, Use of dynamic mechanical analysis (DMA) to evaluate the fatigue and healing potential of asphalt binders in sand asphalt mixtures. Asphalt Paving Technology: Association of Asphalt Paving Technologists-Proceedings of the Technical Sessions, Vol. 71, pp. 176-206.

F1d-7 Barth, E. J., 1962, *Asphalt Science and Technology*, Gordon and Breach Science Publishers, New York.

F1d-7 Buxton, G. A., and A. C. Balazs, 2004, Modeling of Dynamic Fracture of Polymer Blends Processed Under Shear. *Phys. Rev. B.*, 69, 054101.

F1d-7 Cahn, J. W., 1965, Phase Separation of Spinodal Decomposition in Isotropic Systems. *J. Chem. Phys.*, 42(1): 93-99.

F1d-7 Cahn, J. W., and J. E. Hilliard, 1958, Free Energy of a Nonuniform System. I. Interfacial Free Energy. *J. Chem. Phys.*, 28(2): 258-267.

F1d-7 Cahn, J. W., and J. E. Hilliard, 1959a, Free Energy of a Nonuniform System. II. Thermodynamic Basis. *J. Chem. Phys.*, 30(5): 1121-1124.

F1d-7 Cahn, J. W., and J. E. Hilliard, 1959b, Free Energy of a Nonuniform System. III. Nucleation in a Two-Component Incompressible Fluid. *J. Chem. Phys.*, 31(3): 688-699.

F1d-7 Eastgate, L. O., J. P. Sethna, M. Rauscher, T. Cretegny, C.–S.Chen, and C. R. Myers, 2002, Fracture in Mode I Using a Conserved Phase-Field Model. *Phys. Rev. E.*, 65, 036117.

F1d-7 Glansdorff, P., and I. Prigogine, 1971, *Thermodynamic Theory of Structure, Stability and Fluctuations*, Wiley-Interscience, division of John Wiley & Sons, Ltd., London.

F1d-7 Henry, H., and H. Levine, 2004, Dynamic Instabilities of Fracture Under Biaxial Strain Using a Phase-Field Model. *Phys. Rev. Lett.*, 93(10): 105504.

F1d-7 Hopper, R. W., 1976, Viscosity and Viscoelasticity of Two-Phase Systems Having Diffuse Interfaces. *Phys. Rev. Lett.*, 36(5): 289-292.

F1d-7 Igor, S. A., and L. Kramer, 2002, The World of the Complex Ginzburg-Landau Equation. *Rev. Mod. Phys.*, 74(1): 99-143.

F1d-7 Karma, A., D. A. Kessler, and H. Levine, 2001, Phase-Field Model of Mode III Dynamic Fracture. *Phys. Rev. Lett.*, 87(4): 045501.

F1d-7 Kyu, T., R. Mehta, and H-W Chin, 2000, Spatiotemporal Growth of Faceted and Curved Single Crystals. *Phys. Rev. E.*, 61(4): 4161-4170.

F1d-7 Loeber, L., O. Sutton, J. Morel, J.-M. Valleton, and G. Muller, 1996, New direct observations of asphalts and asphalt binders by scanning electron microscopy and atomic force microscopy. *Journal of Microscopy*, 182(1): 32-39.

F1d-7 Marconi, V. I., and E. A. Jagla, 2005, Diffuse Interface Approach to Brittle Fracture. *Phys. Rev. E.*, 71, 036110.

F1d-7 McQuarrie, D. A., and J. D. Simon, 1999, *Molecular Thermodynamics*. University Science Books, Sausalito, CA.

F1d-7 Mehta, R., W Keawwattana, A. L. Guenthner, and T. Kyu, 2004b, Role of Curvature Elasticity in Sectorization and Ripple Formation During Melt Crystallization of Polymer Single Crystals. *Phys. Rev. E.*, 69, 061802.

F1d-7 Mehta, R., W Keawwattana, and T. Kyu, 2004a, Growth Dynamics of Isotactic Polypropylene Single Crystals During Isothermal Crystallization from a Miscible Polymeric Solvent. *J. Chem. Phys.*, 120(8): 4024-4031.

F1d-7 Nellensteyn, F. J., 1933, Theoretical Aspect of the Relation of Bitumen to Solid Matter. *Proc.*, First World Petrol Congress, 2: 616-618.

F1d-7 Netzel, D. A., 2006, Apparent Activation Energies for Molecular Motions in Solid Asphalt, *Energy & Fuels*, 20: 2181-2188

F1d-7 Netzel, D. A., F. P. Miknis, J. C. Wallace, C. H. Butcher, and K. P. Thomas, 1997, Molecular Motions and Rheological Properties of Asphalts: An NMR Study, Chapter 2 in *Asphalt Science and Technology*, Usmani, A. M., Ed., Marcel Dekker, New York.

F1d-7 Pal, R., and E. Rhodes, 1989, Viscosity/Concentration Relationships for Emulsions. *Journal of Rheology*, 33(7): 1021-1045.

F1d-7 Pauli A. T., and J. F. Branthaver, 1998, Relationship Between Asphaltenes, Heithaus Compatibility Parameters, and Asphalt Viscosity. *Petroleum Science and Technology*, 16(9&10): 1125-1147.

F1d-7 Pauli, A. T., and J. F. Branthaver, 1999, Rheological and Compositional Definitions of Compatibility as They Relate to the Colloidal Model of Asphalt and Residua. *American Chemical Society Division of Petroleum Chemistry Preprints*, 44: 190-193.

F1d-7 Redelius, P. G., 2000, Solubility Parameters and Bitumen. *Fuel*, 79: 27-35.

F1d-7 Robertson, R. E., J. F. Branthaver, P. M. Harnsberger, J. C. Petersen, S. M. Dorrence, J. F. McKay, T. F. Turner, A. T. Pauli, S.-C. Huang, J.-D. Huh, J. E. Tauer, K. P. Thomas, D. A. Netzel, F. P. Miknis, T. Williams, J. J. Duvall, F. A. Barbour, C. Wright, 2001, *Fundamental Properties of Asphalts and Modified Asphalts, Volume I: Interpretive Report*, FHWA-RD-99-212. U. S. Department of Transportation, Federal Highway Administration, McLean, VA.

F1d-7 Robertson, R. E., K. P. Thomas, P. M. Harnsberger, F. P. Miknis, T. F. Turner, J. F. Branthaver, S-C. Huang, A. T. Pauli, D. A. Netzel, T. M. Bomstad, M. J. Farrar, D. Sanchez, J. F. McKay, and M. McCann. "Fundamental Properties of Asphalts and Modified Asphalts II, Final Report, Volume I: Interpretive Report," Federal Highway Administration, Contract No. DTFH61-99C-00022, Chapters 5-7 submitted for publication, March 2006.

F1d-7 Robertson, R. E., K. P. Thomas, P. M. Harnsberger, F. P. Miknis, T. F. Turner, J. F. Branthaver, S-C. Huang, A. T. Pauli, D. A. Netzel, T. M. Bomstad, M. J. Farrar, J. F. McKay, and M. McCann. "Fundamental Properties of Asphalts and Modified Asphalts II, Final Report, Volume I: Interpretive Report," Federal Highway Administration, Contract No. DTFH61-99C-00022, Chapters 1-4 submitted for publication, November 2005.

F1d-7 Saal, R. N. J., W. Huekelom, and P. C. Blokker, 1939, Physical Constants of Asphaltic Bitumen Part 1. *Journal of the Institute of Petroleum*, 26: 29-39.

F1d-7 Schabron, J. F., A. T. Pauli, and J. F. Rovani Jr., 2001, Molecular Weight Polarity Map for Residua Pyrolysis. *Fuel*, 80: 529-537.

F1d-7 Sear, R. P., 2000, Phase Separation in Mixtures of Colloids and Long Ideal Polymer Coils. *Phys. Rev. Lett.*, 86(20): 4696-4699.

F1d-7 Sear, R. P., 2002, Interfacial Tension and Nucleation in Mixtures of Colloids and Long Ideal Polymer Coils. *Phys. Rev. E.*, 65, 062401-4.

F1d-7 Serdyukou, S. I., 2004, Generalization of the Evolution Criterion in Extended Irreversible Thermodynamics. *Physics Letters A*, 324: 262-271.

F1d-7 Sheu, E. Y., 2002, Petroleum Asphaltenes-Properties, Characterization, and Issues. *Energy & Fuel*, 16: 74-82.

F1d-7 Sheu, E., M. DeTar, and D. Storm, 1991, Rheological Properties of Vacuum Residue Fractions in Organic Solvents. *Fuel*, 70: 1151-1156.

F1d-7 Tissot, B. P., and D. H. Welte, 1978, *Petroleum Formation and Occurrence A New Approach to Oil and Gas Exploration*. Springer-Verlag, Berlin Heidelburg, Germany.

F1d-7 Turner, T. F., and J. F. Branthaver, 1997, DSC Studies of Asphalts and Asphalt Components. In *Asphalt Science and Technology*, A. M. Usmani, Ed., Marcel Dekker, Inc., New York, 59-101.

F1d-7 Wessling, B., 1995, Critical Shear Rate-The Instability Reason for the Creation of Dissipative Structures in Polymers. *Zeitschrift für Physikalische Chemie*, 191: S. 119-135.

F1d-7 Xu, H., R. Matkar and T. Kyu, 2005, Phase-field Modeling on Morphological Landscape of Isotactic Polystyrene Single Crystals. *Phys. Rev. E.*, 72, 011804.

F1d-7 Yen, T. F., and G. V. Chilingarian, 1994, *Asphaltenes and Asphalts 1. Developments in Petroleum Science, 40A*. Elsevier Science B. V., Copyright & Permissions Department, P. O. Box 521, 1000 AM Amsterdam, The Netherlands.

F1d-8 Carpenter, S. H., and S. Shen. A Dissipated Energy Approach to Study HMA Healing in Fatigue. 85th Annual Meeting of the Transportation Research Board, Washington D.C.

F1d-8 Kim, Y. R., D. N. Little, and R. L. Lytton, 2003, Fatigue and Healing Characterization of Asphalt Mixes. *Journal of Materials in Civil Engineering (ASCE)*, 15: 75-83.

F1d-8 Schapery, R. A., 1989, On the Mechanics of Crack Closing and Bonding in Linear Viscoelastic Media. *International Journal of Fracture*, 39: 163-189.

F1d-8 Wool, R. P., and K. M. O'Connor, 1981, A theory of crack healing in polymers. *Journal of Applied Physics*, 52(10): 5953-5963.

F2a Bhasin, A., and D. N. Little, 2006, Characterization of aggregate surface energy using the universal sorption device. *Journal of Materials in Civil Engineering (ASCE)*, Accepted for publication.

F2a Della Volpe, C., and S. Siboni, 2000, Acid base surface free energies of solids and the definition of scales in the Good van Oss Chaudhury theory. *Journal of Adhesion Science and Technology*, 14(2): 235-272.

F2a Hefer, A. W., A. Bhasin, and D. N. Little, 2006, Bitumen surface energy characterization using a contact angle approach. *Journal of Materials in Civil Engineering (ASCE)*, 18(6): 759-767.

F2a Huang, C. W., E. Masad, A. Muliana, and H. Bahia, 2007, Development and Numerical Implementation of a Nonlinear Viscoelastic Model for Hot Mix Asphalt. *Mechanics of Time Dependent Materials* (In Review).

F2a Little, D. N., and A. Bhasin, 2006, Using Surface Energy Measurements to Select Materials for Asphalt Pavement. *Final Report for Project 9-37*, Texas Transportation Institute.

F2a Masad, E., 2004, X-ray Computed Tomography of Aggregates and Asphalt Mixes. *Materials Evaluation Journal, American Society for Nondestructive Testing*, 62(7): 775-783.

F2a Masad, E., V. Castelo Branco, D. Little, and R. Lytton, 2007, A Unified Method for the Analysis of Controlled-Strain and Controlled-Stress Fatigue Testing. *International Journal of Pavement Engineering* (Accepted for Publication).

F2a Sharon, E., S. P. Gross, and J. Fineberg, 1996, Energy Dissipation in Dynamic Fracture. *Physical Review Letters*, 76(12): 2117-2120.

F2c Findley, W. N., J. S. Lai, and K. Onaran, 1989, *Creep and Relaxation of Nonlinear Viscoelastic Materials with an Introduction to Linear Viscoelasticity*. Dover Publication, Inc., Mineola, New York.

F2c Grasley, Z. C., 2007, "Analysis of the Viscoelastic Poisson's Ratio as Applied to Portland Cement Paste." Unpublished work.

F2d Masad, E., 2004, X-ray Computed Tomography of Aggregates and Asphalt Mixes. *Materials Evaluation Journal, American Society for Nondestructive Testing*, 62(7): 775-783.

F2d Song I., D. N. Little, E. Masad, and R. L. Lytton, 2005, Comprehensive Evaluation of Damage in Asphalt Mastics Using X-ray CT, Continuum Mechanics, and Micromechanics. *Journal of the Association of Asphalt Paving Technologists*, 74: 885-920.

F2d-1 Little, D. N., et al., 1994, Rheological and Rheo-Optical Characterization of Asphalt Cement and Evaluation of Relaxation Properties. Transportation Research Record: Journal of the Transportation Research Board, 1436: 71-82.

F2e Bahia, H. U., D. I. Hanson, M. Zeng, C. Zhai, M. A. Khatri, and M. Anderson, 2001, Characterization of Modified Asphalt Binders in Superpave Mix Design. NCHRP Report 459, Transportation Research Board, National Research Council, Washington DC, 2001.

F2e Chehab, G. R., Kim, Y. R., Schapery, R. A., Witczak, M. W., and Bonaquist, R., 2003, Characterization of Asphalt Concrete in Uniaxial Tension Using a Viscoelastoplastic Model, *J. Assoc. Asphalt Pavement Technology*, 72, 326–370.

F2e Kim, Y. R., D. N. Little, and R. L. Lytton, 2003, Fatigue and Healing Characterization of Asphalt Mixes. *Journal of Materials in Civil Engineering (ASCE)*, 15:75-83.

F2e Kim, Y. R., H. J. Lee, and D. N. Little, 1997, Fatigue Characterization of Asphalt Concrete Using Viscoelasticity and Continuum Damage Theory. *J. Assn. of Asphalt Paving Technologists*, 66: 520-569.

F2e Kutay, M. E., N. Gibson, and J. Youtcheff, 2007, "Conventional and Viscoelastic Continuum Damage (VECD) based Fatigue Analysis of Polymer Modified Asphalt Pavements," paper accepted for publication and presentation at 2008 AAPT Meeting, Philadelphia, Pennsylvania.

F2e Lee, H. J., J. S. Daniel, and Y. R. Kim, 2000, Continuum Damage Mechanics-Based Fatigue Model of Asphalt Concrete. *Journal of Materials in Civil Engineering*, Vol. 12, No. 2, May, 2000.

F3a ARA Inc., 2004, *Guide for mechanistic-empirical design*, Technical Report 1-37A, NCHRP.

F3a Bader, Richard F. W., 1990, *Atoms in Molecules*. Oxford University Press.

F3a Bentz, D. P., E. J. Garboczi, J. W. Bullard, C. F. Ferraris, and N. S. Martys, 2006, Virtual testing of cement and concrete, in *Significance of Tests and Properties of Concrete and Concrete-Making Materials*, Joseph Lamond and James Pielert, eds., ASTM STP 169D.

F3a Bullard, J. W., C. F. Ferraris, E. J. Garboczi, N. S. Martys, and P. A. Stutzman, 2004, Virtual Cement and Concrete, in *Innovations in Portland Cement Manufacturing*, Chapter 10.3, J. I. Bhatty, F. M. Miller and S. H. Kosmatka, eds., Portland Cement Association, pp. 1311-1331.

F3a Buttlar, W. G., D. Bozkurt, G. G. Al-Khateeb, and A. S. Waldhoff, 1999, Understanding asphalt mastic behavior through micromechanics. *Transp. Res. Rec.*, 1681: 157-1690.

F3a Cahn, J. W., 1965, Phase Separation of Spinodal Decomposition in Isotropic Systems. *J. Chem. Phys.*, 42 (1), 93-99.

F3a Cahn, J. W., and J. E. Hilliard, 1958, Free Energy of a Nonuniform System. I. Interfacial Free Energy. *J. Chem. Phys.*, 28 (2), 258-267.

F3a Cahn, J. W., and J. E. Hilliard, 1959a, Free Energy of a Nonuniform System. II. Thermodynamic Basis. *J. Chem. Phys.*, 30 (5), 1121-1124.

F3a Cahn, J. W., and J. E. Hilliard, 1959b, Free Energy of a Nonuniform System. III. Nucleation in a Two-Component Incompressible Fluid. *J. Chem. Phys.*, 31 (3), 688-699.

F3a Depondt, Ph., 2002, A One Dimensional Model of Friction at Nanometric Scale. *Surface Science*, 501: 112-124.

F3a Fu, Y. R., L. B. Wang, and M. Tumay, 2007, Quantification and Simulation of Particle Kinematics and Local Strains in Granular Materials Using X-ray Tomography Imaging and Discrete Element Method. *Journal of Engineering Mechanics*, In Press.

F3a Gao, H., 1996, A Theory of Local Limiting Speed in Dynamic Fracture. *Journal of the Mechanics and Physics of Solids*, 44: 1453-1474.

F3a Gao, H., 1997, Elastic Waves in a Hyperelastic Solid Near Its Plane Strain Equibiaxial Cohesive Limit. *Philosophical Magazine Letters*, 76: 307-314.

F3a Gao, H., and P. Klein, 1998, Numerical Simulation of Crack Growth in an Isotropic Solid with Randomized Internal Cohesive Bonds. *Journal of the Mechanics and Physics of Solids*, 46: 187-218.

F3a Glansdorff, P., and I. Prigogine, 1971, *Thermodynamic Theory of Structure, Stability and Fluctuations*, Wiley-Interscience, division of John Wiley & Sons, Ltd., London.

F3a Hveem, F. N., 1943, Quality Tests for Asphalts – A Progress Report. *Proc.*, Association of Asphalts Paving Technologists, 15: 111-152.

F3a Kennedy, T. W., G. A. Huber, E. T. Harrigan, R. J. Cominsky, C. S. Hughes, H. Von Quintus, and J. S. Moulthrop, 1994, SHRP-A-410, *Superior performing asphalt pavements (Superpave): The product of the SHRP Asphalt Research Program*, National Research Council, Washington, DC.

F3a Kim, Yong-Rak, and D. N. Little, 2004, Linear viscoelastic analysis of asphalt maltics. *J. Mater. Civ. E.*, 16: 122-132.

F3a Li, B., P. C. Clap, J. A. Rifkin, and X. M. Zhang, 2003, Molecular Dynamics Simulation of Stick-Slip. *Journal of Applied Mechanics*, 90 (6): 3090-3094.

F3a Liu, B., Y. Huang, H. Jiang, S. Qu, and K. C. Hwang, 2004a, The Atomic Scale Finite Element Method. *Computer Methods in Applied Mechanics and Engineering*, 193: 1849-1864.

F3a Liu, W., E. G. Karpov, S. Zhang, and H. S. Park, 2004b, An Introduction to Computational Nanomechanics and Materials. *Computational Methods in Applied Mechanics and Engineering*, 193: 1529-1578.

F3a Martys, N., 2005, Study of a dissipative particle dynamics based approach for modeling suspensions. *J. Rheol.*, 49: 401-424.

F3a Masson, J. F., P. Collins, G. Robertson, J. R. Woods, and J. Margeson, 2003, Thermodynamics, phase diagrams, and stability of bitumen–polymer blends. *Energy Fuels*, 17: 714-724.

F3a Mehta, R., W Keawwattana, A. L. Guenthner, and T. Kyu, 2004b, Role of Curvature Elasticity in Sectorization and Ripple Formation During Melt Crystallization of Polymer Single Crystals. *Phys. Rev. E.*, 69, 061802.

F3a Mehta, R., W Keawwattana, and T. Kyu, 2004a, Growth Dynamics of Isotactic Polypropylene Single Crystals During Isothermal Crystallization from a Miscible Polymeric Solvent. *J. Chem. Phys.*, 120(8): 4024-4031.

F3a Pal, R., and E. Rhodes, 1989, Viscosity/Concentration Relationships for Emulsions. *Journal of Rheology*, 33(7): 1021-1045.

F3a Petersen, J. C., R. E. Robertson, J. F. Branthaver, P. M. Harnsberger, J. J. Duvall, S. S. Kim, D. A. Anderson, D. W. Christensen, H. U. Bahia, 1994, SHRP-A-367, *Binder Characterization and Evaluation, Volume 1*. Strategic Highway Research Program, National Research Council, Washington, DC.

F3a Redelius, Per, 2004, Bitumen solubility model using Hansen solubility parameter. *Energy Fuels*, 18: 1087-1092.

F3a Roberts, A. P., and E. J. Garboczi, 2002, Computation of the linear elastic properties of random porous materials with a wide variety of microstructure. *Proc. Royal Soc. London*, A458: 1033-1054.

F3a Robertson, R. E., J. F. Branthaver, P. M. Harnsberger, J. C. Petersen, S. M. Dorrence, J. F. McKay, T. F. Turner, A. T. Pauli, S.-C. Huang, J.-D. Huh, J. E. Tauer, K. P. Thomas, D. A. Netzel, F. P. Miknis, T. Williams, J. J. Duvall, F. A. Barbour, C. Wright, 2001, *Fundamental Properties of Asphalts and Modified Asphalts, Volume I: Interpretive Report*, FHWA-RD-99-212. U. S. Department of Transportation, Federal Highway Administration, McLean, VA.

F3a Sadd, Martin H., 2005, *Elasticity Theory, Applications, and Numerics*, Burlington, MA: Elsevier.

F3a Sadd, Martin H., Qingli Dai, Venkitanarayanan Parameswaran, and Arun Shukla, 2004, Microstructural simulation of asphalt materials: Modeling and experimental studies. *J. Mater. Civ. E.*, 16: 107–115.

F3a Shenoy, A., 2002, Model-fitting the master curves of the dynamic shear rheometer data to extract a rut controlling term for asphalt pavements. *J. Testing Eval.*, 30, 95-102.

F3a Sims, J. S, and N. Martys, 2004, Simulation of Sheared Suspensions with a Parallel Implementation of QDPD. *Journal of Research of the National Institute of Standards and Technology*, 109: 267.

F3a Ulm, F.-J., 2003, Chemomechanics of concrete at finer scales, *Mater. Struct.*, 36: 426–438.

F3a Wang, L. B., B. Zhang, D. Wang, and Z. Q. Yue, 2007c, Fundamental Mechanics of Asphalt Compaction Through FEM and DEM Modeling. *ASCE GSP* 176, pp. 45-63.

F3a Wang, L. B., J. Y. Park, and Y. R. Fu, 2007b, Representation of Real Particles for DEM Simulation using X-ray Tomography. *Journal of Construction and Building Materials*, 21(2): 338-348.

F3a Wang, X., and L. B. Wang, 2006, Continuous Interface Elements Subject to Large Shear Deformations. *International Journal of Geomechanics*, 6(2): 97-107.

F3a Wang, Y. P., L. B. Wang, Q. B. Li, and T. P. Harman, 2007a, Noninvasive Measurement of 3D Permanent Strains In Asphalt Concrete Using X-Ray Tomography Imaging. *Transportation Research Record* (TRR), In Press.

F3a Wiehe, I. A., and K. S. Liang, 1996, Asphaltenes, resins, and other petroleum macromolecules. *Fluid Phase Equil.*, 117: 201-210.

F3a Wolverton, C., 2000, First-principles theory of 250,000-atom coherent alloy microstructure. *Modelling Simul. Mater. Sci. Eng.*, 8: 323-333.

F3a Zhang, B., and L. B. Wang, 2007, Digital Simple Performance Test of Asphalt Concrete. *Proc.*, 7th International Conference of Chinese Transportation Professionals, May 20-21, 2007, Shanghai, China, pp. 98-107.

F3a Zhang, Liqun, and Michael L. Greenfield, 2007a, Molecular orientation in model asphalts using molecular simulation. *Energy Fuels*, 26: 5461-5472.

F3a Zhang, Liqun, and Michael L. Greenfield, 2007b, Relaxation time, diffusion, and viscosity analysis of model asphalt systems using molecular simulation. *J. Chem. Phys.*, 127: 194502.

F3b Espinosa, H. D., and P. D. Zavattieri, 2003, A Grain Level Model for the Study of Failure Initiation and Evolution in Polycrystalline Brittle Materials. Part I: Theory and Numerical Implementation. *Mechanics of Materials*, 35: 333-364.

F3b Geubelle, P. H., and J. Baylor, 1998, The Impact-Induced Delamination of Laminated Composites: A 2D Simulation. *Composites, Part B*, 29B: 589-602.

F3b Kim, Y., D. H. Allen, and D. N. Little, "Damage Modeling of Asphalt Concrete Mixtures through Computational Micromechanics and Cohesive Zone Fracture." In review, submitted in 2008, *Journal of the Association of Asphalt Paving Technologists*, AAPT.

F3b Kim, Y., D. N. Little, and R. L. Lytton, 2002, Use of Dynamic Mechanical Analysis (DMA) to Evaluate the Fatigue and Healing Potential of Asphalt Binders in Sand Asphalt Mixtures. *Journal of Association of Asphalt Paving Technologists*, AAPT, 71, 176-206.

F3b Kim, Y., D. N. Little, and R. L. Lytton, 2003, Fatigue and Healing Characterization of Asphalt Mixtures. *Journal of Materials in Civil Engineering*, ASCE, 15(1), 75-83.

F3b Kim, Y., H. J. Lee, D. N. Little, and Y. R. Kim, 2006, A Simple Testing Method to Evaluate Fatigue Fracture and Damage Performance of Asphalt Mixtures. *Journal of the Association of Asphalt Paving Technologists*, AAPT, 75, 755-787.

F3b Xu, X. P. and A. Needleman, 1993, Void Nucleation by Inclusion Debonding in a Crystal Matrix. *Modelling and Simulation in Materials Science and Engineering*, 1: 111-132.

F3b Xu, X. P. and A. Needleman, 1994, A Numerical Simulations of Fast Crack Growth in Brittle Solids. *Journal of the Mechanics and Physics of Solids*, 42(9): 1397-1434.

F3b-1 Allen, D. H. and C. R. Searcy, 2000, Numerical Aspects of a Micromechanical Model of a Cohesive Zone. *Journal of Reinforced Plastics and Composites*, 19(3): 240-248.

F3b-1 Allen, D. H. and C. R. Searcy, 2001a, A Micromechanical Model for a Viscoelastic Cohesive Zone. *International Journal of Fracture*, 107: 159-176.

F3b-1 Allen, D. H. and C. R. Searcy, 2001b, A Micromechanically Based Model for Predicting Dynamic Damage Evolution in Ductile Polymers. *Mechanics of Materials*, 33: 177-184.

F3b-1 Barenblatt, G. I., 1962, Mathematical Theory of Equilibrium Cracks in Brittle Fracture. *Advances in Applied Mechanics*, v.7, p. 55-129, Academic Press, New York.

F3b-1 Constanzo, F., and D. H. Allen, 1993, A Continuum Mechanics Approach to Some Problems in Subcritical Crack Propagation. *International Journal of Fracture*, 63: 27-57.

F3b-1 Dugdale, D., 1960, Yielding of Steel Sheets Containing Slits". *Journal of Mechanics and Physics of Solids*, 8: 100-104.

F3b-1 Foulk, J. W., 1997, "A Model for Predicting the Damage and Oxidation Dependent Life of SCS-6/TI-β21S$[O]_4$ Metal Matrix Composite". Master´s Thesis, Texas A&M University, College Station, TX.

F3b-1 Frost, N. E., and J. R. Dixon, 1967, A Theory of Fatigue Crack Growth. *International Journal of Fracture Mechanics*, 3(4): 301-316.

F3b-1 Griffith, A. A., 1921, The Phenomena of Rupture and Flow in Solids. *Philosophical Transactions of the Royal Society of London*, Series A 221, p. 163-198.

F3b-1 Jeng, Y. S. and J. D. Perng, 1991, Analysis of Crack Propagation in Asphalt Concrete Using Cohesive Crack Model. *Transportation Research Record*, 1317: 90-99.

F3b-1 Knauss, W. G., 1969, Stable and Unstable Crack Growth in Viscoelastic Media. *Transaction of the Society of Reology*, 13:3, 291-313.

F3b-1 Knauss, W. G., 1970, Delayed Failure - The Griffith Problem for Linearly Viscoelastic Materials. *International Journal of Fracture Mechanics*, 1: 7-20.

F3b-1 Needleman, A., 1987, A Continuum Model for Void Nucleation by Inclusion Debonding. *Journal of Applied Mechanics*, 54: 525-531.

F3b-1 Paris, P. C., and Erdogan, F., 1963, A Critical Analysis of Crack Propagation Laws. *Journal of Basic Engineering*, 85: 528-534.

F3b-1 Schapery, R. A., 1975a, A Theory of Crack Initiation and Growth in Viscoelastic Media; Part I: Theoretical Development. *International Journal of Fracture*, 11(1):141-159.

F3b-1 Schapery, R. A., 1975b, A Theory of Crack Initiation and Growth in Viscoelastic Media; Part II: Approximate Methods of Analysis. *International Journal of Fracture*, 11(3): 369-387.

F3b-1 Schapery, R. A., 1975c, A Theory of Crack Initiation and Growth in Viscoelastic Media; Part III: Analysis of Continuous Growth. *International Journal of Fracture*, 11(4): 549-562.

F3b-1 Tvergaard, V., 1990, Effect of Fiber Debonding in a Whisker-Reinforced Metal. *Materials Science & Engineering A: Structural Materials: Properties, Microstructure, and Processing*, A125(2): 203-213.

F3b-1 Yoon, C., and D. H. Allen, 1999, Damage Dependent Constitutive Behavior and Energy Release Rate for a Cohesive Zone in a Thermoviscoelastic Solid. *International Journal of Fracture*, 96: 56-74.

F3c Masad, E., V. Castelo Branco, D. Little, and R. Lytton, 2007, A Unified Method for the Analysis of Controlled-Strain and Controlled-Stress Fatigue Testing. *International Journal of Pavement Engineering* (accepted for publication).

E1a Findley, W. N., J. S. Lai, and K. Onaran, 1989, *Creep and Relaxation of Nonlinear Viscoelastic Materials with an Introduction to Linear Viscoelasticity*. Dover Publication, Inc., Mineola, New York.

E1a Grasley, Z. C., 2007, "Analysis of the Viscoelastic Poisson's Ratio as Applied to Portland Cement Paste." Unpublished work.

E1a Grasley, Zachary C., and David A. Lange, 2007, "Constitutive Modeling of the Aging Viscoelastic Properties of Portland Cement Paste." Mechanics of time-Dependent Materials, Springer Science, accepted for publication.

E1b-1 Bellenger E., and P. Bussy, 2001, Phenomenological Modeling and Numerical Simulation of Different Modes of Creep Damage Evolution. *International Journal of Solids and Structures*, 38: 577-604.

E1b-1 Delgadillo R., 2007, "Nonlinearity of Asphalt Binders and The Relationship with Asphalt Mixture Permanent Deformation," A preliminary document submitted in partial fulfillment of the requirement for the degree of Doctor of Philosophy (Civil and Environmental Engineering) at the University of Wisconsin – Madison, 2007.

E1b-1 Delgadillo R., D. W. Cho and H. U. Bahia, 2006, Non Linearity of Repeated Creep and Recovery Binder Test and the Relationship with Mixture Permanent Deformation. In *Transportation Research Record: Journal of the Transportation Research Board*, No.1962, TRB, National Research Council, Washington, DC, 2006, pp. 3-11.

E1b-1 Hudson, S. W., and S. B. Seeds, 1988, Evaluation of Increased Pavement Loading and Tire Pressures. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1207, TRB, Washington DC, pp. 197-206.

E1b-1 Kose, S., 2001, Development of a Virtual Test Procedure for Asphalt Concrete, PhD Thesis, UW Madison.

E1b-1 Lakes, R., 1999, *Viscoelastic Solids*. CRC Press.

E1b-1 Masad, E., N. Somevadan, H. U. Bahia, and S. Kose, 2001, Modeling and Experimental Measurements of Strain Distribution in Asphalt Mixes. *Journal of Transportation Engineering*, 127(6): 477-485.

E1b-1 Saadeh, S., E. Masad, and D. Little, 2007, Characterization of Asphalt Mix Response under Repeated Loading Using Anisotropic Nonlinear Viscoelastic-Viscoplastic Model. *Journal of Materials in Civil Engineering*, ASCE, October 1, 2007, 19(10): 912-924.

E1b-2 Ashby, M. F., and D. R. H. Jones, 1995, *Engineering Materials 1*. Butterworth-Heinemann, 306 pp.

E1b-2 Beake, B., 2006, Modelling indentation creep of polymers: a phenomenological approach. *J. Phys. D: Appl. Phys*. 39: 4478–4485.

E1b-2 Cook, R. F., and M. L. Oyen, 2007, Nanoindentation behavior and mechanical properties measurements of polymeric material. *Int. J. Mat. Res*., 98: 5-14.

E1b-2 Li, X., and B. Bhushan, 2002, A review of nanoindentation continuous stiffness measurement technique and its applications. *Materials Characterization*, 48: 11–36.

E1b-2 Lin, D. C., E. K. Dimitriadis, and F. Horkay, 2006, Advances in the mechanical characterization of soft materials by nanoindentation. *Recent Res. Devel. Biophys*., 5, 38 pages. ISBN: 81-7895-215-7.

E1b-2 McGennis, R. B., S. Shuler, and H. U. Bahia, 1994, *Background of SUPERPAVE Asphalt Binder Test Methods*. Federal Highway Administration Report No. FHWA-SA-94-069.

E1b-2 Nanoindentation, 2008, URL: http://www.nanoindentation.cornell.edu/home_main.htm. Accessed on June 10, 2008.

E1b-2 Oyen, M. L., 2006, Nanoindentation hardness of mineralized tissues. Short communication. *Journal of Biomechanics*, 39: 2699–2702.

E1b-2 Oyen, M. L., and C.-C. Ko, 2007, Examination of local variations in viscous, elastic, and plastic indentation responses in healing bone. *J. Mater Sci: Mater Med*., 18: 623–628.

E1b-2 Pichler, C., A. Jäger, R. Lackner, and J. Eberhardsteiner, 2005, "Identification of Material Properties from Nanoindentation: Application to Bitumen and Cement Paste." 22nd Danubia Adria Symposium on Experimental Methods in Solid Mechanics, Sept. 28-Oct. 1, 2005, Moniticelli Terme, Parma, Italy.

E1b-2 Roberts, F. L., P. S. Kandhal, E. R. Brown, D.-T. Lee, and T. W. Kennedy, 1996, *Hot Mix Asphalt Materials, Mixtures, and Construction*. National Asphalt Pavement Association – Research and Education Foundation, Lanham, MD, 585 pp.

E1c-1 Bahia, H., D. Hanson, M. Zeng, H. Zhai, M. A. Khatiri, and R. M. Anderson, 2001, Characterization of Modified Binders in SuperPave Mix Design. NCHRP Report No. 459. Transportation Research Boards, Asphalt Institute.

E1c-1 Faheem, A, H. Bahia, and H. Ajideh, 2005, Estimating Results of a Proposed Simple Performance Test for Hot-Mix Asphalt from SuperPave Gyratory Compactor Results. WisDOT Study 0092-01-02, Wisconsin Department of Transportation, Madison, WI.

E1c-1 Hurley, G., and B. Prowell, 2005, "Evaluation of Aspha-min Zeolite for use in Warm Mix Asphalt." National Center for Asphalt Technology, Auburn University, 277 Technology Parkway, Auburn, AL, June 2005.

E1c-1 Hurley, G., and B. Prowell, 2005, "Evaluation of Sasobit for use in Warm Mix Asphalt." National Center for Asphalt Technology, Auburn University, 277 Technology Parkway, Auburn, AL, June 2005.

E1c-1 Hurley, G., and B. Prowell, 2006, Evaluation of Potential Processes for Warm Mix Asphalt. *Journal of the Association of Asphalt Paving Technologists*, Vol. 75. Association of Asphalt Paving Technologists, Savannah, GA. 2006.

E1c-1 Kanitpong, K., S. Sonthong, K. Nam, W. Martono, and H. Bahia, 2007, Laboratory Study on Warm Mix Asphalt Additives. *Transportation Research Record, Journal of the Transportation Research Board*. Transportation Research Board 2007. Taken from the Annual Meeting CD ROM.

E1c-1 Macosko, C. W., 1994, *Rheology: principles, measurements, and applications*. VCH: New York, p xviii, 550 p.

E1c-1 Mahmoud, A. F., and H. Bahia, 2004, *Using the Gyratory Compactor to Measure Mechanical Stability of Asphalt Mixtures*. Report WHRP 05-02, Wisconsin Highway Research Program.

E1c-1 Mahmoud, A. F., and H. Bahia, 2004, Using the Gyratory Compactor to Measure Mechanical Stability of Asphalt Mixtures. Report WHRP 05-02. Wisconsin Highway Research Program.

E1c-1 NCHRP Report 530, "Evaluation of Indirect Tensile Test (IDT) Procedures for Low Temperature Performance of Hot Mix Asphalt," Transportation Research Board, National Research Council, Washington, DC, 2004.

E1c-1 Patrick, J., and H. Arampamoorthy, 2007, Quantifying the Benefits of Waste Minimisation. Report prepared by OPUS Engineering Consultants, Land Transport New Zealand.

E1c-1 Wen, H., and R. Y. Kim, 2002, Simple Performance Test for Fatigue Cracking and Validation with WesTrack Mixtures. *Transportation Research Record 1789*, Paper No. 02-2924, Transportation Research Board.

E1c-2 Asphalt Institute, 1989, *Asphalt Cold Mix Manual*, Asphalt Institute, Lexington, KY.

E1c-2 ASTM D3628, 2006, Selection and Use of Emulsified Asphalts. *Annual Book of ASTM Standards*, American Society for Testing and Materials, Philadelphia, PA.

E1c-2 ASTM D4867, Standard Test Method for Effect of Moisture on Asphalt Concrete Paving Mixtures. *Annual Book of ASTM Standards*, Vol. 04.03, American Society for Testing and Materials, Philadelphia, PA.

E1c-2 ASTM D7196, Standard Test Method for Raveling of Col Mixed Bituminous Emulsion Samples. *Annual Book of ASTM Standards*, 2006, American Society for Testing and Materials, Philadelphia, PA.

E1c-2 Jenkins, K. J., A. A. A. Molenaar, J. L. A. de Groot, and M. F. C. van de Ven, 2002, Foamed Asphalt Produced Using Warmed Aggregates. Presented at the Association of Asphalt Paving Technologists, March 18-20, 2002, Colorado Springs, Colorado.

E1c-2 Kucharek, A., 2007, "Measuring the Curing Characteristics of Chip Sealing Emulsions." Presentation in the Joint ARRA-ISSA-AEMA Meeting, Bonita Springs, CA, 2007. Asphalt Emulsion Manufactures Association and McAsphalt, Scarborough, Ontario, 2007.

E1c-2 Patrick, J., and H. Arampamoorthy, 2007, Quantifying the Benefits of Waste Minimisation. Report prepared by OPUS Engineering Consultants, Land Transport New Zealand.

E2a Alexander, S. H., 1973, "Method of Treating Asphalt," U.S. Patent #3,751,278, 1973.

E2a Belgian Road Research Center, 1991, BRRC Experimental Procedure, MF 65/91, Brussels.

E2a Burke R.E., and C. H. Whitacre, 1939, "Manufacture of Improved Asphalts", U.S. Patent, # 2,179,208.

E2a De Filippis, P., C. Giavarini, and M. Scarsella, 1995, Improving the aging resistance of straight-run bitumens by addition of phosphorus compounds. *Fuel*, 74(6): 836-841.

E2a De Filippis, P., C. Giavarini, and M. Scarsella, 1996, An Integrated Process for Stabilization and Upgrading of Residues and Bitumens. *Fuel Science and Technology Int'l*, 14(6): 821-838.

E2a Giavarini, C., D. Mastrofini, and M. Scarsella, 2000, Macrostructure and Rheological Properties of Chemically Modified Residues and Bitumens. *Energy & Fuels*, 14: 495-502.

E2a Orange, G., D. Dupuis, J. V. Martin, F. Farcas, C. Such, and B. Marcant, 2004a, Chemical Modification of Bitumen through Polyphosphoric Acid: Properties – Microstructure Relationship. *Proc.*, 3rd Eurasphalt Eurobitume Congress, Book I, Vienna, Austria, pp. 733-745.

E2a Orange, G., J. V. Martin, A. Menapace, M. Hemsley, and G. L. Baumgardner, 2004b, Rutting and Moisture Resistance of Asphalt Mixtures Containing Polymer and Polyphosphoric Acid Modified Bitumen. *Road Materials and Pavement Design*, 5(3): 323-354.

E2b Bautista, E.G., S. Mangiafico, and H.U. Bahia, 2009, Evaluation of Rheological Properties of Binders in RAP Without Extraction and Recovery. Paper submitted for presentation and publication at the Transportation Research Board 88th Annual Meeting, January 11-15, 2009, Washington, D.C.

E2b Bonaquist, R., 2007, Can I Run More RAP? National Asphalt Pavement Association. *HMAT*, 2(5).

E2b Carter, A., and M. Stroup-Gardiner, 2007, Indirect Tension Relaxation Test to Evaluate the Effect of the Addition of RAP to HMA Mixes. American Society of Civil Engineers. *Journal of Materials in Civil Engineering*, 19(3).

E2b Hajj, E.Y., P.E. Sebaaly, and R. Shrestha, 2007, A Laboratory Evaluation on the Use of Recycled Asphalt Pavements in HMA Mixtures. Western Regional Superpave Center, University of Nevada, Reno, Final Report.

E2b Huang, B., G. Li, D. Vukosavljevic, X. Shu, and B. Egan, 2005, Laboratory Investigation of Mixing Hot-Mix Asphalt with Reclaimed Asphalt Pavement. Transportation Research Record, *Journal of the Transportation Research Board No. 1929*.

E2b Kennedy, T., W. Tam, and M. Solaimanian, 1998, Effect of Reclaimed Asphalt Pavement on Binder Properties Using the Superpave System. Center for Transportation Research, The University of Texas at Austin. FHWA/TX-98/1250-1.

E2b McDaniel R., and T. Nantung, 2005, Research Pays Off: Designing Superpave Mixes with Locally Reclaimed Asphalt Pavement: North Central States Jointly Fund Study. Transportation Research Board, TR News No. 239.

E2b McDaniel, R., A. Shah, G. Huber, and V. Gallivan, 2007, Investigation of Properties of Plant-Produced RAP Mixtures. Transportation Research Board 86th Annual Meeting.

E2b McDaniel, R., G. Huber, and V. Gallivan, 2006, Conserving Resources and Quality with High RAP Content Mixes. National Asphalt Pavement Association. *HMAT*, 11(6).

E2b National Asphalt Pavement Association, 2007, Designing HMA Mixtures with High RAP Content: A Practical Guide.

E2b National Asphalt Pavement Association, 2007, Recycling Hot-Mix Asphalt Pavements.

E2b National Cooperative Highway Research Program, 2001, Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method: Technician's Manual, Transportation Research Board, Report 452.

E2b Sargious, M., and N. Mushule, 1991, Behaviour of Recycled Asphalt Pavement at Low Temperatures. Ottawa Canada National Research Council. *Canadian Journal of Civil Engineering*, Vol. XVIII No. III.

E2b Schreck, R., 2007, More RAP in HMA: Is it Worth It? The 2007 Virginia RAP Initiative. National Asphalt Pavement Association. *HMAT*, 12(4).

E2b Sebaaly, P.E., and R. Shrestha, 2004, A Literature Review on the Use of Recycled Asphalt Pavements in HMA Mixtures. Western Regional Superpave Center, University of Nevada, Reno, Final Report.

E2b Shen, J., and J.A. Miller, 2007, Effects of Rejuvenating Agents on Superpave Mixtures Containing Reclaimed Asphalt Pavement. American Society of Civil Engineers. *Journal of Materials in Civil Engineering*, 19(5).

E2b Sondag, M. S., 2000, Investigation of Recycled Asphalt Pavement Mixtures. University of Minnesota, Final Report.

E2b Stroup-Gardiner, M., and C. Wagner, 1999, Use of RAP in Superpave HMA Applications. T*ransportation Research Record 1681*, pp. 1-9.

E2b Vukosavljevic, D., 2006, Fatigue Characteristics of Field HMA Surface Mixtures Containing Recycled Asphalt Pavement (RAP). Thesis (M.S.) – University of Tennessee, Knoxville.

E2b Zofka, A., M. Marasteanu, X. Li, T. Clyne, and J. McGraw, 2005, Simple Method to Obtain Asphalt Binders Low Temperature Properties from Asphalt Mixtures Properties. *Journal of the Association of Asphalt Paving Technologists*, vol. 74.

E2c-1 Gillespie, T. D., 1992, *Fundamentals of Vehicle Dynamics*, Textbook, ISBN 1-56091-199-9.

E2c-1 Gillespie, T. D., and L. Balderas, 1987, An Analytical Comparison of the Dynamic Performance of a European Heavy Vehicle and a Generic U.S. Heavy Vehicle. The University of Michigan Transportation Research Institute, Report No. UMTRI-87-17.

E2c-1 Hajj, E. Y., 2005, "Hot Mix Asphalt Mixtures for Nevada's Intersections," Dissertation, University of Nevada, Reno.

E2c-1 Wong, J. Y., 1993, *Theory of Ground Vehicles*, Second Edition, Textbook, ISBN 0-471-52496-4, Department of Mechanical and Aerospace Engineering Carleton University, Ottawa, Canada.

E2d Bonemazi, E., V. Braga, R. Corrieri, C. Giavarini, and F. Sartori, 1996, Characteristics of Polymers and Polymer-Modified Binders. *Transportation Research Record 1535*: 36-47.

E2d Brandrup, J., and E. H. Immergut, 1975, *Polymer Handbook*.

E2d Coons, R. F., and P. H. Wright, 1968, An Investigation of the Hardening of Asphalt Recovered from Pavements of Various Ages. *Proc.,* Association of Asphalt Paving Technologists, 37: 510.

E2d Glover, C. J., R. R. Davison, C. H. Domke, Y. Ruan, P. Juristyarini, D. B. Knorr, and S. H. Jung, 2005, Development of a New Method for Assessing Asphalt Binder Durability with Field Validation. Report FHWA/TX-03/1872-2, Texas Transportation Institute, College Station, TX.

E2d Mamlouk, M. S., Witczak, M. W., Kaloush, K. E., and Hasan, N., 2005, Determination of Thermal Properties of Asphalt Mixtures. *Journal of Testing and Evaluation*, March 2005, 33(2).

E2d Odian, G., 1991, *Principles of Polymerization*. New York/Chichester/Brisbane/Toronto/ Singapore, John Willey & Sons, Inc.

E2d Ojo, J. O., D. Fratta, H. U. Bahia, C. Daranga, and M. Marasteanu, 2008, "Thermo-Volumetric Properties of Asphalt Binders and Mixtures". 6th RILEM International Conference on Cracking in Pavements (accepted for publication - refereed).

VP2a Ames Engineering, 2007, Company Web Site. URL: http://www.amesengineering.com/amestexturescanner.html. Accessed Nov. 2007.

VP2a ASTM, 2008, E 1050–07 Standard test method for impedance and absorption of acoustical materials using a tube, two microphones and a digital frequency analysis system. American Society of Testing and Materials. West Conshohocken, PA.

VP2a Bernhard, R. J., and R. L. Wayson, 2005, An Introduction to Tire/Pavement Noise. SQDH 2005-1 HL 2005-2. URL: http://meweb.ecn.purdue.edu/~sqdh/ (Accessed November 2007).

VP2a Brown, E. R., P. S. Kandhal, and J. Zhang, 2001, *Performance Testing for Hot Mix Asphalt*. NCAT Report 01-05, National Center for Asphalt Technology, Auburn University, AL.

VP2a Brown, E. R., P. S. Kandhal, and J. Zhang, 2001, *Performance Testing for Hot Mix Asphalt*. NCAT Report 01-05, National Center for Asphalt Technology, Auburn University, AL.

VP2a Chung, J. Y., and D. A. Blaser, 1980, Transfer function method of measuring acoustic intensity in a duct system with flow. *Journal of Acoustic Society of America*, 68(6): 1570-1577.

VP2a Crocker, M. J., D. Hanson, Z. Li, R. Karjatkar, and K. S. Vissamraju, 2004, Measurement of Acoustical and Mechanical Properties of Porous Road Surfaces and Tire and Road Noise. Transportation Research Record. 1891: 16-22.

VP2a Danish Road Institute, 2005, *Noise reducing pavements in Japan - study tour report*. DRI-DWW Noise Abatement Program Road and Hydraulic Engineering Institute, 68 pages.

VP2a Gibbs, D. C., R. H. Iwasaki, R. J. Bernhard, J. F. Bledsoe, D. D. Carlson, C. Corbisier, F. W. Fults, T. M. Hearne, Jr., K. W. McMullen, D. E. Newcomb, J. H. Roberts, J. L. Rochat, L. A. Scofield, and M. E. Swanlund, 2007, "Quiet Pavement Systems in Europe". FHWA Report. URL: http://international.fhwa.dot.gov/quiet_pav/index.htm

VP2a Guisik, K., and H. U. Bahia, 2004, "Incorporating Road Safety into Pavement Management". MRUTC 04-04 Technical Report.

VP2a Hanson, D. I., and B. D. Prowell, 2004, "Evaluation of Circular Texture for Measuring surface Texture of Pavements." NCAT Report 04-05. National Center for Asphalt Technology, Auburn University, Auburn, AL.

VP2a Hanson, D. I., R. S. James, and C. NeSmith, 2004, "Tire/Pavement Noise Study". NCAT Report 04-02, National Center for Asphalt Technology, Auburn University, AL.

VP2a Jones, W., 2005, A Quiet Pavement – Coming to Highway Near You. *Asphalt*, Summer 2005, pp. 24-25.

VP2a Liu, Y., T. F. Fwa, and Y. S. Choo, 2003, Finite-Element Modeling of Skid Resistance Test. *Journal of Transportation Engineering*, 129(3), 316-321.

VP2a Newcomb, D. and L. Scofield, 2004, Quiet Pavement Raise the Roof in Europe. *Hot Mix Asphalt Technology*, September/October 2004, 22-28.

VP2a Noyce, D. A., H. U. Bahia, J. Yambo, J. Chapman, and A. Bill, 2007, Incorporating Road Safety into Pavement Management: Maximizing Surface Friction for Road Safety Improvements. MRUTC Project 04-04, 241 pages.

VP2a Santamarina, J. C., and D. Fratta, 2005, *Discrete Signals and Inverse Problems: An Introduction for Engineers and Scientists*. John Wiley and Sons, Chichester, UK.

V3a Bahia, H. U., D. I. Hanson, M. Zeng, H. Zhai, M. A. Khatri, and R. M. Anderson, 2001, *Characterization of Modified Asphalt Binders in Superpave Mix Design*. Publication NCHRP 459, National Academy Press, Washington, D.C.

V3a Bahia, H., Delgadillo, A. Motamed, and D. Christensen, "Performance of Modified Asphalt Binder and Mixtures under Increased Truck Loading Limits," Accepted at the Fourth International Gulf Conference on Roads, Qatar, November 2008.

V3a Christensen, D., R. Delgadillo, H. Bahia, and R. McQueen, 2007, AAPTP Project 04-01-PG Binder Grade Selection for Airfield Pavements, Draft Final Report, November 2007.

V3a D'Angelo, J. Development of Standard Practice for Superpave Plus Specifications. Presented at the NEAUPG 2005 meeting.

V3a D'Angelo, J., 2005, Development of Standard Practice for Superpave Plus Specifications. Presented at the NEAUPG 2005 meeting.

V3a D'Angelo, J., R. Kluttz, R. Dongré, K. Stephens, and L. Zandotto, 2007, Revisions of the Superpave High Temperature Binder Specification: The Multiple Stress Creep and Recovery Test. *Proc.*, Association of Asphalt Paving Technologists, 2007 meeting, San Antonio, Texas.

V3a Delgadillo, R., D-W Cho and H. Bahia, 2006, Non Linearity of Repeated Creep and Recovery Binder Test and the Relationship With Mixture Permanent Deformation. In *Transportation Research Records: Journal of the Transportation Research Board*, No 1962, TRB, National Research Council, Washington DC, pp. 3-11.

V3a Delgadillo, R., D-W Cho, and H. Bahia, 2006, Non Linearity of Repeated Creep and Recovery Binder Test and the Relationship With Mixture Permanent Deformation. *Transportation Research Records: Journal of the Transportation Research Board*, No 1962, TRB, National Research Council, Washington DC, pp. 3 – 11.

V3a Drakos, C., R. Roque, and B. Birgisson, 2001, Effect of Measured Tire Contact Stresses on Near-Surface Rutting. *Transportation Research Record: Journal of the Transportation Research Board*, No.1764, TRB, National Research Council, Washington, D.C., pp. 59 – 69.

V3a Drakos, C., R. Roque, and B. Birgisson, 2001, Effect of Measured Tire Contact Stresses on Near-Surface Rutting. In *Transportation Research Record: Journal of the Transportation Research Board*, No.1764, TRB, National Research Council, Washington, D.C., pp. 59-69.

V3a Hesp, S.A.M., 2003, An Improved Low-Temperature Asphalt Binder Specification Method. Final Report, NCHRP-IDEA Contract 84 and Ministry of Transportation Ontario Contract 9015-A-000190, December 2003.

V3a Masad, E., N. Somevadan, H. U. Bahia, and S. Kose, 2001, Modeling and Experimental Measurements of Strain Distribution in Asphalt Mixes. *Journal of Transportation Engineering*, 127 (6), Nov/Dec. 2001, pp. 477 – 485.

V3a Performance Graded Specifications & Test Method Tolerances. Combined State Binder Group (Iowa, Michigan, Minnesota, North Dakota, South Dakota & Wisconsin DOTs & Nebraska DOR), January 2006.

V3a Performance Graded Specifications & Test Method Tolerances. Combined State Binder Group (Iowa, Michigan, Minnesota, North Dakota, South Dakota & Wisconsin DOTs & Nebraska DOR), January 2006.

V3a Reinke G., S. Glidden, S. Engber, and D. Herlitzka, 2005, Properties of Polymer Modified Bitumens Related to Mixture Resistance to Permanent Deformation. Presented at 4th Mexican Asphalt Congress. August 24-26, 2005, Guadalajara, Mexico.

V3a Reinke G., S. Glidden, S. Engber, and D. Herlitzka, 2005, Properties of Polymer Modified Bitumens Related to Mixture Resistance to Permanent Deformation. Presented at 4th Mexican Asphalt Congress. August 24-26, 2005, Guadalajara, Mexico.

V3a Witczak, M. W., K. E. Kaloush, and H. Von Quintus, 2002, *Journal of the Association of Asphalt Paving Technologists*, 71: 671-691.

V3a Witczak, M. W., K. E. Kaloush, and H. Von Quintus, 2002, *Journal of the Association of Asphalt Paving Technologists*, 71: 671-691.

V3a Witczak, M., K. Kaloush, T. Pellinen, M. El-Basyouny, and H. Von Quintus, 2002, Simple Performance Tests for Superpave Mix Design. NCHRP Report 465, Transportation Research Board, Washington, DC.