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ASPHALT RESEARCH CONSORTIUM

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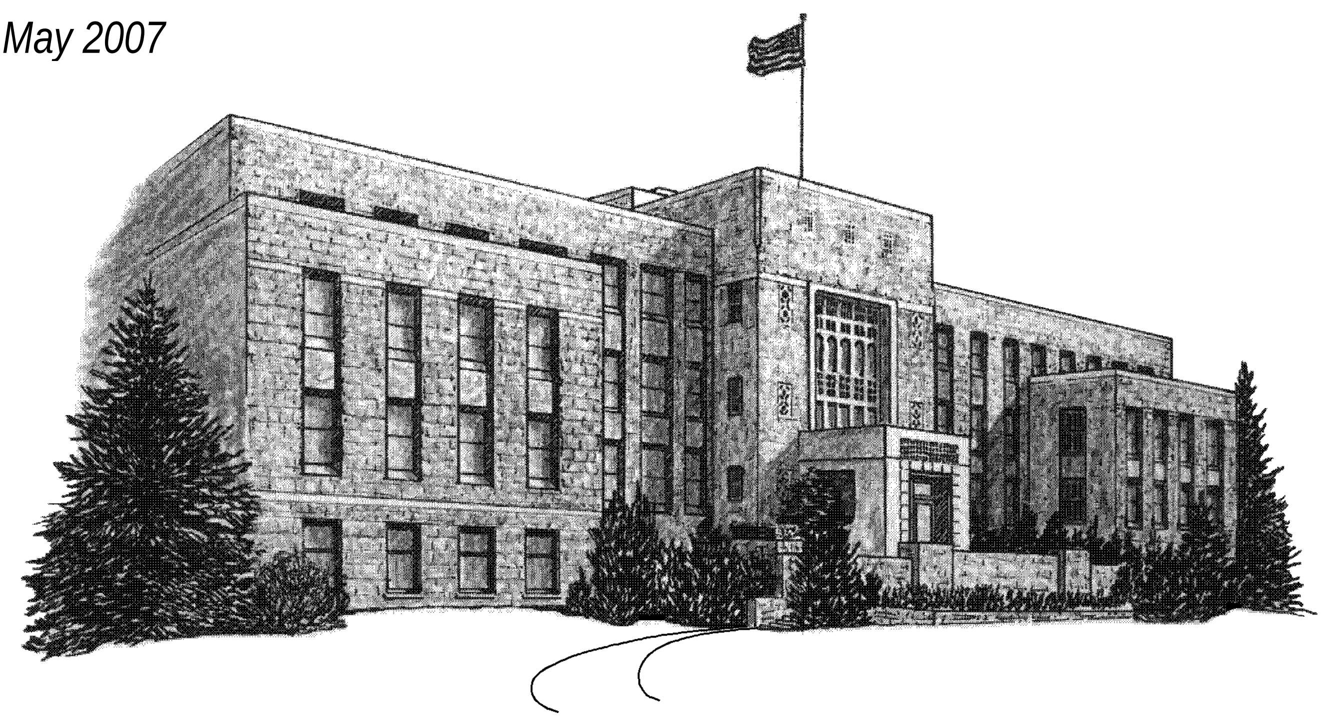

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RESEARCH PLAN FOR YEAR 1 OF FEDERAL HIGHWAY ADMINISTRATION CONTRACT DTFH61-07-H-00009 "ASPHALT RESEARCH CONSORTIUM"

FOREWORD

This document is the proposed Research Plan for Year 1 of the Federal Highway Administration (FHWA) Contract DTFH61-07-H-00009, the Asphalt Research Consortium. 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 Year 1 research plans are grouped into seven areas, Moisture Damage, Fatigue, Engineered Paving Materials, Vehicle-Pavement Interaction, Validation, Technology Development, and Technology Transfer. The format of the presentation of the work plans varies somewhat because of the different interactions of the work elements. 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. For example, in the Moisture Damage area, the principle of measuring surface energy of asphalts and aggregates is being pursued using the "macro" (or bulk) approach using the Wilhelmy plate and Universal Sorption Device for asphalts and aggregates, respectively. The surface energy of asphalts and aggregates is also being pursued using Atomic Force Microscopy at the nano scale. Using the two different methods provides a check on one another so that the true significance and importance of surface energy 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 make 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.

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. 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.

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PROGRAM AREA: MOISTURE DAMAGE

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, 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 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 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 are 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 pavement in the field. One test (the Hamburg wheel-tracking test) is so severe that many moisture-insensitive pavement mixtures 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 (multiple weeks) to perform that it 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 are conducted over a very short period of time (hours to a few days) whereas moisture in pavement may require a few months to a few years to cause (early) failure. So, there is a definite need to develop test methods that simulate the effect of water over time.

The mission of this program is to elucidate all of the major mechanisms of failure that result from the presence of water in pavement. The most promising concept today to evaluate the propensity of pavement to suffer moisture damage is to measure the surface energies of asphalt and aggregate. This method gives fundamentally sound measures of the thermodynamic stability of asphalt-wet aggregate versus water-wet aggregate. Fundamental thermodynamic measurements show that a water-wet aggregate is preferred over an asphalt-wet aggregate. However, there is a need 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 pavement and consequently the properties of asphalts change and vary substantially with age. So, in the future the concept of using fundamental thermodynamic measurements to predict moisture sensitivity must include different aged asphalts. Further, the correlation of thermodynamic stability to the kinetics of displacement must also be established. This type of relationship has been established for other chemical systems, so, in principle, it can be done for asphalt-aggregate systems also.

Moisture damage that leads to early pavement failure consumes a disproportionate amount of highway maintenance funds, so, 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 that are highly resistant to moisture damage. This must also be a system that is rapid enough to be employed as 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 model for evaluating and quantifying 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 also 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 mixes depends on the identification of the mechanisms that contribute to moisture susceptibility. The working hypotheses for the development of a methodology to rapidly and reliably predict moisture susceptibility of mixes is:

> The moisture susceptibility of a mixture is determined based on the combined effect of material properties such as aging of asphalt, pH of the water, aggregate structure, surface energy of the asphalt and the aggregate as well as mixture properties such as void distribution within the mixture.

OBJECTIVES

1. Identify the mechanisms that contribute to moisture susceptibility of mixes.

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 energy 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 and validate the utility of tests and models to evaluate the moisture susceptibility of mixes.

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, 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

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 the 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 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 conducted by 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.

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 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 sub-tasks discussed herein.

<u>Subtask M1a-1: Select Representative Asphalt Binders and Mastics, and Aggregate Materials (Year 1 start)</u>

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), and chemical modification
2) Three different fillers: acidic (quartzite), basic (calcite), and 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: distilled water, sodium chloride solution, and calcium chloride solution.

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)

In this task, 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. 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.

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 Task 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.

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

Based on the results of Task 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 task, 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 Task 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.

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 (Year 1 start)

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 sub task 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.

Subtask M1b-2: Work of Adhesion at Nano-Scale using AFM

Thermodynamics and mechanical properties of asphalt binder adhering to aggregate surfaces compounded by the presence of water are directly related to the physico-chemical properties of each of these materials (asphalt, water, aggregate). To date still much is unknown regarding the processes of soft condensed matter wetting in terms of molecular orientation and phase ordering, that fall within the realm of surface entropic events, in even much simpler systems than the system considered here. Nano-technological methodologies, which include the wide range of scanning probe microscopy techniques, presently make it possible to investigate, at and near molecular scale, entropic events that may be crucial to adhesion in asphalt pavements compounded by moisture attack.

i) Work elements for the present subtask will include investigation via AFM imaging and nano-mechanical techniques of thin-film materials of wet and dry oxidized asphalt binder, mastic samples damaged by freeze-thaw cycle experiments, and core samples, to de-convolute the entropic nature of adhesion mechanisms between asphalt and aggregate, polymer, filler, etc.

ii) Coordinate with research focusing on the fundamental physical-chemical properties of both asphalt and aggregate, by such methods as flocculation titrimetry with an emphasis on hydrogen-bonding mechanisms, NMR imaging techniques to directly quantify asphalt-water interfacial surface free energy as a function of time and temperature, and characterization of the changes in functional composition of the asphalt binder of both wet and dry aged and unaged binder materials. This may include FTIR microscopy and advanced chromatographic techniques.

<u>Subtask M1b-3: Identify Mechanisms of Competition Between Water and Organic Molecules for Aggregate Surface (Year 1 start)</u>

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 likely 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 adhesion in heterogenous materials through an additive mixing model. This sub task 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 mixtures resistance to moisture damage, and ii) refine the existing methods used to measure material properties such as surface free energy.

Work Element 1c: Quantifying Moisture Damage Using 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 #16 sieve. Several field studies and observations have shown that the fine portion of the mixture carries most of the resistance to moisture damage. This phase holds coarse aggregate particles together in an asphalt mixture. The DMA allows for the 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 or 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 2a of the moisture work plan.

Category M2: Cohesion

Work Element M2a: Work of Cohesion Based on Surface Energy

Work of cohesion based of asphalt binder or mastic is a fundamental material property that dictates the magnitude of work required for crack growth within the material. 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 due to the presence of water. 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:

<u>Subtask M2a-1: Methods to Determine Surface Free Energy of Saturated Asphalt Binders (Year 1 start)</u>

Work of cohesion of asphalt binders is an important material property input for various analytical and micromechanics models. A pertinent question is; 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) Conduct literature review to explore possible techniques to determine the work of cohesion for asphalt binders or mastics that have been saturated with water. The literature review will include methodologies used under similar conditions with polymers. Direct and indirect methods will be included in the review. The literature review will provide recommendation on the feasibility to make such measurements and interpretation of data from these methods.

ii) 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 a technique to derive the parameters of interest.

Subtask M2a-2: Work of Cohesion Measured at Nano-Scale using AFM

The thermodynamics and mechanical properties of asphalt binder and cohesive properties compounded by the presence of water are directly related to the physico-chemical properties. Just as with adhesion, cohesive processes of molecular orientation and phase ordering in the native binder fall within the realm of entropic events.

i) Work elements for the present subtask will include investigation of thin-film materials of wet and dry oxidized asphalt binder, via AFM imaging and nano-mechanical techniques. The emphasis will be on AFM force-distance analysis employing chemically functionalized cantilever tips to investigate components of surface free energy, spin coating techniques to investigate dynamic wetting based on lubrication theory, and micro/nano-contact mechanics approaches based on scanning probe technologies.

ii) Again, coordination with research of investigation of the fundamental physical-chemical properties, with the emphasis on the asphalt binder, by such methods as flocculation titrimetry with an emphasis on hydrogen-bonding mechanisms, NMR imaging techniques to directly quantify asphalt-water interfacial surface free energy as a function of time and temperature, and characterization of changes in functional composition of the asphalt binder of both wet and dry aged and unaged materials based on spectroscopic techniques including FTIR microscopy.

Work Element M2b: Impact of Moisture Diffusion in Asphalt Mixtures

Principles of thermodynamics determine the equilibrium state and the potential difference between the current and equilibrium state that drives moisture damage in asphalt mixtures. However, in order to combine environmental conditions and external loads into a model used to predict realistic pavement responses, it is imperative to include kinetics of moisture damage in addition to these thermodynamic quantities. 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 (Year 1 start)

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 the previous experience, the use of psychrometers to measure relative humidity (or suction) appears to be a very good candidate.

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 which water displaces the asphalt binder from its interface with the standardized surfaces (Nguyen et al. 1996). The attenuated total reflectance (ATR) is a technique for using the FTIR that is allows the interface to be subjected to a variety of boundary conditions. Using different controlled thickness of asphalt binder films or mastics, one can determine the rate of diffusion of moisture through the binder or mastic films.

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. 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. For the binder and mastic films, the ATR-FTIR technique as described in (ii) above will be used to make these measurements. Due to equipment limitation, 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 is at the aggregate-binder interface. 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.

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

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 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 it 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 (reference). 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 by combining different aggregate-made discs and varying the binder film thickness, we will be able to gain 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.

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 one to measure load and 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:
    1. The effect of different pulling rates on the PATTI and DSR responses.
    2. 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.
    3. 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.
    4. The temperature during the water conditioning plays an important role in effect of water on cohesion and adhesion of binder or mastic.

<u>Subtask M2c-1: Evaluate Load and Deflection Measurements using the Modified PATTI Test (Year 1 start)</u>

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.

Subtask M2c-2: 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 Sub-Task 2c-3.

Subtask M2c-3: Validation of the Modified PATTI Test using Results from DSR Testing

Selected samples of the modified and unmodified binders tested in sub-task 2c-2 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. Also the comparison between the axial pull-off testing and shear stress sweep will be included in the testing.

Subtask M2c-4: 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.

Subtask M2c-5: Commercialization and Practicality Evaluation of the Modified PATTI Test

The increase in cost of the PATI 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.

Subtask M2c-6: 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.

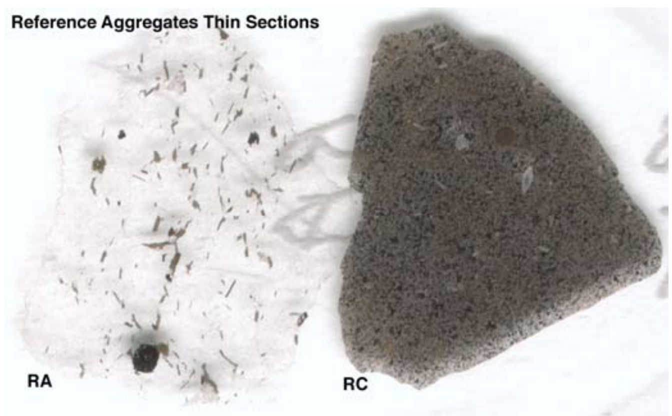
Category M3: Aggregate Surface

Work Element M3a: Aggregate Surface Characterization (Year 1 start)

Physical and chemical properties of aggregates at the macro and micro scale influence the performance of asphalt mixes. 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 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 1). The image to the right shows thin sections of two common aggregates. The images clearly show the mineralogical heterogeneity of the 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]	$Ca_{(0.5\text{-}0.7)}Na_{(0.3\text{-}0.5)}(Al,Si)AlSi_2O_8$	
Andesine	Plagioclase Feldspar[1]	$Na_{(0.5\text{-}0.7)}Ca_{(0.3\text{-}0.5)}(Al,Si)AlSi_2O_8$	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 seperate minerals. The minerals are given the names Magnesio-hornblende, Ferrohornblende, Alumino-ferro-hornblende and Alumino-magnesio-hornblende.

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

Steps involved in the detailed characterization of the aggregates:

i) Examination of 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, suitable individual mineral reference materials will be acquired 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.

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. However, upscaling methods need to be applied in order to transfer the experimental measurements conducted at various scales to the model scale and resolution.

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 mix 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.

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 are solved to determine the moisture distribution within the mixture. The constitutive equations will be solved to determine the mechanical behavior given the moisture present in the mixture.

Moisture will be treated as an external variable that influences the evolution 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 and 2006). The processes that are considered in the Delft model are summarized in Table 2. This work element will build on recent advances by focusing on making the improvements listed in Table 3.

Table 2. Processes simulated in the model of moisture damage of Kringos and Scarpas (2005 and 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 3. 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.

YEAR 1 PROJECT DIRECTION

The focus of year 1 will be to:

- Evaluate mechanical tests (PATTI test and DSR) to determine the affinity of asphalt binders for aggregates.
- Evaluate thermodynamic tests (surface free energy and micro calorimeter) to determine material properties and affinity of asphalt binders for aggregates.
- Develop test methods to determine the rates of diffusion of moisture through asphalt binder and mastic films as well as through asphalt concrete mixtures.
- Evaluate the use of PATTI test to assess thin film rheology of unmodified and modified asphalt binders.
- Conduct thorough mineralogical and chemical characterization of aggregates that will be used in the consortium research.

SCHEDULE

		Year 1	Year 2	Year 3	Year 4	Year 5
M1a	Affinity of Asphalt to Aggregate - Mechanical Tests	**X**	**X**	**X**	**X**	
	1a-1 Use of modified DSR and PATTI tests	x	x			
	1a-2 Evaluate moisture damage of asphalt mixtures	x	x	x	x	
	1a-3 Compare moisture damage from 1a-1 and 1a-2		x	x	x	
	1a-4 Propose a novel test protocol			x	x	
M1b	Work of Adhesion	**X**	**X**	**X**	**X**	**X**
	1b-1 Adhesion using Micro calorimeter and SFE	x	x	x	x	x
	1b-2 Evaluating adhesion at nano scale using AFM		x	x	x	x
	1b-3 Mechanisms of water-organic molecule competition	x	x	x	x	x
M1c	Quantifying Moisture Damage Using DMA		**X**	**X**	**X**	**X**
M2a	Work of Cohesion Based on Surface Energy	**X**	**X**	**X**	**X**	**X**
	2a-1 Methods to determine SFE of saturated binders	x	x	x		
	2a-2 Evaluating cohesion at nano scale using AFM		x	x	x	x
M2b	Impact of Moisture Diffusion in Asphalt	**X**	**X**	**X**	**X**	
	2b-1 Diffusion of moisture through asphalt/mastic films	x	x	x		
	2b-2 Kinetics of debonding at binder-aggregate interface		x	x	x	
M2c	Thin Film Rheology and Cohesion	**X**	**X**	**X**	**X**	
	2c-1 Evaluate measurements from PATTI test	x	x			
	2c-2 Evaluate PATTI test to detect effect of modifications	x	x	x		
	2c-3 Validating PATTI test based on results from DSR		x	x		
	2c-4 Mastic testing using PATTI and DSR tests			x	x	
	2c-5 Practicality evaluation of modified PATTI test			x	x	
	2c-6 Recommendations for modified PATTI test				x	
M3a	Impact of Surface Structure of Aggregate	**X**	**X**	**X**		
	3a-1 Aggregate surface characterization	x	x	x		
M4a	Development of Model		**X**	**X**	**X**	**X**
	4a-1 Micromechanics model development		x	x	x	x
	4a-2 Analytical fatigue model for use during mixture design		x	x	x	x
	4a-3 Unified continuum model			x	x	x
M5a	Moisture Damage Prediction System				**X**	**X**

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.

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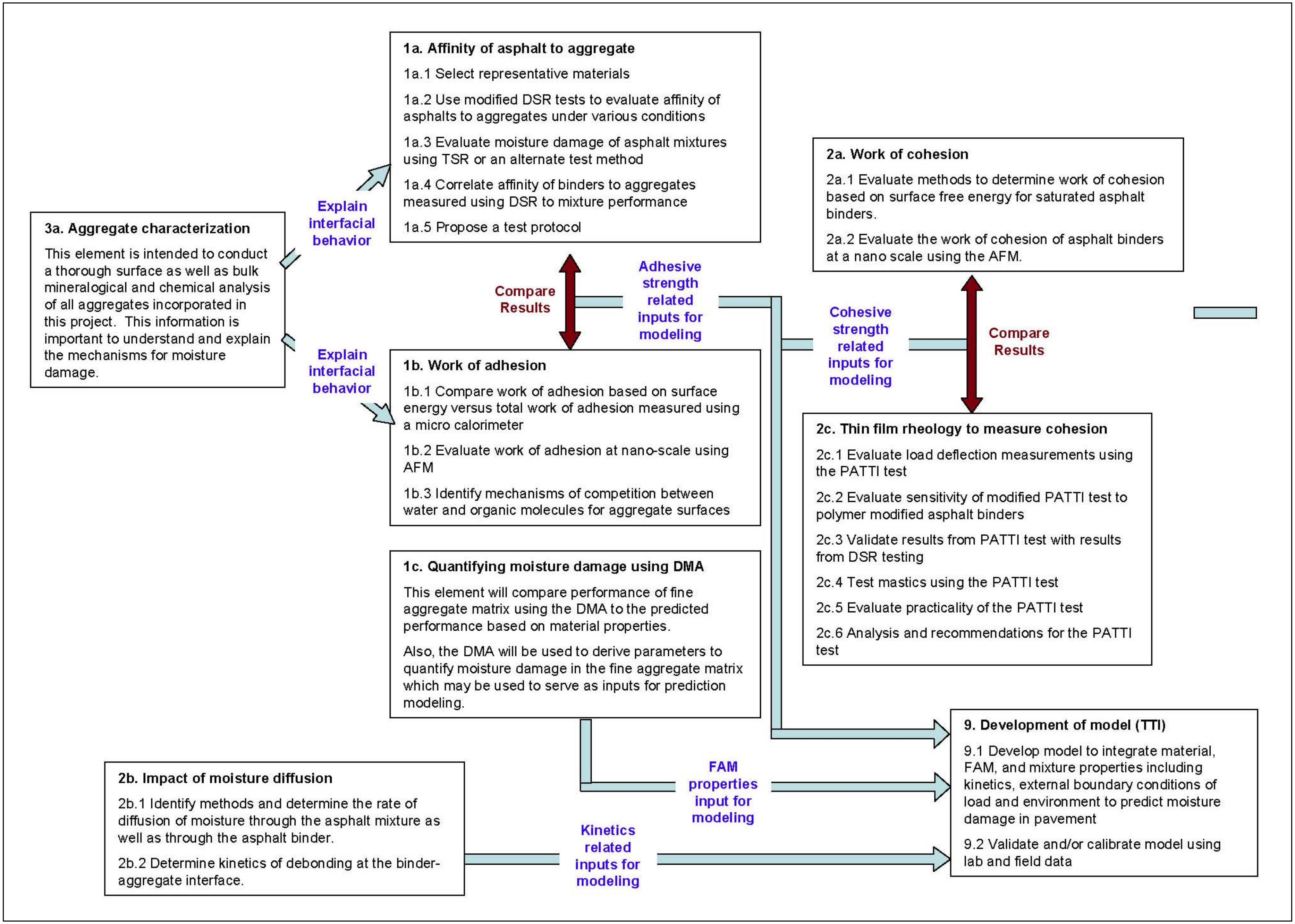
Appendix M1

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

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 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, even 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, 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.

This research must remain focused on the deliverables that the Consortium is committed to provide. In the area of fatigue, the Consortium 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 Consortium, 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

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, 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 on 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

Subtask F1a-1: Critical Review of Measurement and Application of Cohesive and Adhesive Bond Strengths (Year 1 start)

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. 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.

In summary, the literature review conducted in this task will cover the 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.

Subtask F1a-2: Develop Experiment Design (Year 1 start)

A detailed experiment design will be developed to accomplish the objectives identified in the work element F1a. The experiment design will include details pertaining to the statistical analysis that will be used for each element, including number of samples, and replicate measurements required. The materials selected for the detailed experiment design will be from the common material library for the consortium project. A preliminary list of materials for this library is identified in element 3d of this work plan. Additional materials may be used if the materials library does not contain materials that exhibit the desired range of properties of interest.

Subtask F1a-3: Thermodynamic Work of Cohesion and Adhesion (Year 1 start)

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) Assess existing protocols to determine surface energy components for modified asphalt binders and mastics. 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 this subtask, these existing protocols will be evaluated for their applicability to mastics, aged, and polymer modified asphalt binders. Factors such as specimen preparation and uniformity will be addressed. Results will be cross evaluated using analytical methods and alternate experimental techniques such as the static sessile drop method.

ii) Develop recommendations and revised test protocol for measuring surface free energy on asphalt binders and guidelines to use and interpret surface energy measurements for asphalt mastics.

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 consortium project 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 consortium project 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.

<u>Subtask F1a-4: Mechanical Work of Adhesion and Cohesion</u>

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.

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. Possible test methods for consideration in this element are the direct transverse tension test on asphalt films of varying thicknesses using standardized and aggregate substrates.

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.

<u>Subtask F1a-5: Evaluate Acid-Base Scale for Surface Energy Calculations</u>

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.

Work Element F1b: Viscoelastic Properties (Year 1 start)

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.

Subtask F1b-1 Separation of nonlinear viscoelastic deformation from fracture energy under cyclic loading

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: (a) 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 reversible within each cycle.

The nonlinear response will cause the viscoelastic properties (phase angle and modulus) to change within the cycle. In this subtask, we will derive the Schapery's nonlinear viscoelastic model under the boundary conditions of cyclic loading in order to obtain functions for viscoelastic material properties within a loading cycle. This will allow separating the nonlinear response from the linear response predicted using properties measured at small stresses. The permanent strain is quantified by monitoring the material response every quarter of a cycle. This might require some changes to standard software used in test methods in order to obtain the response at points within loading cycles and not only the properties measured at peak stress values.

The fracture parameters will be identified by monitoring the material response by applying fatigue loading until changes in material properties are measured at a given stress level. As cyclic loading proceeds, the nonlinear viscoelastic response should be the same so long as the stress level remains the same. As such, any change in the material response at a given stress level with an increase in loading cycles will be used to quantify fracture damage.

Subtask F1b-2 Separation of nonlinear viscoelastic deformation from fracture energy under repeated and monotonic loading

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.

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 F3. Ultimately, the results must be able to provide insight to the asphalt microstructural model, the micromechanics model, and the unified continuum fatigue model. Activities of this work element in Category F1 will coordinate with those of Category F3.

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 (Year 1 start)</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 (Year 1 start)</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 (Year 1 start)</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.

Subtask F1c-4: The Effects of Binder Aging on Mixture Viscoelastic, Fracture, and Permanent Deformation Properties

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.

Work Element F1d: Healing

This work element will begin in year one, and the work plan is described in the following paragraphs.

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

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.

The product of Subtask F1d-1 will be a white paper synthesizing the pertinent literature on healing with a major emphasis on the work done under FHWA contracts DTFH61-C-92-00170 and DTFH61-C-99-00022.

<u>Subtask F1d-2: Select Materials with Targeted Properties (Year 1 start)</u>

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 sub task 1d-2, 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.

Subtask F1d-3: Develop Experiment Design (Year 1 start)

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

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 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 tasks F2a and F2b.

Subtask F1d-5: Testing of Materials

The binders and additives selected in F1d-2 and F1d-3 will be tested using the methods identified in 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 (Year 1 start)

During the last 10-15 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 DSR. This task will focus on two main areas, apply methods developed for healing of mixtures to results of binder fatigue testing in the DSR, and develop 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 one to estimate the effect of stress/strain on fatigue life and also to predict 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.

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 world wide literature on methods for measuring healing of asphalt mixtures and other visco-elastic 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 2-5, 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.

<u>Subtask F1d-7: Coordinate with Atomic Force Microscopic (AFM) Analysis.</u>

As described previously healing characteristics of an asphalt binder depend on its surface properties as well as the molecular morphology. AFM imaging and interaction measurements on the asphalt binders selected in this task will provide valuable insight at a nano scale into understanding the mechanism and modeling of the healing phenomenon.

In this effort nanotechnology (AFM imaging; friction and morphology, contact-force AFM, nanoindentation AFM, chemical-force AFM, etc.), interpreted based on contact mechanics and statistical mechanics theories of irreversible energy dissipation at diffuse interfaces may be adopted to describe/model material integrity (equilibrium compositional and phase transformation stability, inter and intra molecular compatibility) fracture, slow crack growth and crazing phenomena. Nanoindentation techniques may for example be adopted for measuring stiffness and creep relaxation properties of asphalt binder material thin-films Sample thin films may be analyzed by AFM imaging techniques, force-distance work of adhesion measurements (nano-contact mechanics) and nanoindentation, each conducted as a function of time and temperature. The results that 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 models, etc.) will be investigated. This approach is 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.

i) Develop experimental techniques that require the minimum amounts 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 Tensiometer, AFM solidification analysis, programmable dynamics wetting/Spin-Coating via Lubrication Theory, and programmable combinatorial-automated flocculation titrimetry (PC-AFT).

ii) Develop approaches (Experimental) based on nanotechnology which lead to data-input computational software (e.g., Virtual Asphaltic Concrete Testing Laboratory (VACTL) to model physico-chemical and chemo-mechanical systems.

Subtask F1d-8: Coordinate Form of Healing Parameter with Micromechanics and Continuum Damage Models.

This subtask will be conducted in coordination with tasks 3b and 3c. 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 continuum fatigue model. This sub task will be critical to ensure that healing is appropriately incorporated along with other material properties as a part of these models.

Subtask F1d-9: Design Experiment on Selected Binders with Synchrotron.

Texas A&M has secured the opportunity to use the synchrotron at the University of Saskatchewan. This synchrotron is one of the most modern and powerful in the world. It is possible that the changing image of the molecular structure at a crack face may be able to be captured with this device as it is capable of micro and nano-scale analysis. A cooperative relationship with the University of Saskatchewan provides an opportunity for this testing during the fall of 2007. We will investigate whether or not this opportunity is meaningful. If so a small exploratory initial experiment will be proposed.

Category F2: Test Method Development

Work Element F2a: Binder Tests and Effect of Composition

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, than 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 have 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. 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. The following tasks will be completed in order to achieve the objectives of this research effort.

<u>Subtask F2a-1: Analyze Existing Fatigue Data on Polymer Modifies Asphalts (Year 1 start)</u>

Fatigue studies of unmodified, SBS and acid modified binders have been performed by UW-Madison in collaboration with FHWA for the last 3 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 along side 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.

<u>Subtask F2a-2: Select Virgin Binders and Modifiers and Prepare Modified Binder (Year 1 start)</u>

Based on the results of subtask F2a-1, a complimentary 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.

<u>Subtask F2a-3: Subject Samples of Virgin and Modified Binder to Several Laboratory Aging Procedures</u>

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.

<u>Subtask F2a-4: Collect Fatigue Test Data for All Samples</u>

This task will concentrate on testing the previously prepared samples according to the work plan in Task 2.

<u>Subtask F2a-5: Analyze data and propose mechanisms by which aging and modification influence fatigue of binders.</u>

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 we believe that 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.

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.

<u>Subtask F2b-1: Develop specimen preparation procedures (Year 1 start)</u>

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.

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

This subtask will develop 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 micro mechanics and continuum fatigue damage models as well as model crack growth in asphalt mastics and mixtures. For example, procedures developed in subtask 1b 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 1d-6 will be standardized and documented.

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.

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.

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.

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.

Category F3: Modeling

Work Element F3a: Asphalt Microstructural Model

For nearly a century, heavy crude oil has been viewed by a majority of investigators as colloidal in nature. Although naturally occurring (Trinidad Lake deposit), asphalt is generally defined as the residuum from the distillation of petroleum. Heavier residua such as asphalt consist of a rather grand number of different "petrol" organic compound types (molecules) comprising their chemical makeup. These compound types vary in a complex manner in terms of their molecular composition; hydrogen-to-carbon ratio, shape, molecular weight or size, polarity, density, surface activity, etc. Asphalt molecules are generally thought to range in molecular character from that of non-polar hydrocarbon, waxy and oily type molecules, to condensed poly-aromatic sheet, heteroatom-containing (graphite-like) molecules. Hence, common logic would dictate that a concise description of the composition of the molecules present in heavy residua and their associated interactions with each other and with other foreign materials should directly relate to the physico-chemical properties of asphalts and their propensity to bind with aggregate, polymer, fillers, etc., if used as the gluing agent in pavement construction applications.

A logical approach to take to guide studies which will lead to the most accurate and realistic description of the compositional nature of asphalt binder should rely heavily on theoretical modeling of asphalt nano-structure grounded in such fields of study as that of non-equilibrium statistical mechanics. This type of modeling approach assumes that idealized materials such as polymers, or in the present case, complex petrol-organic molecules found in asphalts, tend to undergo such phenomena as phase separation and nucleate, flocculation/dissolution, crystallizing and melting, all contributing to material softening and embitterment, when characterized as a function of time and temperature. One may then attempt to describe irreversible non-equilibrium thermodynamic processes involving phase ordering vis energy dissipation in asphalt molecular moieties leading to such processes as solidification/melting events by assuming the coupling of material (molecular particles) transport and heat flow between "classes" of petro-chemical molecules to describe diffuse interface dynamics. In these kinds of studies asphalt may be described as a continuum nano-emulsion, that is to say, a solution comprised of a molecular distribution (M.W., H/C, density, etc.) of petro-chemicals (much like a complex true solution mixture), when defined specifically at temperatures above the material's glass transition temperature, or as an amorphous glass specifically defined through and below the material's glass transition temperature. For an example, past research has demonstrated that the Pal-Rhodes model for concentrated micro-emulsions serves well as a first approximation for quantifying asphalt "micro/nano structuring" events at midrange service temperatures. On the other hand asphalt may be described as an amorphous solid at sub-zero temperatures, but why? This task will attempt to answer this question.

In this task, models of asphalt-binder, coupled with nanotechnology (AFM imaging; friction and morphology, contact-force AFM, nanoindentation AFM, chemical-force AFM, etc.), will continue to be developed or improved that strictly adhere to both quantum mechanical and classical mechanical laws of physics to describe well defined molecular components that accurately represent asphalts as functions of crude source. Phase-field modeling, for example, which may be derived from the theory of extended irreversible thermodynamics (EIT) , has been utilized for almost fifty years to describe such phenomena as phase separation in heterogeneous material phases, growth of new phases such as polymer crystals, phase-field modeling has even been utilized to describe brittle fracture in solid materials.

i) Collaborate with academic and private institutions (Consortium members, NIST, U of RI, TU Delft, etc.) to develop compositional modeling tools. This endeavor may include computational molecular simulations based on *ab initio* calculations, density function theory and Monte Carlo (fluctuation-dissipation theory) simulations, dissipative-structure theory, diffuse interface and phase–field approaches, which stem from the extended irreversible thermodynamics (EIT).

ii) Collaborate with academic and private institutions to develop physical/rheological modeling tools. These endeavors may include development and utilization of contact and fracture mechanics approaches, strain energy models and other continuum mechanics models, and phase-field modeling grounded in EIT theories, as previously alluded to. It is anticipated that a chemo mechanical model will emerge from these efforts to target direct relationships between material composition and pavement performance.

iii) Develop approaches (Theoretical) which lead to computational software (e.g., Virtual Asphaltic Concrete Testing Laboratory (VACTL), chemo-metrics, data mining, and neural-networks) to model physico-chemical and chemo-mechanical systems pertinent to continuum mechanics models already in place in current and future asphalt pavement technologies.

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 F1) 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 and will collaborate with TAMU who will lead the experimental-analytical part.

The third approach will further develop the multi-scale lattice micromechanical model. Lattice modeling was developed by North Carolina State University (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, with the most important being the difference between the scale at which experimental measurements are conducted and the scales captured in the model. The extensive experimental program proposed in various work elements in this research 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 the data from 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. The lattice model development will be led by NCSU. TAMU will lead the experimental part, providing NCSU with all the data.

<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 scaled up prior to its use in a micromechanical model. The scaling 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 F1 of the work plan.

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 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 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.

Work Element F3d: Calibration and Validation

The same set of materials will be used in all the Categories discussed above. The researchers will use the materials from the FHWA-ALF experiment and the test sections currently being monitored by WRI. These sections are described in Table 1.

Table 1. A List of mixes used in the field validation study.

Project	**Binders**
Wyoming HWY 216	PG 58-28 WY1-1 WY-Canadian Blend
	PG 58-28 WY1-2 WY-Rocky Mtn Blend
Nevada I-15	PG 64-22 NV1-1 WY-Rocky Mtn Blend
	PG 64-22 NV1-2 Nevada
	PG 64-22 NV1-3 Venezuelan
	PG 64-22 NV1-4 Canadian
Arizona US 93	PG 76-16 AZ1-1 West Tx Sour & Int Blend
	PG 76-16 AZ1-4 Rocky Mtn Blend B
	PG 76-16 AZ1-3 Rocky Mtn Blend A
	PG 76-16 AZ1-2 Venezuelan
Kansas US 77	PG 64-22 KS1-1 Mid Continent Blend A
	PG 64-22 KS1-2 OK Blend
	PG 64-22 KS1-3 TX/OK Blend
	PG 64-22 KS1-4 KS/UK Blend

In addition to the use of materials with known field performance, the researchers will utilize materials that represent the different combinations of mixtures. It is envisioned that these materials will include the following:

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), and chemical modification
2) Different fillers: acidic (quartzite), basic (calcite), and 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: distilled water, sodium chloride solution, and calcium chloride solution.

Mixtures will be designed using the Superpave system to have fine gradation, coarse gradation and stone matrix asphalt (SMA) gradations. The researchers will seek input from the FHWA and ETGs on the selection of mixtures to maximize the comparisons with field performance. We will also seek to coordinate efforts with ongoing national studies (NCHRP and pool fund) in the selection of materials and mixtures.

YEAR 1 PROJECT DIRECTION

In Category F1: Material Properties, the focus of year 1 will be to:

- Conduct a comprehensive literature review to identify the most critical areas that need to be addressed in this project including properties and mechanisms related to cohesive and adhesive bonding, binder oxidative aging, and healing.
- Develop detailed experiment designs to support the relevant areas.
- Begin measuring the thermodynamic work of adhesion and cohesion for a suite of selected asphalt binders, mastics, and aggregates, including modified and unmodified binders.
- Develop a transport model for binder oxidation.
- Determine the relationship between healing and the fatigue endurance limit.

In Category F2: Test Method Development, the focus of year 1 will be to;

- Evaluate fatigue life of polymer modified asphalt binders and prepare modified asphalt binders and investigate the impact of this modification on fatigue life.
- Finalize the mixture design and specimen preparation procedures for the testing of mastics and the fine aggregate matrix using the Dynamic Mechanical Analyzer (DMA).
- Evaluate and define the relationship (or correlation) between fatigue performance of asphalt binder (and/or mastic) to the fatigue performance of the asphalt mixture.

In Category F3: Modeling, the focus of year 1 will be to:

- Refine the micromechanics model using the discrete element and finite element (cohesive zone) approaches for mastics and mixtures.
- Develop an analytical model for fatigue damage that can be used to evaluate the fatigue cracking life of asphalt mixtures during the mixture design process.
- Develop the unified continuum fatigue model to incorporate various material properties.

SCHEDULE

		Year 1	Year 2	Year 3	Year 4	Year 5
Category F1: Material and Mixture Properties						
F1a	Cohesive and Adhesive Properties	**X**	**X**	**X**		
	1a-1 Critical review of literature	X				
	1a-2 Develop experiment design	X				
	1a-3 Thermodynamic work of adhesion and cohesion	X	X	X		
	1a-4 Mechanical work of adhesion and cohesion		X	X		
	1a-5 Evaluate acid-base scales for surface energy		X			
F1b	Viscoelastic Properties	**X**	**X**	**X**	**X**	
F1c	Aging	**X**	**X**	**X**	**X**	**X**
	1c-1 Review of binder oxidative aging	X				
	1c-2 Develop experiment design	X				
	1c-3 Develop transport model for binder oxidation	X	X	X		
	1c-4 Effect of binder aging on properties and performance		X	X	X	X
	1c-5 Polymer modified binders			X	X	
F1d	Healing	**X**	**X**	**X**	**X**	**X**
	1d-1 Critical review of literature	X				
	1d-2 Select materials with targeted properties	X	X			
	1d-3 Develop experiment design	X				
	1d-4 Test methods to determine properties relevant to healing		X	X		
	1d-5 Validate contribution of healing using DMA		X	X	X	
	1d-6 Determine relationship between healing and endurance limit	X	X	X	X	X
	1d-7 Coordinate with AFM analysis		X	X		
	1d-8 Develop form for healing parameter to incorporation in models		X	X	X	X
	1d-9 Design experiment on selected binders with synchrotron		X	X		
Category F2: Test Method Development						
F2a	Binder Tests and Effect of Composition	**X**	**X**	**X**	**X**	**X**
	2a-1 Analyze existing fatigue data for polymer modified asphalts	X				
	2a-2 Select virgin binders and modifiers to prepare modified binders	X	X			
	2a-3 Subject virgin and modified binders to several aging procedures		x	X		
	2a-4 Collect fatigue test data for all samples			x	x	X
	2a-5 Mechanisms for aging & modification effects on binder fatigue					X
F2b	Mastic Testing Protocol	**X**				**X**
	2b-1 Develop specimen preparation procedures	X				
	2b-2 Document test and analysis procedures in AASHTO format					X
F2c	Mixture Testing Protocol				**X**	**X**
F2d	Tomography and microstructure characterization		X	X	X	
F2e	Verification: DSR fatigue & Mixture performance	**X**	**X**	**X**	**X**	**X**
	2e-1 Evaluate binder fatigue correlation to mixture fatigue data	X				
	2e-2 Selection of mixture testing protocols		X			
	2e-3 Binder and mixture fatigue testing		X	X	X	
	2e-4 Verification of surrogate fatigue test				X	
	2e-5 Interpretation and modeling of data				X	
	2e-6 Recommendations for use in unified model					X

Category F3: Modeling						
F3a	Asphalt Microstructure Model		X	X	X	X
F3b	Micromechanics Model	X	X	X	X	X
	3b-1 Model development	x	x	x	x	x
	3b-2 Account for fundamental material properties in model		x	x	x	x
F3c	Unified Continuum Fatigue Model	X	X	X	X	X
	3c-1 Analytical fatigue model for use during mixture design	x	x	x	x	x
	3c-2 Unified continuum model	x	x	x	x	x
	3d-2 Multi-Scale modeling		x	x	x	x
F3d	Calibration and Validation			X	X	X

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.

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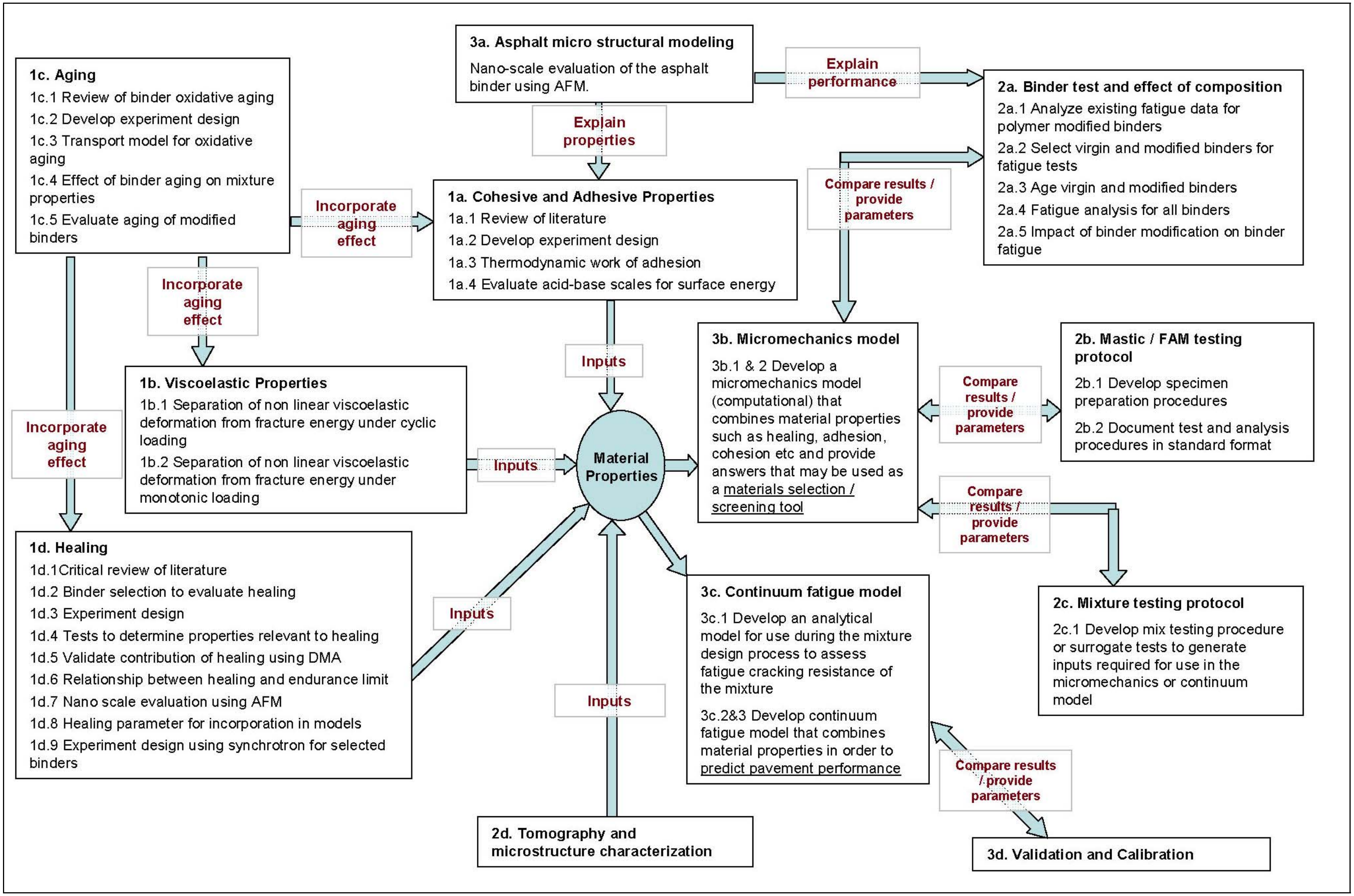
Appendix F1

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
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
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
Explain properties
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
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

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% while lane miles have increased by only 2%. The total vehicle mile travel in the United States is expected to increase by 50% 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.

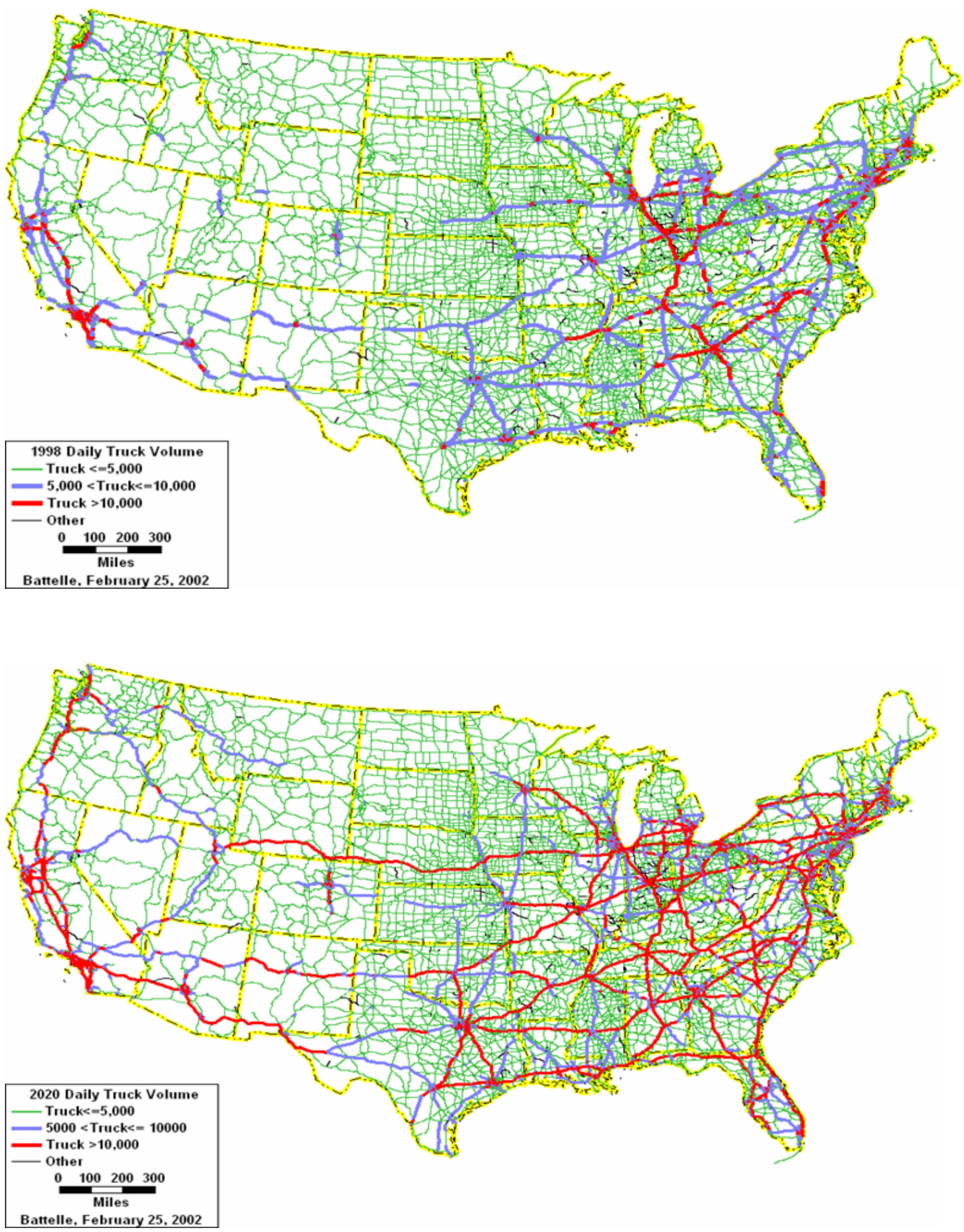


Figure 1. Expected growth of truck traffic on the national highway system. Source: FHWA office of asset management.

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% of the market to more than 15% 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:

1. 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.
2. 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.
3. 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.
4. 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.

<u>Hypothesis</u>

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 of translating the variance of the input values into the variance of the predicted result and the resulting reliability.

<u>Objectives</u>

1. Develop analytical models of the properties of binders using the principles of mechanics. Relate the properties of the binder to the molecular composition, structure, and energy potentials.
2. Develop analytical models of the properties of mastics as binders are altered by the addition of modifiers, fillers, and fine aggregates using the principles of micromechanics.
3. Develop models for the mechanical behavior of asphalt mixtures.
4. Verify with laboratory tests the predicted materials properties of the models from Items 1, 2, or 3.
5. 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.
6. 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 Items 1, 2, or 3 and verify the predicted distress with pavements that were not used in the calibration process.
7. Incorporate into the model of Item 6 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.
8. Design and initiate materials properties catalogues including all of the materials properties which are needed for the models of Items 1, 2, or 3 and which do not change or have predictable changes.
9. 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 material 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 Consortium and with the ongoing binder characterization work in the FHWA.

Experimental Design

The development of the material property models of the binder, mastic, and mixture will not require an experiment design but will require that the other tasks in this project conduct the necessary tests to provide an evaluation of the accuracy of the models that are developed. This will require coordination with every task within this project in which characterization work is being accomplished. To the extent that no other task in this project is focused on developing a needed property, such as the coefficient of thermal 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

This task will focus the development of the following micro-mechanical models that relate binder molecular composition and morphology to:

- Compliance
- Diffusivity
- Thermal Coefficient of Expansion and Contraction
- Time-Temperature Shift
- Time-Aging Shift
- Surface Energy Components

Subtask E1a-2: Analytical Micro-mechanical Models of Modified Mastic Systems

Micro-mechanical models of mastic will be developed to relate the mastic physical and chemical properties to:

- Stress-Pseudo-Strain Curve
- Mastic Compliance
- Non-linearity in Compliance

- Time-Temperature-Aging Shift
- Thermal Coefficient of Expansion and Contraction
- Viscoplastic Properties of Mastic
- Adhesive Bond Energy
- Cohesive Bond Energy
- Healing Rate and Healing Capacity
- Thermal Conductivity
- Dielectric Permittivity

Subtask E1a-3: Analytical Models of Mechanical Properties of Asphalt Mixtures

The micromechanical models for the asphalt and the binder will be incorporated in micromechanical models for asphalt mixtures to predict the following properties and quantities:

- Mixture Relaxation Modulus
- Micro-structural Stress Tensor
- Viscoplasticity Properties
- Time-Temperature-Aging Shift
- Mixture Permeability and Diffusivity
- Mixture Thermal Expansion and Contraction Coefficient
- Mixture Fracture Properties
- Mixture Healing Properties
- Mixture Thermal Conductivity
- Mixture Dielectric Permittivity

Subtask E1a-4: Analytical Model of Asphalt Mixture Response and Damage

This task will be coordinated with the modeling efforts discussed in the fatigue and moisture damage plans. As discussed in the fatigue plan, a 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.

Year 1 Project Direction

Year 1 will focus on subtasks E1a-1 and E1a-2 of the work plan.

Schedule

Subtask	Year 1	Year 2	Year 3	Year 4	Year 5
E1a-1. Analytical Micro-mechanical Models of Binder Properties	**X**	**X**	**X**		
E1a-2. Analytical Micro-mechanical Models of Modified Mastic Systems	**X**	**X**	**X**		
E1a-3. Analytical Models of Mechanical Properties of Asphalt Mixtures		**X**	**X**	**X**	
E1a-4. Analytical Model of Asphalt Mixture Response and Damage			**X**	**X**	**X**

Budget

The estimated budget for this work element is $820,000 over five years and the work will be conducted by Texas A&M University.

Relationship to FHWA Focus Areas

This work element is related to the focus area of Optimize Pavement Performance by concentrating on materials characterization and mix design. It targets developing analytical micro-mechanical models to relate binder, mastic, and mixture properties to its performance characteristics.

Work element E1b: Binder Damage Resistance Characterization (DRC)

Subtask E1b-1: Rutting of Asphalt Binders

While linear viscoelastic rheology is considered a major step forward in binder performance modeling, DRC 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 the topic. A limited amount of binders and mixtures are currently being used to find a relationship between the binder non linear 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), indicates that stresses much higher than 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 stress level is not the only important parameter in rutting testing but the accumulated loading time. 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.

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 task 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:

i. Literature Review. A detailed search of existing data and published papers on the subject will be compiled. The review will include world wide 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 and also a data base will be established for data available.

ii. Selection of Asphalt Binders and Aggregate Properties and Development of Work 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. It will also include critical mixture variables.

- High temperature PG grades: PG58-XX, 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 %

The plan will also list the testing methods that are needed. It will include the following binder and mixture tests

- The binder test should include creep and recovery testing using the Dynamic Shear Rheometer. Creep test 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: 46C and 58C.
- 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)

iii. 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.

iv. Analysis and Interpretation. 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 in work element 1a 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.

v. 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 develop. The limits will be based on the correlations to mixture response and on LTPP data of rutting performance.

Schedule

Activity	Year 1	Year 2	Year 3	Year 4	Year 5
i. Literature Review	**X**	**X**			
ii. Select Materials & Develop Work Plan	**X**	**X**			
iii. Conduct Testing		**X**	**X**	**X**	
iv. Analysis & Interpretation			**X**	**X**	
v. Std Testing Procedure and Recommendation for Specifications		**X**	**X**	**X**	

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.

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.

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Subtask E1b-2: Feasibility of Determining rheological and fracture properties of thin films of asphalt binders and mastics using nano-indentation (Year 2 start)

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 in year 2, it will be complimentary 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 13.5μm to 600μm, with 30 to 50% in the range of 13.5 to 17μm. Presently, there are no documented research studies that address the determination of mechanical properties of thin films of asphalt in an asphalt mixture non-destructively. If such technology is developed it can revolutionize the methods of accepting pavement materials after construction is complete. It will greatly simplify the task of monitoring changes in materials due to aging or repeated loading in the field and eliminate the need for expensive and destructive methods used today; and, perhaps most importantly, allows for rapid and simple quality control for contractors. The purpose of this study is to evaluate the usefulness of nano-indentation devices to measure asphalt binder or mastic properties. The work will be conducted in collaboration with the University of MN and will focus on utilizing nano-indentation equipment available at the University of MN 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.

Hypothesis

In-situ properties of asphalt binders in asphalt mixtures can be determined using nano-indentation equipment with or without minor modifications.

Objectives

The proposed study has the following objectives:

- Determine the rheological and fracture properties of asphalt binders and mastics using nano-indentation equipment.
- Compare the rheological and fracture properties of asphalt mastics determined with the current PG grading test methods to the similar properties determined using nano-indentation.

Experimental Design

The experimental work may include the following activities:

i. Literature Review and Identification of Equipment

ii. Exploratory Use of Nano-indentation devices

iii. Conducting of Exploratory Tests on Mixture Samples
iv. Testing Binders and Mastics Using PG Grading Test Methods
v. Analysis and Report

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Work element E1c: Warm and Cold Mixes

Subtask E1c-1: Warm Mixtures

This subtask will focus on evaluation of the impact of Warm Mix Asphalt (WMA) additives on Binder and Mixture Performance

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. Both of these additives achieve 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 115ºC, allowing for 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% water by mass and it is expected that the entrapped water is released in the asphalt at temperatures between 85 - 180ºC. 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 be first 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 some 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.

Hypotheses

1. 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.
2. 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. Previous research results and the overall objective of this project necessitate that the following binder properties be investigated:

   - Viscosity (Brookfield RV): The reduction in viscosity due to the addition of warm mix additives must be quantified over a wide range of additive concentration and binder temperatures. Furthermore, the time effect associated with creation and evaporation of the water vapor produced with the mineral additives must be understood.
   - Cohesion (Tack Test developed by UW): 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): Rutting resistance has been identified as a major issue in the literature review, the following parameters will be used to quantify effects of warm mix additive on binder rutting:

    - SuperPave Rutting Parameter: $G^*/\sin\delta$
    - Accumulated Strain: Multiple Stress Creep and Recovery (MSCR)
- Fatigue (Dissipated Energy Ratio): Fatigue life will be measured to identify any effects caused by the wax lattice structure or entrapped water from the mineral additives.
- Low Temperature Properties (BBR): Effects of both additives on low temperature binder properties must be investigated. Both entrapped water from the mineral additives and increased stiffness from wax additives could have negatively affect performance.
- 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.

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 by Faheem has defined two indices, the Construction Energy Index (from 88%Gmm to 92%) to quantify mix workability and the Traffic Energy Index (92% - 98% Gmm) to evaluate the stability of the mixture [1]. All mixes will be compacted past Nmax to allow for measurement of both these parameters. A list of the specific factors that will be investigated is provided below:

- Compactive Effort: Two levels (600 kPa and 250 kPa).
- 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.
- Nominal Aggregate Size: Previous research has established nominal aggregate size as a significant effect on the contribution of the warm mix additives to workability. Nominal aggregate sizes of 9.5 mm, 12.5 mm, and 19.5 mm will be investigated.
- Gradation: Fine and Coarse or S-Shaped aggregate blends will be used.
- Traffic Level: ESAL designation dictates the gradation limits of the blend. The investigation of E3, E10, E30, and E30X will be investigated.

- 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 [2,4].
- Additive Concentration: Define high and low levels of warm mix additive concentration.

Nine parameters at two – 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 [3]. The following tests will be used in conjunction with binder cohesion testing to investigate moisture damage in warm mixes and its causes.
    - Adhesion: PATTI Testing will be conducted between different aggregate surfaces and binders modified with warm mix additives.
    - 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 [5,6].

iv. Develop Revised Mix Design Procedures

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 Task 4 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 tasks 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.)

Year 1 Project Direction

Year one will focus on Activities i and ii in the work plan.

Schedule

Activity	Year 1	Year 2	Year 3	Year 4	Year 5
i. Effects of Warm Mix additives on rheological properties	**X**	**X**			
ii. Effects of Warm Mix additives on mixture workability and stability	**X**	**X**			
iii. Mixture Performance Testing		**X**	**X**		
iv. Develop Revised Mix Design Procedures			**X**	**X**	**X**
v. Field Evaluation of Mix Design Procedures and Performance Recommendations		**X**	**X**	**X**	**X**

Budget

The estimated budget for this subtask is $375,000 over five years. The subtask will be conducted by the University of Wisconsin-Madison.

Relationship To FHWA Focus Areas

- Environmental Stewardship
- Will develop the use of the gyratory plate as an improved measure of mix workability.
- Clear definition of mix design and construction procedures will provide basis for modeling of energy savings associated with the use of warm mixes.
- Field investigation quantifies the risk of compromising performance at the expense of energy savings.

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<u>Subtask E1b-2: Development and Evaluation of a Volumetric Mix Design Process for Cold Mix Asphalt</u>

Rising energy costs and increasing environmental awareness have led to an interest in the research and development of cold mix asphalt technologies as a replacement for conventional HMA pavement. Cold mix 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 [5]. The economic and environmental implications of successful implementation of cold mixture technology in the construction of flexible pavements have the potential to provide a sustainable alternative to current practice. However, further research is needed to develop of a mixture design procedure and subsequent materials testing and characterization to ensure that the performance of pavements is not significantly compromised at the expense of environmental sensitivity. Incomplete understanding of the impacts of cold mix technology on pavement performance could lead to premature, drastic pavement failures resulting in increased agency costs and user delay.

In cold mixes, the workability of the material is derived from reduction of viscosity in the asphalt binder through emulsification or foaming. The reduced viscosity 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 [1]. In this mixture the water serves as the continuous phase with the asphalt suspended in discontinuous droplets throughout the medium. This phase dispersion allows for coating of the aggregates and compaction of the mixture at ambient temperatures. After a certain period of time the emulsion sets or "breaks" and evaporates, leaving behind an asphalt mixture. The cure time of an emulsion is based on the grade of emulsion used. In foamed asphalts the asphalt and water mixture is pressurized and sprayed to allow for coating of the aggregates and compaction of the mixture. Similar to emulsions, the mix becomes stable given a certain cure time for the water to evaporate from the mixture.

The implementation of cold mix technology, as a viable option for paving operations, is a promising concept. However a volumetric mixture design procedure consistent with current Superpave specifications is needed. Specifically, this mix design procedure must include guidance on mixing and compaction temperatures, quantify the rate of curing of the mixture, and evaluate test methods to assess the moisture susceptibility of cold mixes relative to that of conventional HMA. If it is expected that cold mixes will serve as pavement layers, they need to be held to the same standard as conventional HMA mixes. Furthermore, the mix design procedure must be verified through mixture testing to quantify the effect of water entrapped in the mixture. Development of a mixture design process will help define potential uses for cold mixes and facilitate development of specifications and construction guidance to allow for wide spread application of this technology.

Hypotheses

1. Further understanding of required cure time, the effects of moisture damage, and recommended mixing and compaction conditions (temperature and humidity) will allow for development of a reliable Cold Mix Asphalt (CMA) design procedure.
2. Mixture performance testing (such as E* and FN used in the MEPDG) will provide understanding of the effect residual water and emulsifiers on mechanical properties and the risks in terms of pavement performance that could result from incomplete water evaporation.

Objectives

The overall objective of this study is to identify and resolve the outstanding issues preventing the definition a mix design procedure for cold mixes. The mix design procedure will include definition of the cure (setting) times required for the CMA pavement to perform as expected. The effects of residual water and emulsifiers will be investigated through comparing mixture testing results of cold mixes to conventional HMA. Establishment of a mix design procedure and evaluation of the mechanical properties of cold mixtures is the first step in practical application of cold mix technologies.

Experimental Design

The following activities will be completed in order to achieve the objectives of this research effort.

i. Development of a Specification for the use of Emulsions in Cold Mixes

   The first step in development of a mix design procedure is defining a clear specification for the use of emulsions in cold mixes. Currently emulsions are classified by their chemical charge (anionic or cationic), cure rate (rapid, medium, or slow), and relative viscosity (1,2). For example a MS-2 emulsion is more viscous than an MS-1 emulsion [1]. It is clear that this methodology is inadequate in terms of specifying appropriate emulsions for paving applications based on performance grading. In order to better understand the differences in commercially available emulsions as specified by ASTM D2397 [2] the following properties of emulsions will be further investigated.

- Rate of Setting / Curing: Curing of an emulsion is controlled by the rate of change of viscosity in the emulsion/asphalt mixture. The current definition of rapid, medium, and slow curing times alone is inadequate. The change in viscosity and its dependence on emulsion concentration and temperature must be quantified.
    - Field Applications: Further understanding of factors affecting setting of emulsions in the field will aid in providing guidance for field applications (mixing and compaction) of emulsified asphalts. For example, given a certain ambient temperature, how can field temperatures and humidity be used to select the concentration and type of emulsion to ensure practical field application?
    - Opening to Traffic: Understanding of the setting rate will also provide initial indications of when the emulsified asphalt has an adequate viscosity to resist traffic loading without detriment to pavement performance.
- Modified Asphalt Emulsions: How does the rate of setting and its dependence on concentration change with the use of a polymer modified asphalt? How is emulsifier selection affected by modification?
- These questions will be answered using the following properties:
    - Viscosity: The Brookfield Viscometer will be used to investigate rate of setting as a function of concentration, polymer type, and temperature
    - Cohesion (Tack Test Developed by UW): Strength of the mixture is related to the cohesion developed in the asphalt as the emulsion breaks [5]. A range of curing times based on viscosity testing will be defined and tested using the tack test to determine when the asphalt has attained similar cohesive strengths to those found in normal binders. Comparison of cohesive strength will also provide insight into the effects of entrapped water on binder cohesion.

ii. Evaluation of Asphalt Emulsion Rheological Properties

In addition to the effect of curing times on viscosity as studied in Task 1, binder performance properties of emulsified asphalts will be measured and compared to conventional asphalts. This investigation will evaluate the assumption that given appropriate curing time, emulsified asphalts will have the same performance as conventional binders. It will also allow for understanding of the loss of binder performance due to entrapped water that was not able to evaporate from the binder. The following properties will be measured:

- Rutting ($G^*/\sin\delta$ and MSCR): The use of cold-mix technology prevents short term aging of the binder, the effects of the lack of aging on binder rutting must be quantified.

    - SuperPave Rutting Parameter: $G^*/\sin\delta$
    - Accumulated Strain (Multiple Stress Creep and Recovery):
- Fatigue (Dissipated Energy Ratio and $G^* \sin\delta$).
- Low Temperature Properties (BBR)
- Aging (RTFO and PAV): It is expected that the cold-mix process will result in minimal aging of the binder. Therefore, the effects of short term and long term aging of the binder will be investigated.

The time of setting before testing and temperature at which emulsion will be conditioned will be varied. The end result of this investigation will be recommended thresholds to quantify binder performance and a comparison of these thresholds to current binder specifications.

iii. Development of Volumetric Mix Design Procedures

The results of Tasks 1 and 2 will serve as the basis for development of mix design procedures. Specifically the following issues must be resolved.

- Emulsifier charge selection: The interaction between aggregate mineralogy and emulsifier charge will be investigated further. General guidance provided recommends the use of a cationic charge with siliceous aggregates and an anionic charge with calcareous aggregates [1,2]. These guidelines must be further refined to account for aggregate blends that may use a natural sand of different mineralogy.
- Optimum emulsified asphalt content: Optimum emulsified asphalt content is currently determined using the Centrifuge Kerosene Equivalent Test [1]. This test will be evaluated and refined for application to mix design guidelines. Optimum emulsified asphalt content is known to be a function of aggregate gradation, aggregate moisture content, and emulsifier type. The rate of curing and aggregate properties will be considered in the development of a method to estimate optimum emulsified content. This includes definition of parameters to evaluate the mixes. Initial review indicates that evaluation of aggregate coating, workability, and volumetrics are possible evaluation criteria.
- Mixing and compaction conditions (temperatures and humidity): The current recommendation of preparing cold mixes at ambient temperature is inadequate. The effects of mixture gradation, temperature, and humidity will be used in conjunction with the predicted binder rates of curing to clearly define recommendations for mixing and compaction temperatures. Test methods will be developed to quantify the change in workability of the mix over time and its dependency on temperature.
- Gradation: Rate of curing is dependent on aggregate gradation [1]. Dense graded aggregate blends or fine aggregate gradations will result in longer curing times and less efficient asphalt dispersion. These effects will be investigated using the

gyratory shear plate to examine changes in workability based on aggregate gradation.

- Moisture Damage: It is expected that cold mixes will be more moisture susceptible due to the use of aggregates at field moisture content and the water entrapped in the mix. Currently moisture damage is quantified for cold mixes using ASTM D7196 [4] which is a test to quantify raveling. This test will be evaluated for use in mixture design to predict moisture susceptibility. TSR testing per ASTM D4867 [3] will also be conducted. If moisture susceptibility is defined as a problem, anti-stripping agents in cold mixes will be evaluated.
- Use of RAP: Is it feasible to use RAP in cold mixes? From an environmental standpoint it would be of benefit to have the option of using recycled materials in the mix.
- Timing: Given the varying cure times, what is the appropriate timing of mixing, compaction, and sample preparation? The rate of curing of the mixture has to be understood to ensure the mix design process is providing practical information.
- Volumetrics: Can N_{ini}, N_{des}, and N_{max} thresholds for conventional mix designs be used for cold mixes?

iv. Mixture Performance Testing

The mixture design process will be evaluated using mixture performance testing.

- Mixture Workability and Stability: Mixes of varying aggregate type and gradation will be combined with the appropriate emulsified asphalt as defined in Task 1. Samples will be evaluated for workability immediately after mixing then allowed to cure. After appropriate curing times the stability of the mix will be evaluated through compaction past N_{max}. The sensitivity of curing time on the mixture stability will also be investigated.
- Moisture Damage: Intuitively the use of field moist aggregates presents the potential for increased moisture susceptibility. Guidelines for moisture susceptibility will be developed using the following tests:
    - Mixture testing: Moisture damage will be defined using TSR testing [3].
    - Stripping: The stripping of aggregates will be evaluated using the ASTM D7196 test for raveling currently in place for cold mixes [4].
    - If moisture damage is found to be a problem, the use of liquid anti-stripping additives and hydrated lime will be investigated.
- Simple Performance Tests (E* and FN)
    - Dynamic Modulus (E*) and Flow Number tests will be used to characterize the stiffness and rutting resistance of cold mixtures and to compare the results to conventional HMA mixes. Tests will be performed on short and long term aged mixtures. Preliminary investigations into mix

stability using the gyratory load plate developed by UW will provide recommended cure times.

v. Develop Revised Mix Design Procedures and Recommendations for Applications

Results of mixture performance testing will be used to define any deficiencies in the previously established mixture design procedures. Areas of improvement will be corrected and re-evaluated using focused testing. Specific guidelines will be provided for the following, this list is not comprehensive:

- Emulsifier Selection based on PG grading
- Optimum Emulsified Asphalt Content
- Mixing and Compaction Temperature
- Timing of mixing and compaction to prepare samples for mix performance evaluation.

The results of this task will also use the mixture design and performance testing results to provide a preliminary evaluation of the feasibility of incorporating cold mixtures into the pavement construction process. Recommendations will include identification of constructability issues (i.e. weather, lift thickness, etc.) that must be addressed before widespread application of this technology. Mixture performance test results will also allow for verification that cold mixes are viable material alternatives in both the binder and surface layers.

Year 1 Project Direction

Year one will focus on Activities i and ii in the work plan.

Schedule

Activity	Year 1	Year 2	Year 3	Year 4	Year 5
i. Development of a Specification for the use of Emulsions in Cold Mix	**X**	**X**			
ii. Evaluation of Asphalt Emulsion Rheological Properties	**X**	**X**			
iii. Development of Volumetric Mix Design Procedures		**X**	**X**	**X**	
iv. Mixture Performance Testing				**X**	**X**
v. Develop Revised Mix Design Procedures and Recommendations		**X**	**X**	**X**	**X**

Budget

The estimated budget for this subtask is $630,000 over the five year time frame and will be conducted by the University of Wisconsin-Madison and the University of Nevada.

Relationship to FHWA Focus Areas

- Environmental Stewardship
- This subtask will develop the use of the gyratory plate as an improved measure of mix workability.
- A clear definition of mix design and construction procedures will provide basis for modeling of energy savings associated with the use of cold mixes.
- Mixture performance testing will provide insight into the risk of compromising performance at the expense of energy savings.

References

1. Asphalt Institute: "Asphalt Cold Mix Manual" Asphalt Institute, Lexington, KY, 1989.

2. ASTM D3628. "Selection and Use of Emulsified Asphalts." Annual Book of ASTM Standards, 2006, American Society for Testing and Materials, Philadelphia, PA.

3. 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.

4. 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.

5. Jenkins K. J., Molenaar, A, de Groot, Van de Ven. "Foamed Asphalt Produced Using Warmed Aggregates." Association of Asphalt Paving Technologists, Colorado Springs, CO 2002.

Category E2: Design Guidance

Work element E2a: Comparison of Modification Techniques (Later start)

It is well known that cost vary significantly among common asphalt modification techniques. Although modeling can be blind, materials' selection can be significantly improved if knowledge of trends in effects of modification types can be plotted or mapped. This work element will start in the second year and will be based on data collected in other work elements conducted by the consortium.

Work element E2b: Design System for HMA Containing a High Percentage of RAP Material (Year 1 Start)

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 et al. (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% 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.

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 mixtures) through the mix design process and the performance evaluation of the final HMA mixture containing RAP materials.

Experimental Design

The following tasks will be completed in order to achieve the objectives of this research effort. The following Consortium members will participate in this effort: University of Nevada, Reno (UNR), University of Wisconsin, Madison (UWM), Western Research Institute (WRI), Advanced Asphalt Technologies, LLC (AAT), Granite Construction Company (Dr. Jon A. Epps). The following tasks are planned:

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 task 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 mastic from the RAP, without using solvents, will be pursued. A method for estimating RAP binder properties from the mastic deploying the technology currently used in binder testing will be developed.
3. If mastic 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 task will identify a standard method for measuring the specific gravity of RAP and aggregate and develop a standard procedure.

Subtask E2b-2: Compatibility of RAP and Virgin Binders

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 % 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 task 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.

Subtask E2b-3: Develop a Mix Design Procedure

This task 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 task 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 Tasks 1 and 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 task 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

Subtask E2b-4: Impact of RAP Materials on Performance of Mixtures

This task 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 task will conduct an experimental program to evaluate the fundamental properties and resistance to distresses of the RAP mixtures that were used and designed in Task 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 task 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.

<u>Subtask E2b-5: Field Trials</u>

This task 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 tasks.

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 task will attempt to develop an acceptance guideline based on simple tests either on the entire RAP mix or on RAP components. This task 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 practical and reliable.

<u>Year 1 Project Direction</u>

It is anticipated that Subtasks E2b-1 and E2b-2 will start in Year 1.

Schedule

Subtask	Year 1	Year 2	Year 3	Year 4	Year 5
E2b-1. Develop a System to Evaluate the Properties of RAP Materials	**X**	**X**			
E2b-2. Compatibility of RAP and Virgin Binders	**X**	**X**			
E2b-3. Develop a Mix Design Procedure		**X**	**X**		
E2b-4. Impact of RAP Materials on Performance of Mixtures			**X**	**X**	**X**
E2b-5. Field Trials				**X**	**X**

Relationship to FHWA Focus Area

This research effort supports the FHWA Focus Areas of Optimize Pavement Performance and Environmental Stewardship.

Budget

The anticipated budget of the research partners are listed in the Table below. The participation of Granite Construction Co. will be used as a cost share component.

ARC Member	Year 1	Year 2	Year 3	Year 4	Year 5
UNR ($)	75,000	250,000	325,000	300,000	300,000
UWM	45,000	45,000	75,000	45,000	45,000
WRI	20,000	40,000	10,000	10,000	20,000
AAT	12,500	33,500	34,000	28,000	17,000

References

Hajj, E. Y., P. E. Sebaaly, and R. Shrestha, "A Laboratory Evaluation on the Use of Recycled Asphalt Pavements in HMA Mixtures," Western Regional Superpave Center, University of Nevada, Reno, Final Report, 2007.

Sebaaly, P. E. and R. Shrestha, "A Literature Review on the Use of Recycled Asphalt Pavements in HMA Mixtures," Western Regional Superpave Center, University of Nevada, Reno, Final Report, 2004.

Stroup-Gardiner, M., and C. Wagner, 1999, Use of RAP in Superpave HMA Applications. Transportation Research Record 1681, pp. 1-9.

Sondag, M. S., 2000, Investigation of Recycled Asphalt Pavement Mixtures. University of Minnesota, Final Report.

Work element E2c: Critically Designed HMA Mixtures (Year 1 start)

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.

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 immediately be subjected to the local environmental conditions and traffic loading. Due to the viscoelastic 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 task 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).

Subtask E2c-2: Conduct Mixture Evaluations

The objective of this task 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 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. It is anticipated that a total of 50 HMA mixtures will be evaluated. The permanent deformation curves similar to the one shown in Figure 1 will be developed for each mixture under the various combinations of temperature and rate of loading as determined in Task 1.

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 impractical test for routine applications.

This task will use the evaluation data from the RLT tests conducted in Task 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 proved unfeasible, then other tests will be investigated.

Subtask E2c-4: Develop a Standard Test Procedure

The objective of this task 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.

Subtask E2c-5: Evaluate the Impact of Mix Characteristics

The objective of this task is to identify the mix characteristics that impact the critical temperature and loading rate of HMA mixtures. This task will use the test procedure developed in Task 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 task 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 task 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 task 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.

Year 1 Project Direction

It is anticipated that Subtasks E2c-1 and part of Subtask E2c-2 will be completed in the first year.

Schedule

Subtask	Year 1	Year 2	Year 3	Year 4	Year 5
E2c-1. Identify the Critical Conditions	**X**				
E2c-2. Conduct Mixture Evaluations	**X**	**X**			
E2c-3. Develop a Simple Test			**X**	**X**	
E2c-4. Develop Standard Test Procedure				**X**	
E2c-5. Evaluate the Impact of Mix Characteristics				**X**	**X**

Relationship To FHWA Focus Area

This research effort supports the FHWA Focus Areas of Optimize Pavement Performance and Advanced Quality Systems.

Budget

The estimated budget of this work element is $600,000.

Work element E2d: Thermal Cracking Resistant Mixes for Intermountain States (Year 1 start)

Thermal cracking of HMA mixtures is caused by the non-polar oily or neutral fractions of the binder becoming a rigid solid at low temperature. Glass is a common example of such an amorphous super-cooled liquid and thus the analogy to glass is responsible for the term "glass transition temperature" of asphalts which is the temperature at which the liquid component of the asphalt freezes to a solid. Any attempt to deform the frozen structure results in 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. The work by Coons and Wright in 1968 concluded that binder oxidation occurs only in the top inch of the pavement and that below the top inch, the binder is left virtually unaffected by years of use and years of environmental exposure. On the other hand, recent work by Glover et al (2005) indicated strongly that in fact binders can age in pavements well below the surface and that the hardening of binder in the pavement is virtually unabated over time. Recent studies on glass transition behavior during the SHRP program on binders, and subsequently at the University of Wisconsin, Madison (UWM) on binders and mixtures, has shown that sources of asphalt binders, modification, aging, and aggregate properties can alter the glass transition behavior significantly. In addition, recent studies at UWM, as part of a pooled fund study TPF-05 lead by MnDOT, showed that thermal cycling has an important effect. Results show 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 cracking prediction.

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

In order to achieve the objectives of this research effort, the following subtasks will be completed. The following Consortium members will participate in this effort:

- University of Nevada, Reno (UNR)
    - Dr. Claine Petersen (Consultant)
    - Dr. Charles Glover (Consultant)
- University of Wisconsin, Madison (UWM)

Subask E2d-1: Identify Field Sections

This task 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**.**

Subtask E2d-2: Identify the Causes of the Thermal Cracking

This task 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 task 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 task 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 1 and 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 task 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.
- A thermal cracking test that simulates the actual tensile mode of loading that is experienced by the HMA layer.

The activities of this task 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-4: Modeling and Validation of the Developed System

This task will develop a software program for prediction of critical cracking temperatures using the input variables measured in Subtask 3. The software will include variables that are found to be important in Subtask 3 and that have shown clear role in predicting the performance observed in the field.

The task 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 task 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.

Subtask E2d-5: Develop a Standard

This task will develop a standard testing procedure for the system developed in Subtask 3 and validated in Subtask 4. The standard will be prepared in AASHTO format.

Year 1 Project Direction

It is anticipated that Subtask E2d-1 will be started in Year 1.

Schedule

Subtask	Year 1	Year 2	Year 3	Year 4	Year 5
E2d-1. Identify Field Sections	**X**	**X**			
E2d-2. Identify the Causes of the Thermal Cracking		**X**	**X**		
E2d-3. Identify an Evaluation and Testing System		**X**	**X**	**X**	
E2d-4. Modeling and Validation of the Developed System				**X**	**X**
E2d-5. Develop a Standard				**X**	**X**

Relationship to FHWA Focus Area

This research effort supports the FHWA Focus Areas of Optimize Pavement Performance and Advanced Quality Systems.

Budget

The estimated budget of this work element is $930,000 and will be conducted by the University of Nevada and the University of Wisconsin-Madison.

References

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.

Work element E2e: Design Guidance for Fatigue and Rut Resistance Mixtures (Year 1 Start)

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.

Hypothesis

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 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 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 (1). In this task, 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 Task 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 task 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 task 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.

Year 1 Project Direction

It is anticipated that Subtasks E2e-1 and part of Subtask E2e-2 will be completed in Year 1.

Schedule

Subtask	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**
E2e-1. Identify Model Improvements	**X**				
E2e-2. Design and Execute Laboratory Testing Program	**X**	**X**	**X**		
E2e-3. Perform Engineering and Statistical Analysis to Refine Models			**X**	**X**	
E2e-4. Validate Refined Models				**X**	
E2e-5. Prepare Design Guidance					**X**

Relationship to FHWA Focus Area

This research effort supports the FHWA Focus Area of Optimize Pavement Performance.

Budget

The estimated budget for this work element is $371,500 and will be conducted by Advanced Asphalt Technologies.

References

Dongre, R., L. Myers, J. D'Angelo, C. Paugh, and J. Gudimettla (2005). Field Evaluation of Witczak and Hirsch Models for Predicting Dynamic Modulus of Hot-Mix Asphalt. *Journal of the Association of Asphalt Paving Technologists*, Vol. 74.

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.

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

BACKGROUND

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 mid-western region 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 reduced 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.

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.

OBJECTIVE

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.

In order to achieve the objectives of this work plan, the following subtasks will be completed.

<u>Subtask VP2a-1: Evaluate common physical and mechanical properties of asphalt mixtures with enhanced frictional skid characteristics</u>

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 mixtures' 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. NCHRP most recent reports and the world wide literature will be covered.

<u>Subtask VP2a-2: Evaluate pavement macro and micro-textures and their relation to tire and pavement noise-generation mechanisms</u>

There are 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 tasks 1 and 2 and the laboratory testing protocol developed in Task 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 Tasks 4 and 5 will be correlated to pavement mixture design parameters (e.g., porosity, rugosity, granulometry, 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.

YEAR 1 PROJECT DIRECTION

It is estimated that subtasks VP2a-1 though VP2a-3 will start during the first year.

SCHEDULE

Task	Year 1		Year 2		Year 3		Year 4		Year 5	
	Month									
	6	12	18	24	30	36	42	48	54	60
1	X	X								
2	X	X								
3		X	X	X	X					
4			X	X	X	X				
5				X	X	X				
6					X	X	X	X		
7							X	X		

RELATIONSHIP TO FHWA FOCUS AREA

This research effort fits under the flowing FHWA Focus Areas:

1. Advanced quality systems: Further development of test methods and design procedures that are more related to actual pavement performance.
2. Environmental Stewardship: Reduce noise of pavements is an environmental issue.

BUDGET

The anticipated budget is $325,000.

ARC Member	Year 1	Year 2	Year 3	Year 4	Year 5
UW-Madison	$75,000	$100,000	$100,000	$50,000	$0

REFERENCES

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/.

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". Report to the FHWA. URL: Html:// http://international.fhwa.dot.gov/quiet_pav/index.htm

Guisik, K., D. Noyce, and H. U. Bahia (2004). "Incorporating Road Safety into Pavement Management". MRUTC 04-04 Technical Report.

Category VP3: Modeling

Work element VP3a: Pavement Response Model to Dynamic Loads (Later start)

The researchers will develop a computer model to predict the responses of flexible pavements to dynamic loads generated by traffic moving at speeds ranging from stopping at intersections to highway cruising speed. The 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.

Two major input components to the pavement response model are: magnitude of vehicle dynamic loads and stress distributions at the tire-pavement interface. The proposed model will incorporate results from existing state of the art technology in vehicle dynamics to predict the distribution of dynamic loads as a function of road roughness and vehicle speed. In the case of stress distributions at the tire-pavement interface, results of previous field and laboratory studies conducted by the UNR researchers and others will be incorporated. It is anticipated that the University of Nevada will conduct this task.

PROGRAM AREA: VALIDATION

TITLE: FIELD VALIDATION

BACKGROUND

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.

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.

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.

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.

Category V3: R&D Validation

Work element V3a: Continual Assessment of Specifications (Year 1 start)

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, 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.

Work element V3b: Validation of the MEPDG Asphalt Materials Models using new MEPDG Sites and Selected LTPP Sites.

<u>Background</u>

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. For example the 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 data base can serve as basis for early validation because sections included in the data base have had several years of traffic and aging.

Hypothesis

The performance of the MEPDG designed flexible pavements coupled with the data generated by the Consortium research activities 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 (Start Year 1, Year 2, and Year 3)

This task 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 task 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. It is anticipated that a total of 25 sections will be constructed throughout the duration of the research. The sources and properties of the materials will be incorporated into the Materials Database.

Subtask V3b-2: Additional Testing (Start Year 2, Year 3, and Year 4)

This task 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 task will be conducted by researchers from UNR, AAT, 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. For the LTPP sections, the samples stored in the materials' library will be used.

Subtask V3b-3: Select LTPP Sections (Start Year 1 thru Year 5)

This subtask will be focused on screening the available sections for which noticeable good or poor performance have been recorded. Also, 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 task cannot be estimated at this stage but an attempt will be made to have 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 intended to validate. UNR will focus on the low temperature thermal cracking and UW-M will focus on new binder rutting and fatigue testing. Every effort will be spent to coordinate the activities among consortium members and with LTPP. The binder rutting and fatigue validation will start in year 1.

Subtask V3b-4: Testing of Extracted Binders from LTPP sections. (Start Year 1)

This subtask will be focused on testing extracted binders using the DSR and BBR as required for the current PG grading system with the objective of integrating the new data in the LTPP database and thus enhance the information about the relationship between the PG grading and actual pavement performance. During the first year, the Consortium will work with the FHWA LTPP Team to identify the materials that will be tested and establish protocols for data transfer. Actual testing of materials will begin in Year 2 and continue through the middle of Year 4.

Subtask V3b-5: Review and Revisions of Materials Models (Start Year 2, Year 3, Year 4, and Year 5)

The first part of this task 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 Tasks 1, 2 and 3, the research team will evaluate the prediction equations and E* Master curves and modify them to accommodate polymer-modified binders and mixtures. Another example is the evaluation of the Superpave-plus binder specifications and the need for the elastic recovery test or the MSCR test. Using the pavement performance data from the LTPP sites and the laboratory test results of mixtures for the new MEPDG sections, an assessment of the value of these tests and there relationship to performance could be determined.

Subtask V3b-6: Evaluate the Impact of Moisture and Aging (Start Year 3, Year 4, and Year 5)

This task will evaluate the effects of moisture and aging on materials 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….

Researchers from UNR, AAT, UWM, and WRI will examine the aging models currently used in the MEPDG and identify the need for any modifications.

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 having aging models based on the RTFO, which is not useful for many modified asphalts. In this task, researchers from UNR, AAT, UWM, and WRI will assess the gaps in the models and specifications and the need to revisions for aging models and the need to incorporate the impact of moisture damage on the properties and behavior of HMA mixtures in models of the MEPDG and in materials specifications.

YEAR 1 PROJECT DIRECTION

The first year project direction is to begin work on Work elements V1a, V1b, V3a, and V3b.

SCHEDULE

Activity	Year 1	Year 2	Year 3	Year 4	Year 5
Work element V1a	X	X	X	X	X
Work element V1b	X	X	X	X	X
Work element V2a			X	X	
Work element V2b			X	X	
Work element V3a	X	X	X	X	X
Subtask V3b-1	X	X	X		
Subtask V3b-2		X	X	X	
Subtask V3b-3	X	X	X	X	X
Subtask V3b-4	X	X	X	X	
Subtask V3b-5		X	X	X	X
Subtask V3b-6			X	X	X

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 performance in order to validate laboratory tests, performance models, and methods.

BUDGET

The budget for all of the work elements in the Validation area is estimated to be $5.08M over the five years of the project but is subject to the number of projects identified and completed.

PROGRAM AREA: TECHNOLOGY DEVELOPMENT

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.

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

WORK ELEMENTS PLANNED

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 (Year 1)

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. A Product Review Committee composed of one representative from each Consortium partner, one FHWA representative, and three representatives from each of the ETG's will review the product summaries and rate the products based on two criteria:

1. The relevancy of the product to current critical issues in asphalt pavement technology,
2. The practicality of implementing the product by highway agencies, industry, and research agencies.

Products receiving the highest overall ratings will be recommended for further development. For those products that are recommended, a Product Review Team will be established by the Product Review Committee to guide the additional development that will take place in Work Element TD2.

Work element TD2: Develop Early Products (Year 2)

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 Product Review Team and 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 (Year 2, 3, and 4)

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 assigned to the Product Review Committee for detailed review based on the criteria established in Work Element TD1. The Product Review Committee will recommend the 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.

For those products recommended for development, a Product Review Team will be established by the Product Review Committee to guide the additional development that will take place in Work Element TD4.

Work Element TD4: Develop Mid-Term and Long-Term Products (Years 3, 4, and 5)

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 Product Review Team and the FHWA AOTR. Once agreement is reached on the scope and budget, the assigned Consortium partner will undertake the development effort.

Anticipated Participation of the Consortium Partners in Technology Development

Element	Title	Consortium Partner				
		WRI	TTI	UWM	UNR	AAT
TD1	Prioritize and Select Products for Early Development	X	X	X	X	X
TD2	Develop Early Products	X	X	X		X
TD3	Identify Products for Mid-Term and Long-Term Development	X	X	X	X	X
TD4	Develop Mid-Term and Long-Term Products	X	X	X	X	X

YEAR 1 PROJECT DIRECTION

First year efforts in the Technology Development Program Area will be directed at completing Work Element TD1: Prioritize and Select Products for Early Development. To accomplish this it is critical that the FHWA and each ETG identify its Product Review Committee members during the July meetings of the ETGs.

SCHEDULE

Activity	Year 1	Year 2	Year 3	Year 4	Year 5
Work Element TD1	**X**				
Work Element TD2		**X**			
Work Element TD3		**X**	**X**	**X**	
Work Element TD4			**X**	**X**	**X**

RELATIONSHIP TO FHWA FOCUS AREAS

The Technology Development Program Area supports the FHWA Focus Areas of Optimizing Pavement Performance, Advanced Quality Systems, and Technical Capability Building.

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 of the Consortium while the training effort will start in the second year 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 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 tasks will be completed in order to achieve the objectives of this research effort. The following Consortium members will participate in this effort:

- University of Nevada, Reno (UNR)

Work element TT1a: Development and maintenance of consortium website (Duration: Year 1 through Year 5)

A Consortium Website will be de 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. It is anticipated that the University of Nevada will develop and maintain the consortium website.

Work element TT1b: Communications (Duration: Year 1 through Year 5)

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. It is planned that the University of Nevada will produce the communication materials and the other Consortium partners will contribute with information pertinent to their activities.

Work element TT1c: Prepare presentations and publications

Work element TT1d: Development of materials database (Duration: Year 2 through Year 5)

A materials database will be developed and designed to store information related to the sources and properties of the materials that are being used in the various research activities of the consortium. The overall structure of the database will be defined based on the type of the data collected and the information that needs to be stored. The consortium website developed in Task 1.0 will serve as a mean to access the database. A dynamic database-driven web application will be developed allowing data users to present information retrieved from the database on the web pages. Additionally, authorized personnel of the Consortium partners will have a secured access to populate the database with information pertinent to their activities. The subsequent steps will be followed to design the materials database system.

Subtask TT1d-1: Identify the overall features of the web application

Under this task, UNR will identify and list the aspects of the web application. The list of the identified features will be sent to the Consortium partners for inputs and modifications. It is anticipated at this point that the web application will include the following features:

- Allow any user to request and retrieve information from the Consortium materials database through an electronic format.
- Allow authorized users to add, delete, and edit materials information through an electronic format.
- Allow authorized users to create a new category of materials.

Subtask TT1d-2: Identify materials properties to include in the materials database system

This task will identify the specific materials information that needs to be included in the materials database system. UNR will contact the Consortium partners and collect the anticipated type of materials properties to be reported.

Subtask TT1d-3: Define the structure of the database

After identifying the features of the web application, the type of information requested by users will be the basic step for defining the structure of the database. This task will define how the database should be structured to best answer users' needs. 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 Micromedia 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 TT1d-4: Create the database

The final design step is to create the database using a database system like Microsoft Access, SQL Server, or Oracle9i. A quality control (QC) system for data checks during acquisition and prior to database loading will be developed. QC checks on the information consist of validity of the provided information. Range checks on the validity and reasonableness of values entered in a field will be conducted. Additionally, relational checks between data stored in other fields will be conducted.

Work element TT1e: Development of research database (Duration: Year 2 through Year 5)

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 system

This task 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 the database

The final design step is to create the database using a database system like Microsoft Access, SQL Server, or Oracle9i.

YEAR 1 PROJECT DIRECTION

It is anticipated that Tasks 1 and 2 will start in Year 1.

SCHEDULE

Task	Time Frame				
	Year 1	Year 2	Year 3	Year 4	Year 5
1	x	x	x	x	x
2	x	x	x	x	x
3		x	x	x	x
4		x	x	x	x

RELATIONSHIP TO FHWA FOCUS AREA

This research effort fits under the FHWA Focus Area of Technical Capabilities Building.

BUDGET

The anticipated budget is listed in the Table below.

	Year 1	Year 2	Year 3	Year 4	Year 5
UNR	50,000	150,000	150,000	150,000	150,000