Asphalt Research Consortium

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RESEARCH PLAN FOR YEAR 4 OF FEDERAL HIGHWAY ADMINISTRATION CONTRACT DTFH61-07-H-00009 "ASPHALT RESEARCH CONSORTIUM"

INTRODUCTION

This document is the proposed Research Plan for Year 4 of the Federal Highway Administration (FHWA) Contract DTFH61-07-H-00009, the Asphalt Research Consortium (ARC). The Consortium is coordinated by Western Research Institute with partners Texas A&M University, the University of Wisconsin-Madison, the University of Nevada Reno, and Advanced Asphalt Technologies.

The Year 4 Work Plans continue the research that was extensively detailed in the Year 2 and Year 3 Work Plans and are grouped into seven areas, Moisture Damage, Fatigue, Engineered Paving Materials, Vehicle-Pavement Interaction, Validation, Technology Development, and Technology Transfer.

The Year 2 Work Plans, originally submitted in January 2008, were reviewed and responses to the reviewer comments were prepared and discussed with FHWA Co-AOTR's Dr. Jack Youtcheff and Mr. Eric Weaver. In August 2008, agreement with the Co-AOTR's on a Revised Year 2 Work Plan was achieved. Subsequently, a Revised Year 2 Work Plan was prepared and placed on the ARC website, www.ARC.unr.edu . The Revised Year 2 Work Plan is intended to be master document for the ARC research. Similarly, the Year 3 Work Plans were prepared and submitted in January 2009 and subsequently reviewed. A considerable amount of the background information for the Year 4 Work Plan is contained in the Revised Year 2 and Year 3 Work Plans, Quarterly Reports, and associated documents on the website. A master list of references that have been used in all ARC documents was also prepared and can be found at the ARC website, www.ARC.unr.edu.

PROGRAM AREA: MOISTURE DAMAGE

CATEGORY M1: ADHESION

Work Element M1a: Affinity of Asphalt to Aggregate

Major Findings and Status

In Year 3, tests were conducted to correlate tack test results measured using the Dynamic Shear Rheometer (DSR) to the Pneumatic Adhesion Tensile Testing Instrument (PATTI) results. Evaluation of the tack test was performed using the plate-and-rock geometry in which the 8-mm-diameter parallel-plate geometry was used on a 25-mm-diameter rock disk. Although every attempt was made to carefully conduct the experiment, the results obtained were not repeatable.

A modified PATTI test procedure was developed and successfully implemented. The modified PATTI procedure is able to differentiate between the performances of different binder-aggregate systems. The effect of different modifications on bond strength and on moisture effects can be clearly identified with the new PATTI procedure.

As an alternative to the PATTI test, the research group investigated the feasibility of determining the pull-off strength of binder-aggregate systems using the portable Posi test. Preliminary correlations between test results of the PATTI and Posi test results were calculated. However, the Posi device still presents a major challenge in terms of controlling the loading rate. Previous quarterly reports indicate that there is a significant difference between the results obtained from these two devices.

Moisture susceptibility of the aggregate/binder interface was investigated by means of strain sweep tests in the DSR. Rheological properties of a small set of asphalt-aggregate interfaces before and after water conditioning were obtained. The test methodology allows for differentiating the susceptibility of binder-aggregate systems to moisture conditions. However, the experimental method poses a major issue in terms of testing time (i.e., seven hours to run one specimen).

Issues Identified During the Previous Year and Their Implications on Future Work

The experimental results from the tackiness tests performed after conditioning with water on rock disks showed inconsistent and highly variable results. The research team proposes removing the DSR tack test for moisture susceptibility characterization from the work plan. The low repeatability of test results is due to several factors, including difficulties in trimming the 8-mm-diameter sample on a 25-mm-diameter rock plate.

Research performed in Year 3 also indicates that the Posi test may not be used to measure adhesion/cohesion in binder-aggregate systems due to the highly variable loading rate. Measurements that are not representative and inconsistent will be obtained when the loading rate during testing is variable. The research team proposes removing the Posi test from the work plan.

For Year 4, the research team decided to combine the work elements M1a, Affinity of Asphalt to Aggregate, and M2c, Measuring Thin Film Cohesion and Adhesion Using the PATTI Test and the DSR, due to their similarities and overlapping objectives. All the research activities to be performed in work element M2c are included in this work plan for the M1a work element.

Year Four Work Plan

Subtask M1a-1: Select materials

The work for this subtask was completed during Year 2. Detailed information for this subtask can be found in previous quarterly reports.

Subtask M1a-2: Conduct PATTI and modified DSR tests

An extended experimental matrix, which includes binders of different bases, modifications and rock types to account for different chemical and physical conditions in the aggregate/binder interface, will be completed in Year 4. The experimental plan will focus on use of the modified PATTI test procedure, which is called the Bitumen Bond Strength (BBS) test. Verification of the BBS test will be conducted by performing a limited number of modified DSR strain sweep tests. Preliminary results in Years 2 and 3 indicate that performing modified DSR tests are very time-consuming compared to the PATTI procedure. For example, in a period seven hours, only one specimen can be tested in the modified DSR as compared to the PATTI test, in which 5 to 6 specimens (depending on the number of stubs available) can be tested in the same period of time. Table M1a.1 summarizes the proposed extended experimental matrix for the PATTI and DSR testing in Year 4.

Table M1a.1. Proposed tests on asphalt binders.

Testing Techniques	Modified PATTI DSR strain sweep (limited)
Mineral Surfaces	Three: Granite, limestone, and sandstone
Binders	Three (with significantly different chemistry)
Modifications	Four: SBS, Elvaloy, PPA and warm mix additives

SBS = styrene-butadiene-styrene. PPA = polyphosphoric acid.

Subtask M1a-3: Evaluate the moisture damage of asphalt mixtures

Using the binders tested in subtask M1a-2A, mixture specimens will be compacted and tested for moisture susceptibility following the latest protocol for Tensile Strength Ratio (TSR) testing.

Table M1a.2 lists the set of materials to be used in this subtask. The results obtained from mixture testing will be correlated with the experimental data generated in subtask M1a-2.

Table M1a.2. Proposed tests on asphalt mixtures.

Testing techniques	TSR or newly developed moisture-susceptibility test
Aggregates	Two: Granite and limestone
Binders	Three (with significantly different chemistry)
Modifications	Four: SBS, Elvaloy, PPA, warm mix additives

Subtask M1a-4: Correlate moisture damage between PATTI, DSR and mix tests

The research team will focus on obtaining statistical correlations between the moisture susceptibility performance obtained from modified PATTI procedure—the BBS test—and from mixture testing using the TSR. Correlations between the limited data obtained from the modified DSR and the PATTI tests will also be calculated.

The research team will focus on explaining from a fundamental point of view the promising preliminary results obtained in Year 3 from the PATTI procedure. An extensive literature review will be performed on the chemical and physical mechanisms driving the moisture susceptibility phenomena of asphalt-aggregate systems.

Subtask M1a-5: Propose a novel testing protocol

Before a novel testing protocol is proposed, several numerical simulations of the PATTI test using the finite element method (FEM) will be performed to determine the influence of binder stiffness, loading rates, and eccentricity of the pull-off load on the testing results. These mechanistic analyses will allow the research team to have a better understanding of the stress conditions in the sample.

Subtask M1a-6: Standard testing procedure and recommendation for specifications

This subtask is taken from the work plan of work element M2c, subtask M2c-5. The research team has contacted manufacturers of the PATTI device and completed the modified PATTI test apparatus. The new device is called the Quantum Gold PATTI. In Year 4, state departments of transportation 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 offered to collect feedback from experts. The feedback will be summarized and used to make modifications in the developed system. Based on the extensive experimental data obtained during Year 3 and the proposed experimental work for Year 4 as reflected in table M1a.1, the research team plans to develop a final testing protocol for the PATTI test following an AASHTO format.

Table for Decision Points and Deliverables

Date	Deliverable	Description
04/10	Presentation	Presentation at ETG or technical conference.
08/10	Journal Paper	TRB or AAPT paper submission summarizing findings on moisture susceptibility characterization of aggregate-binder interface using PATTI and DSR.
09/10	Presentation	Presentation at the Binder or Mixture ETG.
01/11	Presentation	Presentation on correlation between moisture susceptibility of mixtures and results from PATTI.
01/11	Journal Paper	Paper to a technical journal on the effect of modifiers on moisture damage.
03/11	Final Report	Final Report on work element.

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

Major Findings & Status

A test protocol to determine the enthalpy of adhesion between the aggregate and asphalt binder using a micro calorimeter at room temperatures was developed in the previous years. The test protocol was developed jointly to address the needs of this research project as well as another FHWA research project on warm asphalt mixtures. Test methods to measure surface free energy of asphalt binders and aggregates were developed in the previous NCHRP research project 9-37. The main goal of this subtask is to provide material property inputs required in other work elements. The data obtained from this subtask is being compiled in the materials property database.

Year Four Work Plan

The plan for year four is to utilize these three tests to measure surface properties of materials that have been included in the test plan. The information generated from this sub-task will serve as an input for other subtasks on materials characterization and modeling.

Table for Decision Points and Deliverables

Date	Deliverable	Description
09/30/09(1)	Journal Paper	Use of micro calorimeter to measure total energy of adhesion

(1) Vasconcelos et al. (2009a and b)

References

Vasconcelos, K.L., **A. Bhasin**, and D. N. Little, 2009a, Influence of Surface Properties of Aggregates on Adhesion and Performance of Asphalt Fine Aggregate Matrix. *Road Materials and Pavement Design* (In Review).

Vasconcelos, K.L., **A. Bhasin,** and D. N. Little, 2009b, Influence of Asphalt Mixture Production Temperatures on the Surface Properties of Aggregates and Mixture Performance. CD ROM *88th Annual Meeting, Transportation Research Board*, Washington, D.C.

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

Major Findings & Status

The detailed work plan for this subtask is presented in the Year 3 ARC Work Plan.

An automated sample thin-film spin-caster has been completely assembled and tested, figure M1b-2.1. This system will be used to prepare all forms of asphaltic and model compound thin-films to be further studied by nano-mechanical analyses and scanning probe imaging

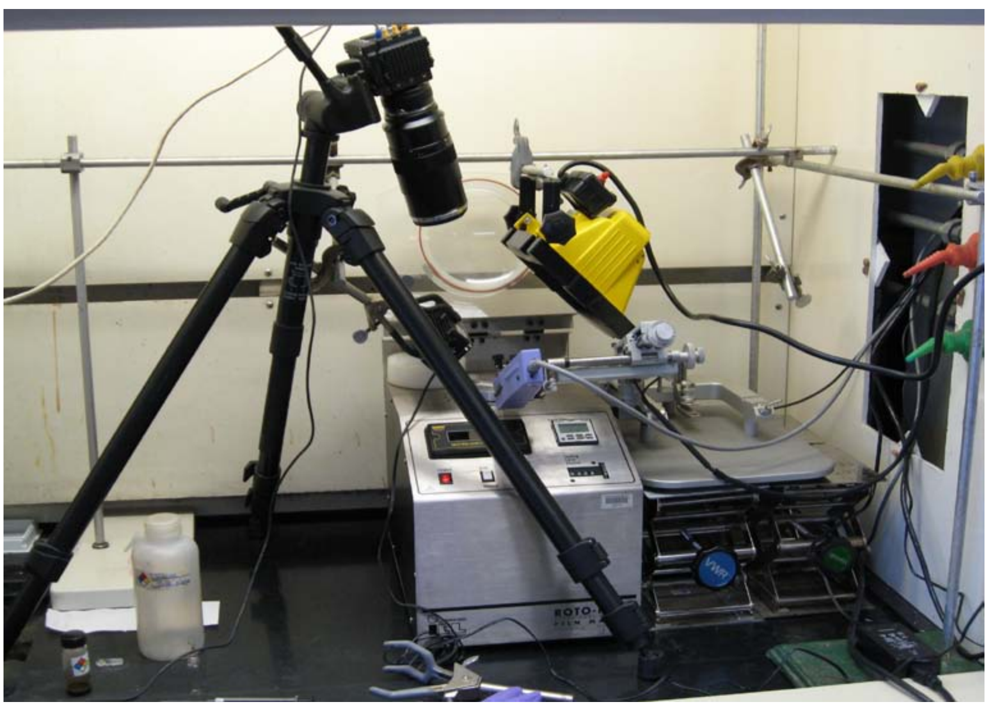


Figure M1b-2.1. Automated sample thin-film spin-caster, equipped with spin-caster, robotic-arm syringe-pump dispenser, and high speed digital camera for film instability control.

Work Plan Year Four

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

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

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

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

Subtask M1b-3: Identify Mechanisms of Competition Between Water and Organic Molecules for Aggregate Surface (TAMU)

Major Findings and Status

Physical and chemical properties of aggregates at the macro and molecular scale influence the performance of asphalt mixes. These properties control the nature and durability of the bond between aggregates and asphalt in wet and dry conditions and its resistance to moisture induced damage and fatigue cracking. Recent research by Little and colleagues have shown that surface energy of the aggregate-asphalt 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-asphalt combination.

Surface energy of natural substances can be divided into two major components: van der Waals and polar forces. Van der Waals forces are present in all molecules to varying degrees. Polar forces are found where electron donor/electron acceptor interactions take place. The ability to predict the magnitude of these components (and subcomponents) is valuable in understanding species behaviour. Surface energy is controlled by three master variables: surface chemistry, surface morphology, and surface coatings. Each of these has been studied on natural minerals and aggregates; however there has not yet been a comprehensive study of the surface energies of a variety of the most common minerals and aggregates. In addition there has not yet been a study of the effect of these three master variables on surface energies of natural minerals and rocks.

Our research measured the surface energy of 22 common minerals and 7 aggregates. The surface energies were broken down into van der Waals, Lewis Acid, and Lewis Base components. The samples' bulk and surface chemistries were characterized with wavelength and energy dispersive spectra (WDS & EDS) analyses on an electron microprobe and x-ray photoelectron spectroscopy (XPS). The XPS was also used to quantify the organic and inorganic coatings on the mineral and aggregates surfaces. The surface morphology was analyzed for roughness with processing software on SEM images. These data were used to predict the surface energies of aggregates based on their mineralogical content. The analyses highlighted the importance of all three variables in the type and magnitude of surface energy of natural minerals and rocks in the environment.

Year 4 work Plan

Reference year 2 and 3 work plans (M3a-1) were focused on characterizing the surface energy of a suite of minerals and aggregates. This work is completed and will be used to support the next phase of research on aggregate surfaces. In Year 4, we plan on using a flow- through calorimeter to characterize the influence of surface chemistry on organic-water-aggregate interactions as a function of the surface energy of the aggregate.

We have completed the design and construction of a dual-mode flow adsorption calorimeter (figure M1b-3.1). Differences in molar heats of reaction of different absorbates with the same absorbent are indicative of differences in the bonding strength of each adsorbate with the adsorbent of interest. Larger molar heats of reaction, in this case molar heat of adsorption, are usually indicative of stronger bond formation. The calorimeter will be used to determine the molar heats of reaction occurring at the mineral-solution interface using pure mineral phases (commonly found in aggregates) as adsorbents and model organic compounds (containing functional groups commonly found in asphalt binders) as adsorbates.

The dual-mode flow adsorption calorimeter is capable of operating in both injection and/or flow-through modes and is currently being tested and optimized. The sensing unit of the calorimeter is thermistor based and consists of: (i) a reference thermistor (Thermistor 1), which senses the temperature of the incoming adsorbate; (ii) a calibrating resistor, for calibrating calorimetric response to known heat input; (iii) a column, containing the adsorbent of interest; and (iv) a column thermistor (Thermistor 2), which senses the temperature of the adsorbate after interacting with the adsorbent. The difference in temperature between Thermistor 1 and 2 is amplified and recorded as a voltage output over time, with a return to baseline (or zero difference) considered to be the end of the reaction. The output is attributed to adsorbent-adsorbate interaction and can be used along with calibration data and the difference between initial adsorbate and effluent concentrations to directly determine molar heats of reaction.

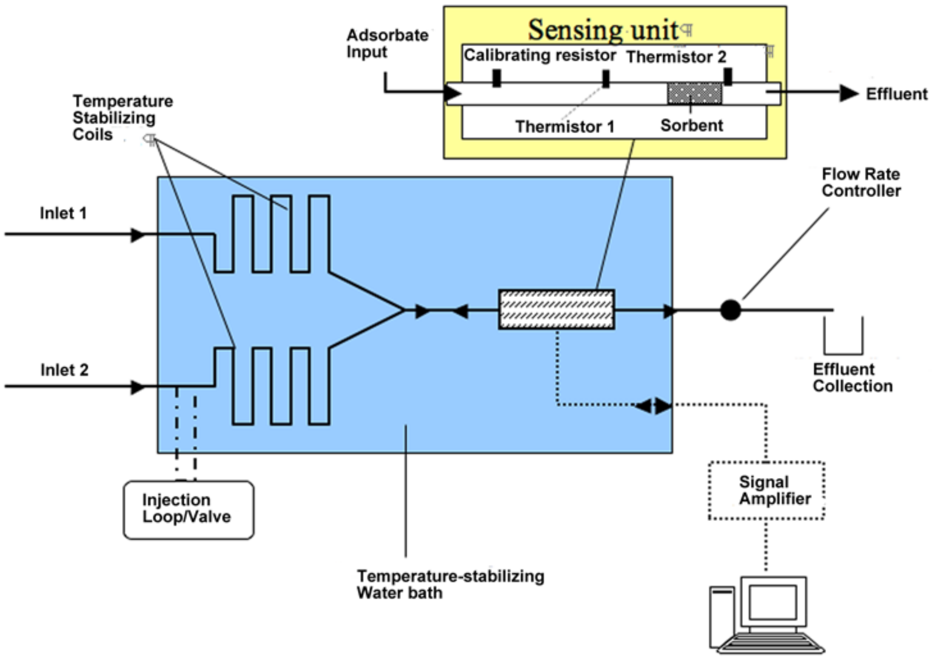


Figure M1b-3.1. Schematic of dual mode flow adsorption calorimeter.

The planned activity for Year 4 is to develop a synthesis of mechanisms of interaction between organic functional groups commonly found in asphalt and mineral surfaces. In addition this synthesis will also identify: i) minerals that can be used to represent aggregate surfaces, as well as aggregate standards and ii) model organic compounds that can be used to represent the most common functional groups in asphalt binders, based on asphalt binder and aggregate analysis data from the Strategic Highway Research Program's (SHRP) Materials reference library, and (iii) treated aggregates with lime and binders.

For multi-mineral investigations, different pure phase minerals will be mixed in ratios typical of what is found in aggregates. Interactions between these mineral mixes and single functional groups will be investigated to determine the effect of mixed mineralogy on interaction mechanism. Interactions between the mineral mixes and solutions containing multiple organic functional groups will also be investigated. Multiple organic functional group solutions will be configured consistent with ratios commonly found in different asphalt binders. Results from these multiple-functional groups experiments will be used to determine the effect of mixed solution chemistry on organic-mineral interactions.

Experiments characterizing the molecular interactions of water, rather than organic functional groups, will also be conducted with single- as well as multi-mineral mixes. Results from these experiments will be compared to those obtained from experiments with organic functional groups in order to get a first comparative look at possible mechanisms involved in asphalt water damage.

We plan on initiating flow through experiments to measure the molar heat of reaction of the adhesion of model organic compounds that represent asphalt to minerals and aggregates, as well as the molar heats of reactions of water adsorption to organic-coated minerals and aggregates. Adhesion will be modeled in the flow-through calorimeter by organic sorption from nonaqueous phase solvents. Experimental variables include the chemistry of the model organic, single versus mixtures of model organics, ionic salt content of the nonaqueous phase solvent, and the surface chemistry of the mineral or aggregate. Competition of water and the model organics for the mineral or aggregate surfaces will be characterized through flow-through experiments that introduce small amounts of water to the systems created during the adhesion studies above.

Table for Decision Points and Deliverables

Date	Deliverable	Description
05/30/10	Decision Point	Validate methods
10/31/09	Draft Report	Report on findings from subtasks M3a-1
11/30/10	Final Report	Final Report on findings from subtasks M3a-1
12/20/10	Journal Paper	Organic-aggregates interactions

Work Element M1c: Quantifying Moisture Damage Using DMA

Major Findings and Status

A new method for preparing Fine Aggregate Matrix (FAM) specimens for the DMA testing was developed. This method aims at preparing FAM specimens that represent the composition and structure of the fine portion of the mixture. The method involves preparing loose full asphalt mixtures and sieving them into different sizes. Then, ignition oven is used to determine the binder content associated with the small size materials (passing sieve #16). The sieve # 16 is used to separate fine aggregates from the coarse aggregates. Four different asphalt mixtures and three replicates from each mixture were evaluated. The binder content results from different replicates were consistent for a given mixture. FAM specimens were produced using binder content that was determined using the new method as well as the old one. The old method determines the binder content for the FAM mixture based on the binder content in the full mixture and the aggregate batch size. The FAM mixtures that were produced using the new method were easily mixed, compacted and cored compared to the ones that were prepared using the old method. The binder content in the new method is calculated as follows.

- Prepare three asphalt mixture samples similar to the G_{mm} samples according to AASHTO T 209. The minimum sample size is given in table M1c.1**.**

Table M1c.1. Minimum sample size.

Nominal Maximum Aggregate Size (mm)	Minimum Sample Size (g)
≥ 37.5	4,000
19 or 25	2,500
≤ 12.5	1,500

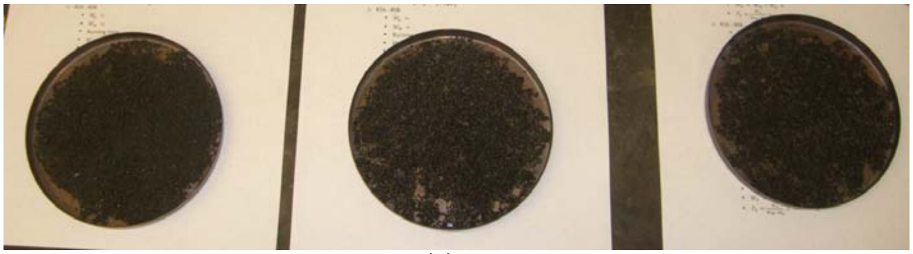
- Separate the asphalt mixture particles manually. If the mixture is too sticky, warm it up in a flat pan to get it loose.
- Use a mechanical sieving machine to sieve the loose asphalt mixture on sieve No. 16 (1.18 mm). Using 9.5mm stainless steel balls helps in separating the sticky particles during the sieving as shown in figure M1c.1.
- Dry the materials that pass through sieve No. 16 to a constant mass at a temperature of 110°C.
- Place the materials in a pan (figure M1c.2) and record the mass of the pan (W_P) and the mass of the pan and the materials (W_M) using a balance with a minimal precision of 0.001g. The total mass (W_M) should not exceed the limit of the balance and can be spread on a thin layer.
- Place the pan with the materials in an ignition oven apparatus to burn all the binder in the loose materials according to AASHTO T 308.
- After the binder burning is completed, remove the pan from the furnace and place over a cooling plate to rest for approximately 30 minutes.
- Record the mass of the pan with the left materials (W_A).
- Calculate the binder content as follows:

$$P_b = \frac{W_M - W_A}{W_M - W_P} \times 100\%$$

(a)

(b)

Figure M1c.1. (a) Loose mixture before sieving and set of sieves with stainless steel balls; (b) Sieving the loose mixture using mechanical sieving machine.



(a)

(b)

Figure M1c.2. Test materials (a) before the ignition oven; (b) after the ignition oven.

Table M1c.2 presents the determined binder contents using the new method and estimated one by the old method. It should be pointed out that the FAM specimens produced using the new method are relatively stiffer. The current available DMA has limited torque capacity (0.20 N.m), so the test temperature in the new method is 30^{o}C, which is higher than the room temperature that was used in the old method. It is planned to acquire a new DMA that has more torque capacity (5.6 N.m) in the fourth year. The FAM specimens can be tested at the room temperature using the new DMA.

Table M1c.2. Calculated binder content.

Mixture	Binder Content, %	
	Old method	New method
Limestone	10.7	8.0
Granite	12.0	7.0
Gravel	8.9	7.3
Texas	15.9	8.6

Year Four Work Plan

A new DMA (ElectroForce 3330 by Bose, Inc.) will be used to test various mixtures that will be prepared using the new method. In addition, software will be developed to analyze the DMA test data with the aim of simplifying the analysis procedure to predict fatigue life and evaluate the moisture susceptibility. This software will be developed using C++ programming language. In this software the user is required to load the DMA test raw data and specify some test information as presented in figure M1c.3. This software has two levels for processing and analyzing the test data based on the available information. Level I is used to calculate the dissipated pseudo-strain energy, and the regression parameters a and b from the following relationship (Castelo Branco 2008):

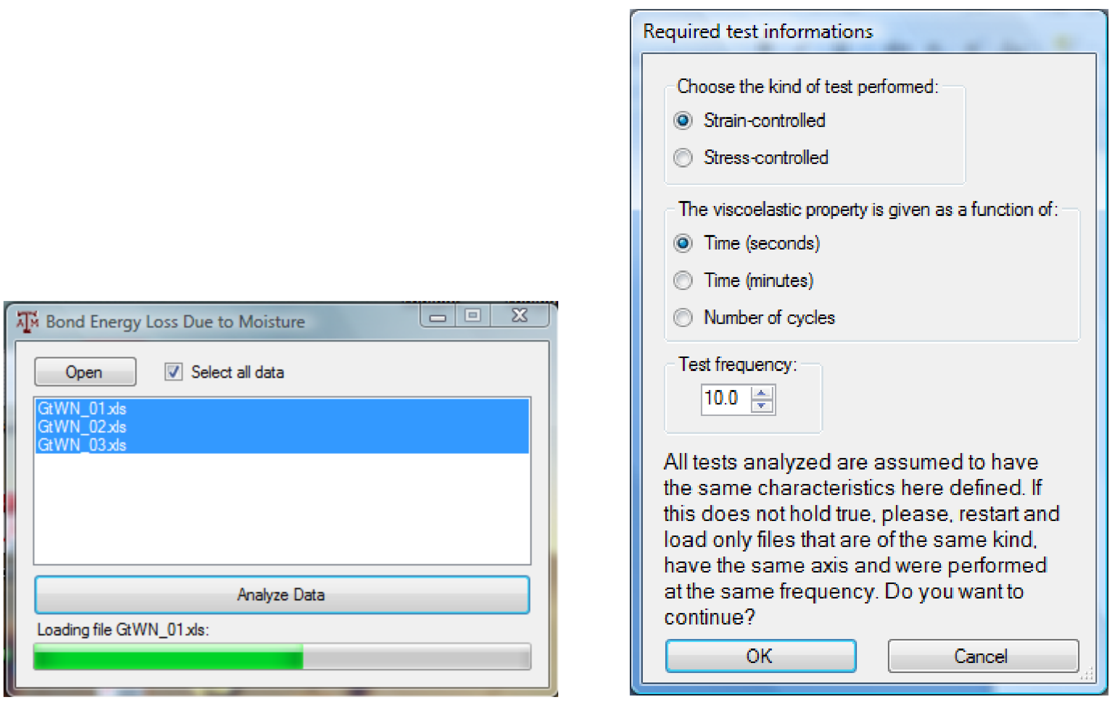
$$W_R = a + b.\ln(N) \tag{M1c.1}$$

Where N: the load cycles

Level II is used to calculate the crack growth index as a function of the load cycles $\Delta R(N)$ in dry and wet conditions as presented in the following equation (Caro et al. 2008).

$$\Delta R(N) = \left[(2n+1)^{n+1}\left(\frac{G_R\, b}{4\pi G_1\, \Delta G_f}\right)^{n} N\right]^{1/2n+1} \tag{M1c.2}$$

Where G_R is the reference modulus; ΔG_f is the work of adhesion between the asphalt binder and the aggregate. Level II can be only executed if the surface energy components of the aggregate and asphalt binder are available. The results of this software will be presented in graphs and charts to simplify the analysis.



(a) (b)

Figure M1c.3. User interface.

Cited References

Castelo Branco, V. T. F., 2008, A unified method for the analysis of nonlinear viscoelasticity and fatigue cracking of asphalt mixtures using the dynamic mechanical analyzer. Ph.D. dissertation, Texas A&M University, College Station.

Caro, S., E. Masad, E., G. Airey, A. Bhasin, and D. N. Little, 2008, Probabilistic analysis of fracture in asphalt mixtures caused by moisture damage. In *Transportation Research Record: Journal of the Transportation Research Board. No. 2057*, TRB, National Academies, Washington, D.C., 2008, pp. 28–36.

CATEGORY M2: COHESION

Work Element M2a: Work of Cohesion Based on Surface Energy

Subtask M2a-1: Methods to Determine Surface Free Energy of Saturated Asphalt Binders

Major Findings & Status

No activity was planned on this subtask for year 3 of this project.

Year Four Work Plan

The detailed work plan for this subtask from year 2 identifies two components for this Subtask. The first component is to determine the surface free energy of asphalt binders that have been saturated under water using previously developed test methods such as the Wilhelmy plate device or sessile drop method. The second component is to determine the practical work of cohesion of asphalt binders submerged under water for different durations of time. For years four and five, this subtask will focus on the first component, i.e. to measure surface free energy of asphalt binders submerged in water. The hypothesis and research approach is the same as described in the detailed year two work plan. The second component will be addressed as a part of Task F1a under fatigue. The detailed and unified experiment design for the practical work of cohesion and adhesion under wet and dry conditions is discussed in Task F1a.

Table for Decision Points and Deliverables

Date	**Deliverable**	**Description**
09/30/11	Journal Paper	Surface properties of saturated asphalt binders

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

Major Findings & Status

The detailed work plan for this subtask is presented in the Year 3 ARC Work Plan.

A custom designed nano-contact mechanics scanning probe microscope (AFM) has been assembled and tested, figure M2a-2.1. This system allows for independent stress/strain control and detection of both a nano-actuated sample stage and AFM probe. This device will be used to conduct nano-rheological measurements as discussed in FP-III Subtask 2-3, and ductile/brittle contact mechanics measurements.

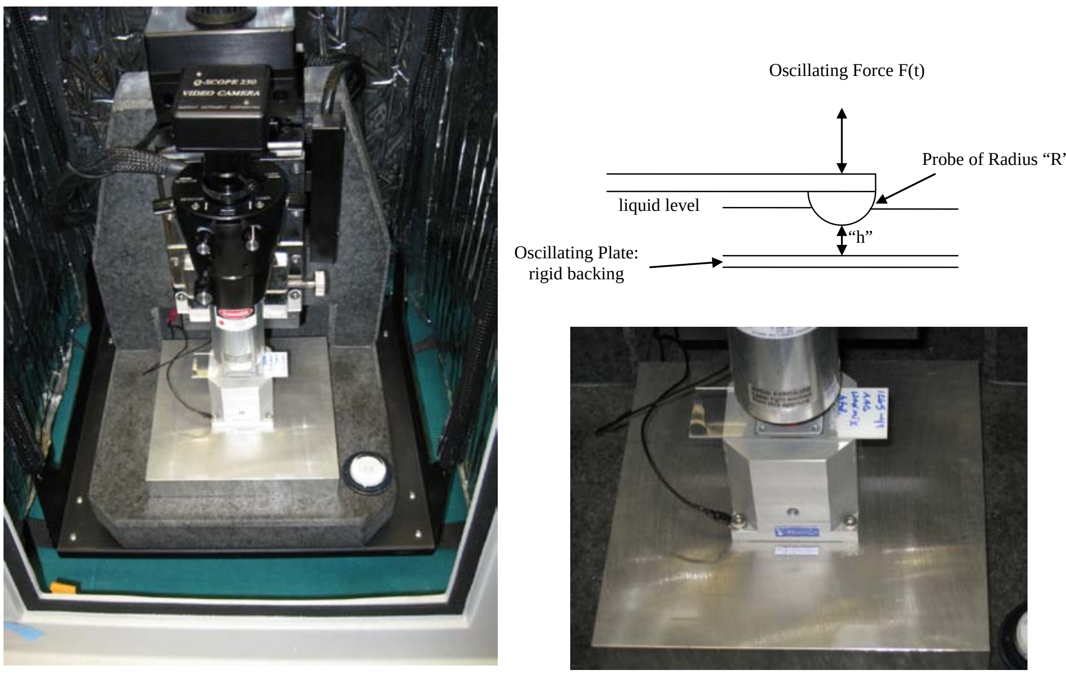


Figure M2a-2.1. Nano-mechanical AFM.

The cohesive properties of asphalt, when considered as a function of temperature, directly impact the viscoelastic properties of the material in terms of molecular orientation at free interfaces as well as within the bulk material. Thus, thermodynamically speaking, "self" cohesion may be modeled as a process of nucleation which leads to the solidification of the binder from a soft to hardened state. Cohesive breakdown of the binder then becomes dependent upon the tendency of asphalt to soften, and then possibly mix with water by processes of emulsification, at exposed cracked interfaces. Mechanically, cohesive failure may be considered in terms of the Griffith model (Roylance 2001), i.e.,

$$\sigma = \sqrt{\frac{2\gamma E}{\pi a_c}} \qquad \text{(M2a-2.1)}$$

given the work of cohesion, $W = 2\gamma$, crack length, a_c, and Young's modulus, $E = \sigma / \text{ò}$. It is assumed that when plastic deformation occurs in a material, which accounts for dissipation of energy at the crack tip, equation M2a-2.1 is re-written as

$$\sigma = \sqrt{\frac{\mathrm{G}_c E \mathrm{a}}{\pi a_c}} \qquad \text{(M2a-2.2)}$$

where

$$\mathrm{G}_c = W + \mathrm{G}_p \qquad \text{(M2a-2.3)}$$

G_c is referred to as the critical strain energy, which is expressed as the sum of both the surface energy term, $W = 2\gamma$, and a plastic deformation energy term G_p. In materials which exhibit ductility, G_p is often observed to be orders of magnitude greater than W.

Compositionally, the cohesive energy of the binder, E_{coh}, is further defined in terms of the solubility parameter,

$$\delta \equiv \sqrt{\mathrm{E}_{coh}} = \sqrt{\frac{2\gamma T_c}{r_c \Delta T}} \qquad \text{(M2a-2.4)}$$

given the surface free energy, γ (mN/m), the temperature change, $\Delta T = T_c - T$ from an equilibrium temperature, T, to a critical phase transition temperature, T_c, and a critical radius of material solidification (nucleation), r_c. This expression is analogous in form to the Griffith model (Eq. M2a-2.2). Equation M2a-2.4 may be substituted into equation M2a-2.2 to give a "chemo-mechanical" description of cohesive failure of the binder,

$$\sigma = \sqrt{\frac{\left(r_c \delta^2 \dfrac{\Delta T}{T_c} \right) E}{\pi a_c}} \qquad \text{(M2a-2.5)}$$

The Ewell's and Eyring's (Ewell and Eyring 1937) equation, $\Delta U_{vap} = n_E E_{a,vis}$, may be used to relate the flow activation energy, $E_{a,vis}$, of a material, given the internal energy of vaporization, ΔU_{vap} and n_E referred to as the Eyring number, to the cohesive energy,

$$\delta = \sqrt{\frac{\Delta U_{vap}}{\bar{V}}} = \sqrt{\frac{n_E E_{a,vis}}{\bar{V}}} = \sqrt{\frac{2\gamma T_c}{r_c \Delta T}} \qquad \text{(M2a-2.6)}$$

suggesting that energy dissipation and material flow and softening are interrelated. Table M2a-2.1 lists activation energies of viscous flow measured for the eight SHRP asphalts based on low shear viscosity versus temperature measurements in the 25°C to 60° temperature range, and the 25°C solubility parameters and surface tensions determined based on equation M2a-2.6.

Table M2a-2.1. Activation energies of viscous flow measured for the eight SHRP asphalts based on low shear viscosity versus temperature measurements in the 25°C to 60° temperature range, and 25°C solubility parameter and surface tension determined based on equation M2a-2.6.

Asphalt	$E_{a,vis}$ (kJ/mol)	Solubility Parameter (J/m^3)	Surface Tensions (mJ/m^2)
AAA1	138	24	39
AAB1	156	25	45
AAC1	158	26	45
AAD1	144	24	41
AAF1	175	27	50
AAG1	165	26	47
AAK1	151	25	43
AAM1	171	27	49

Note: parameters used to calculate solubility parameters and surface tensions base on equation M2a-2.6.
$T_c = 300^{\circ} C$, $\bar{V} = M / \rho = (850 g/mol)/(1.0 g/mL) = 850 mL/mol$, and $r_c = 0.29 mm$.

Based on this approach it was hypothesized that mechanical properties of cohesive failure associated with fatigue and healing should correspond to activation energies of viscous flow associated with the compositional nature of the binder. Thus, Tayebali (Tayebali et al. 1994) determined the fatigue life, N_f, for asphalt mixtures, modeled based on the Flexural Beam Fatigue Test as

$$N_f = a\left(\frac{1}{\varepsilon_0}\right)^b \left(\frac{1}{S_0}\right)^c \qquad \text{(M2a-2.7)}$$

given
ε_0: initial tensile strain
S_0: initial stiffness of mixture
a, *b*, and *c*: fitting coefficients

In this work tests were carried out employing the Flexural Beam Fatigue Test to determine the number of load cycles to failure of test specimens prepared as asphalt-aggregate mixtures. Based on this approach the cumulative dissipated energy to failure, W_N may be related to the fatigue life as

$$W_N = A\left(N_f\right)^z \qquad \text{(M2a-2.8)}$$

given A, z : fitting parameters. Figure M2a-2.2 depicts the relationship for W_N as a function of N_f for test data obtained for mixtures prepared from the eight SHRP core asphalts and two SHRP aggregates, RD and RH, where this data listed in Table M2a-2.2. This particular data represents the average in an 8 X 2 experimental matrix. With the exception of mixtures prepared with SHRP asphalt AAM-1, the remaining data fit the relationship expressed in equation M2a-2.8 where *A* and *z* are determined as 11.4 and 0.49, respectively.

Table M2a-2.2. Flexural stiffness, fatigue life, and cumulative dissipated energy (Tayebali et al. 1994), fracture temperature (Jung and Vinson 1993), and activation energy of viscous flow of SEC-II materials listed for the Eight SHRP core asphalts.

Asphalt Source	Flexural Stiffness	Fatigue Life	Cumulative Dissipated Energy	Fracture Temp	Ea(SEC-II)
AAA-1	295,400	99,300	3100	-30.50	20
AAB-1	409,900	70,300	2700	-25.00	23
AAC-1	552,700	41,200	2100	-23.00	33
AAD-I	386,200	74,400	2800	-26.00	17
AAF-1	1,033,000	25,100	1800	-17.00	39
AAG-1	1,172,700	7,200	600	-16.00	46
AAK- 1	592,800	46,200	2400	-22.50	23
AAM-1	604,800	71,200	3400	-21.00	39

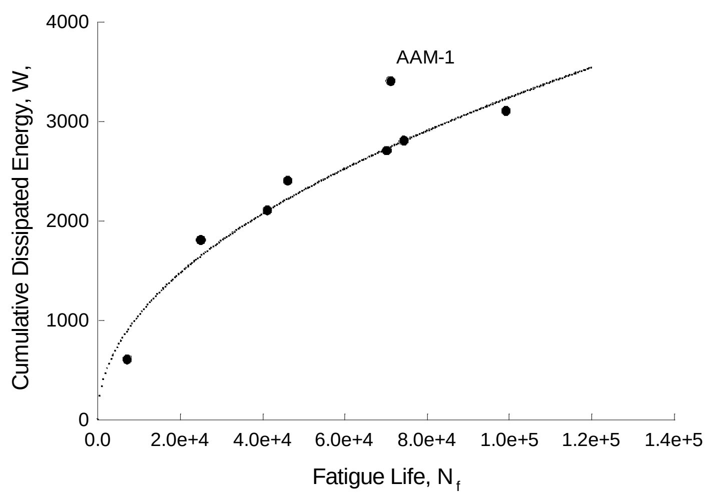


Figure M2a-2.2. Cumulative dissipated energy to failure, W_N (psi), determined based on the flexural beam fatigue test, plotted as a function of the fatigue life, N_f, reported as the number of cycles to failure.

Based on discussions presented here, the cumulative dissipated energy could be expected to correlate with an activation energy of viscous flow, thus, activation energies of viscous flow of neat asphalts, n-heptane maltenes and SEC-II fractions were each considered. Figure M2a-2.3 depicts the best correlation found for activations energy and cumulative dissipated energy.

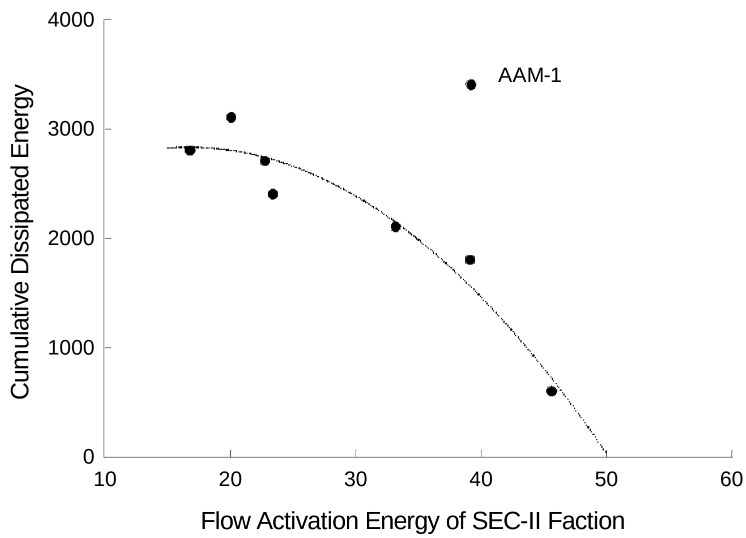


Figure M2a-2.3. Cumulative dissipated energy to failure, W_N (psi), determined based on the flexural beam fatigue test, plotted as a function of the viscous flow activation energy of SEC-II materials, $E_a(SECII), kcal/mol$, determined for the eight SHRP core asphalts.

Healing Associated with Fatigue

Little et al. (2001), had the following to report in regard to fatigue and healing: *"Surface energy density (SED) is explained by Schapery (1988) to be an integral part of the fracture and healing processes. Furthermore, Lytton et al. (1998) propose an allied theory of how the rate of fracture and the rate of healing (in asphalt mixtures) can be explained by the first principles of fracture originated by Schapery and considering the effects of SED. Since SED is a measurable parameter for both of the two major components of the asphalt mixture (bitumen and aggregate), and since it is related fundamentally to fracture and healing theory, the authors considered it wise to develop a theoretical understanding that links SED to the fatigue process and hopefully to explain differences in fatigue and healing among different bitumen and aggregates based on their different SED values (for both bitumen and aggregate). Furthermore, it should follow that SED values of the bitumen should relate to differences in the aromatic, amphoteric, and wax contents of these bitumen."*

In this work (Lytton et al. 2001) showed how healing mechanisms could be explained in terms of surface energies, where the surface energy density, γ_f ,

$$2\gamma_f \equiv E_R D_f(t_d) J_v \qquad \text{(M2a-2.9)}$$

given E_R, the reference modulus, $D_f(t_d)$, the tensile creep compliance as the time required to propagate the crack length distance ahead of the crack within the process zone and J_v, the J-integral may be related to both short term, $\dot{h}_1$, and long term, $\dot{h}_2$, healing rates, expressed as

$$\frac{\partial h_1}{\partial t} \equiv \dot{h}_1 = \beta \cdot \left[\frac{k_{th} E_R D_{1c} H_v}{2\gamma_h} \right]^{1/m_c} \qquad \text{(M2a-2.10)}$$

and

$$\frac{\partial h_2}{\partial t} \equiv \dot{h}_2 = \beta \cdot \left[\frac{2\xi_m E_R^2 D_{1c} \gamma_h}{(1-v) C_m^{1/m_c} H_v} \right]^{1/m_c} \qquad \text{(M2a-2.11)}$$

given

β: size of crack healing zone

E_R: reference modulus

D_{1c}: compressive creep compliance constant

γ_h: wetting surface energy

v : Poisson's ratio

k_{th} , ξ_m , C_m : fitting constants

H_v : healing integral

m_c : creep compliance slope

According to Lytton et al. (2001) *"In order to understand the healing mechanism of asphalt concrete, it is helpful to keep the healing models developed for polymers in mind. Petersen (1984) claims that the association force (secondary bond) is the main factor controlling the physical properties of asphalt. That is, the higher the polarity, the stronger the association force is, and the more viscous the fraction is, even if molecular weights are relatively low. Petersen also presented a vivid description of the effect of degree of peptization on the flow properties as follows: Consider what happens when a highly polar asphaltene fraction having a strong tendency to self-associate is added to a petrolene fraction having a relatively poor solvent power for the asphaltenes. Intermolecular agglomeration will result, producing large, interacting, viscosity-building networks. Conversely, when an asphaltene fraction is added to a petrolenes fraction having relatively high solvent power for the asphaltenes, molecular agglomerates are broken up or dispersed to form smaller associated species with less inter-association; thus, the viscosity-building effect of the asphaltenes is reduced. Traxler (Traxler, 1960) also suggested that the degree of dispersion of the asphalt components is inversely related to the complex (non-Newtonian) flow properties of the asphalt."*

Based on the hypotheses proposed by Lytton (Lytton et al. 2001), correlations were sought by our group which would relate colloidal dispersion properties of neat asphalts to the healing rates determined by Lytton. Figure M2a-2.4 depicts a correlation between the short term healing rate determined by DMA (Dynamic Mechanical Analysis) fatigue testing of asphalt mixtures plotted versus the reversible asphaltene peptizability "compatibility" parameter, determined based on ASTM D04 6703, Standard Method for Automated Heithaus Titrimetry. Figure M2a-2.5 depicts a correlation relating the long term healing rate determined by DMA testing of asphalt mixtures to the activation energy of viscous flow of the SEC-II fraction solvent material of asphalt.

The correlation depicted in figure M2a-2.4 suggests that asphalts which are more compatible (i.e., more solvent-like in their colloidal composition, less asphaltenes, and more ductile), tend to heal at a faster rate compared to less compatible materials, (i.e., asphalts, which are more brittle and tend to have a higher asphaltene content). The correlation depicted in figure M2a-2.5, on the other hand, is counter intuitive, in that, asphalts which require more energy to move molecules (i.e., higher activation energy of viscous flow) correlate with a more rapid long term healing rate.

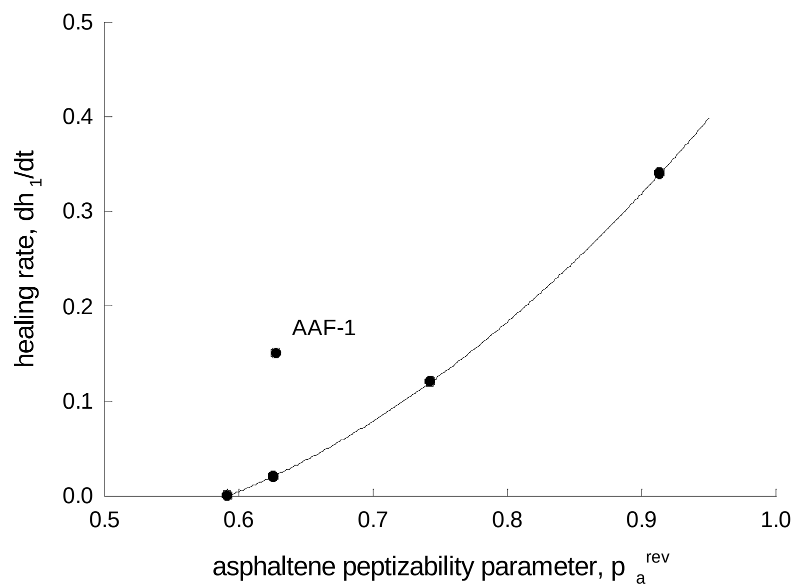


Figure M2a-2.4. Short term heating rate determined by DMA analysis of asphalt mixtures plotted versus the reversible asphaltene peptizability "compatibility' parameter, determined based on ASTM D04-6703, Standard Method for Automated Heithaus Titrimetry (ASTM 2008).

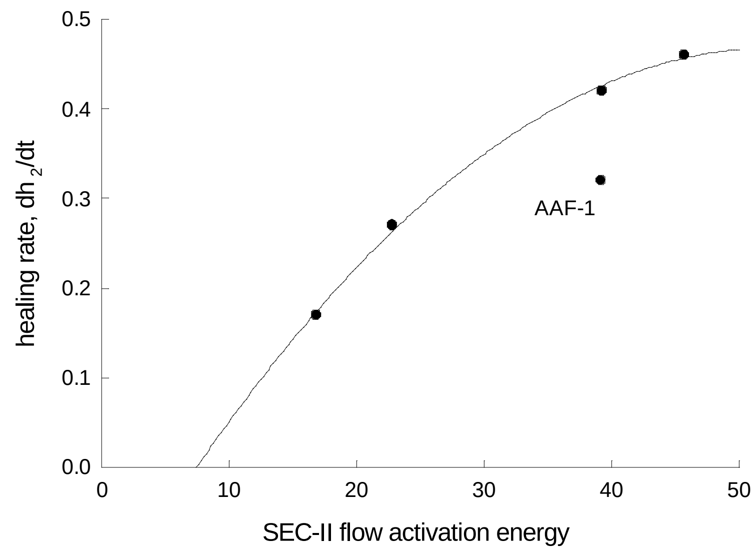


Figure M2a-2.5. Long term heating rate determined by DMA analysis of asphalt mixtures plotted versus the activation energy of viscous flow of the SEC-II fraction solvent material of asphalt.

<u>Work Plan Year Four</u>

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

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

Sub-Subtask M2a-2.3: Conduct AFM pull-off force "nano-contact mechanics" measurements on asphalt thin-film and aggregate surfaces employing chemically functionalized cantilever tips. Determine polarity components of surface energy of both asphalt thin-films and aggregate fine particles and relate these properties to the tendency of these materials to promote emulsification. Asphalt films, 1-5 micrometers in thickness, will be prepared on glass substrates via solvent spin casting followed by thermal annealing in an inert gas atmosphere. Samples will then be tested by conducting rate and temperature dependent nano-indentations, followed directly by a pull-off action to record penetration depth, from which hardness and adhesion-capillarity interactions with the film are calculated. Indentation cantilevers will be selected based on reported stiffness's of asphalts at very cold temperatures increasing to near ambient conditions. Tests will be run by starting at a low temperature and increasing the temperature of the film until a transition is observed. The change in stiffness transitioning to "stickiness" will be evaluated to determine the temperature (range) at which these transitions take place as a function of crude source. Additionally, tests will be performed at different locations on the surface of the film where notable differences in the surface morphology are subsequently observed. In this sense, a stiffness map of the surface of the film will be obtained. Correlations will be sought to compare between the data gathered from these tests and rheological and mechanical test data related to stiffness (relaxation), fracture temperature and healing rates generated at other scales, most particularly at macroscopic scale based on conventional asphalt rheology.

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Work Element M2b: Impact of Moisture Diffusion in Asphalt Mixtures

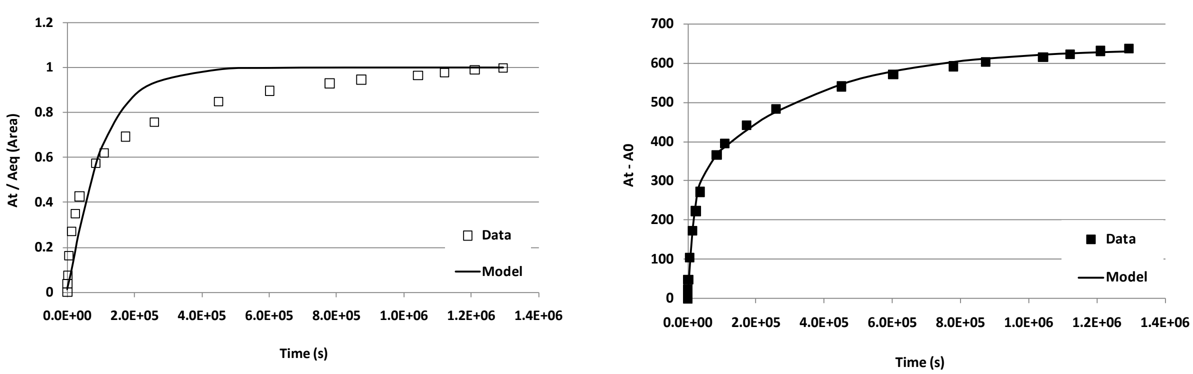
Subtasks M2b-1: Measurements of Diffusion in Asphalt Mixtures and M2b-2: Kinetics of Debonding at the Binder-Aggregate Interface

<u>Major Findings & Status</u>

In a previous research study we had developed a method to measure the rate of moisture diffusion through asphalt mixtures and Fine Aggregate Matrix (FAM) or sand-asphalt mortars. Findings from this study were reported in Kassem et al. (2006).

As a part of this research study we developed and used a methodology to determine the rate of water diffusion through thin films of asphalt binders using FTIR spectroscopy. Important conclusions and findings from this study are as follows:

- The diffusivity of water through four different asphalt binders was measured. At least one of these binders had a diffusivity that was significantly higher than the other three binders indicating that diffusivity may be an important material variable that influences the rate of moisture damage.
- A dual mode diffusion model was shown to better represent the diffusion of water through asphalt binders. Figure M2b.1 illustrates a typical example of how the dual mode diffusion model better represents the experimental data as compared to the conventional Fickian diffusion. This model suggests that water molecules may diffuse at two different rates within the asphalt binder with the slower rate being associated with interaction between water molecules and polar functional groups within the material. The implication of this mode of diffusion through asphalt binders in terms of performance and asphalt chemistry requires further investigation. However, these results do suggest that future efforts related to modeling of moisture damage should consider the use of a dual mode diffusion model rather than simple diffusion based on Fick's second law. Table M2b.1 lists the values for diffusivities for some of the asphalt binders.



(a) (b)

Figure M2b.1. Typical results obtained by (a) Analysis 1 (Fickian diffusion model) and (b) Analysis 2 (Dual Mode diffusion model) for asphalt AAB.

Table M2b.1. Diffusivities measured for some asphalt binders using the FTIR technique.

Asphalt	Number of Replicates	Dual Model Diffusion Values				
		D_1(nm^2/s)	D_2(nm^2/s)	x_1	Average D_{eff} (nm^2/s) [CV]	R^2 (fitting with the model)
AAB	6	23.02	0.79	0.51	12.17 [49%]	0.989
AAD	4	38.26	1.75	0.57	16.79 [37%]	0.978
ABD	6	75.07	0.40	0.53	39.82 [45%]	0.969

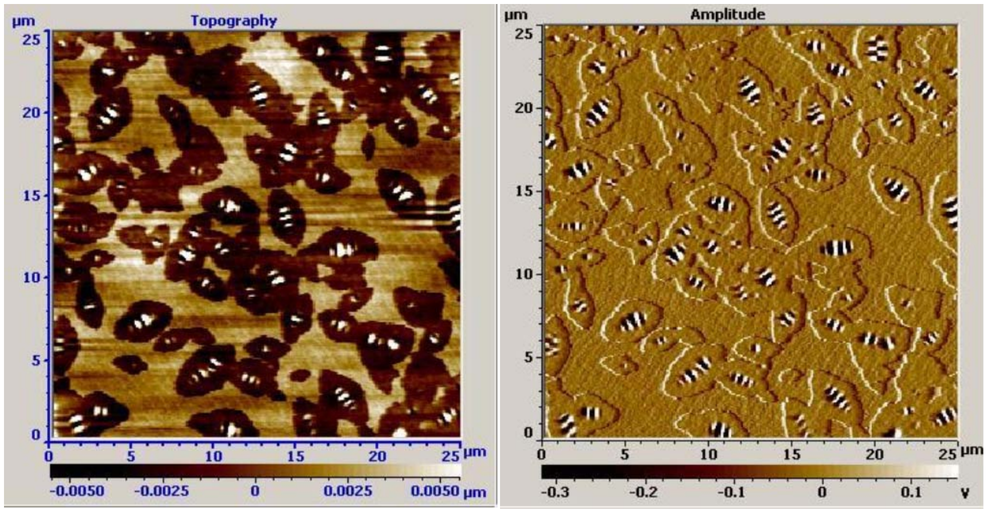
- The values of diffusivity reported in this study are much smaller than the values reported by Arambula et al. (2009) and Kassem et al. (2006). However, the values reported in this paper pertain to the diffusion of liquid water through thin films of asphalt binder which is different from diffusion of moisture through mixtures or mastics. The latter is dictated by macroscopic properties including interconnected air voids that allow moisture to travel much faster through the bulk. In contrast, the results shown in this study are relevant to the diffusion of moisture through the binder as in the case of microstructural entities that interconnect voids to the binder-aggregate interface. The impact of this could be that binders that develop a tenacious bond with aggregate surfaces and also resist moisture diffusion to the binder-aggregate interface may be more resistant to moisture damage. Further study is underway to evaluate the difference in diffusivity values when water is in liquid versus vapor form.
- The results obtained in this study are in the same order of magnitude of the results presented by Wei (2009) using the Electrochemical Impedance Spectroscopy (EIS). Wei used thin binder film on aluminum plate substrate.

The second objective of this subtask was to evaluate the influence of history of exposure to moisture on the rate of water transport in thin films of asphalt binder. This portion of the study was completed as well. Important conclusions and findings from this study are as follows:

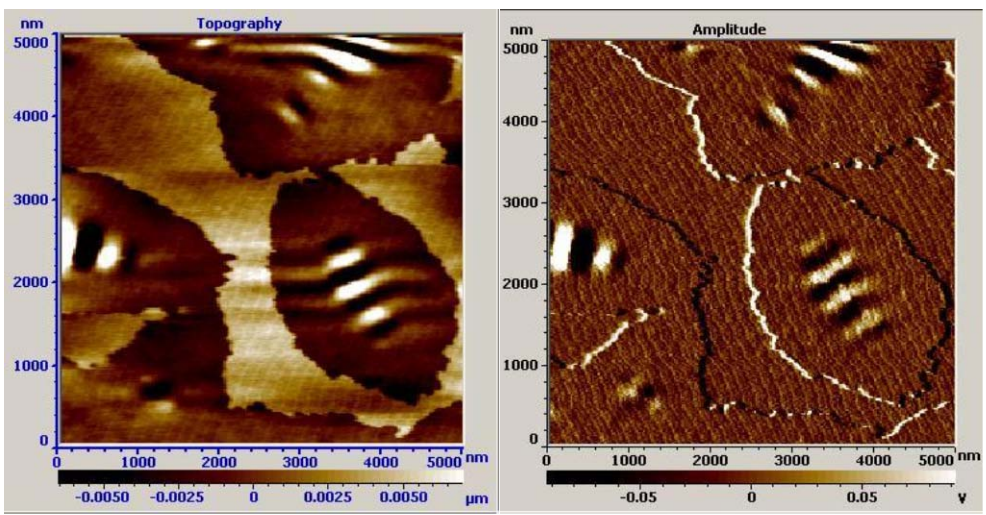
- The rate of moisture diffusion in asphalt binders depends on the history of exposure of the moisture to asphalt binder.
- In most cases, the diffusivity of moisture increased with every subsequent cycle of exposure to moisture. The increase in diffusivity was most significant after the first cycle. The change in diffusivity was dependent on the type of asphalt binder. Table M2b.2 presents some of the results indicating the history dependence of diffusivity.
- The increase in moisture diffusivity was mostly due to the change in microstructure of the asphalt binder after being exposed to the moisture. This was supported by AFM images of asphalt binder before and after being exposed to water (figure M2b.2). There was some evidence of increase in moisture trapped in the form of vapors even after dehydration that could also contribute to the increase in diffusivity.

Table M2b.2. History dependence of diffusivities measured using the FTIR technique.

Asphalt	Cycle	D_1(nm^2/s)	D_2(nm^2/s)	x_1	Average D_{eff} (nm^2/s) [CV]	R^2 (fitting with the model)
AAB	1	28.97	1.23	0.50	14.95 [29.8%]	0.992
	2	167.87	2.17	0.46	80.75 [47.3%]	0.984
	3	194.73	2.76	0.47	92.10 [20.5%]	0.984
AAD	1	41.72	1.84	0.41	16.19 [40.6%]	0.988
	2	59.90	1.04	0.48	28.22 [33.5%]	0.991
	3	102.98	1.45	0.43	41.34 [34.2%]	0.992
ABD	1	102.72	0.53	0.55	52.04 [34.6%]	0.974
	2	371.82	1.40	0.62	178.26 [50.3%]	0.906
	3	571.45	2.25	0.44	244.36 [21.6%]	0.946

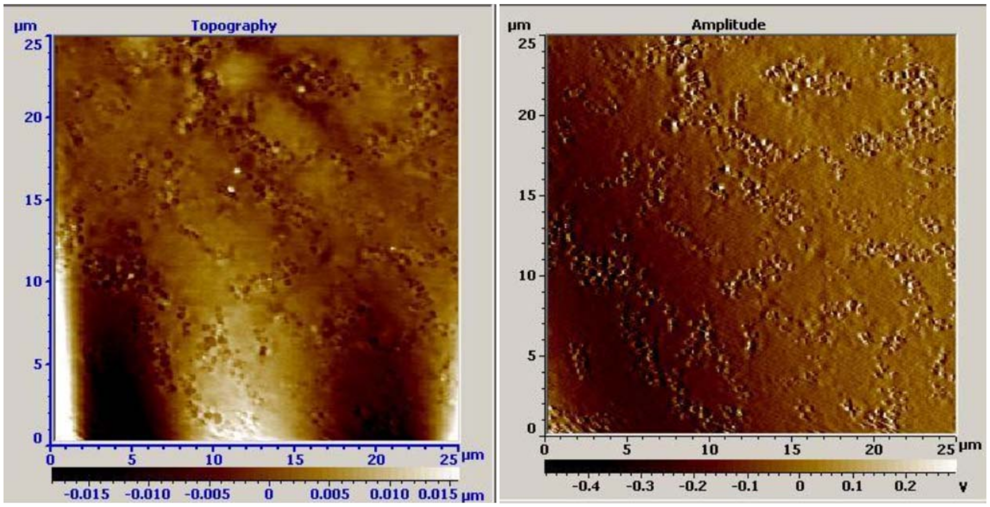


(i)

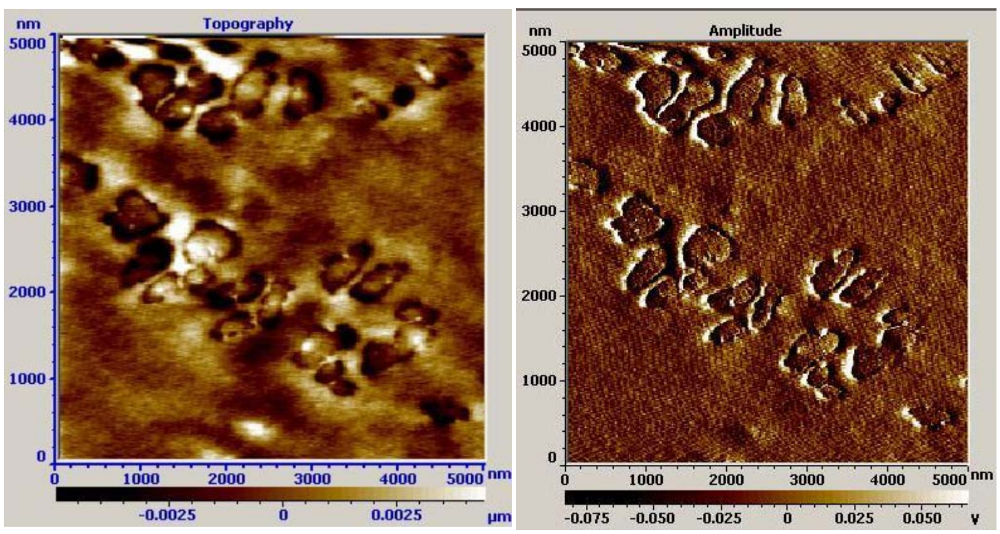


(ii)

Figure M2b.2(a). AFM images from asphalt AAD, (i) 25µm^2 and (ii) 5µm^2.



(i)



(ii)

Figure M2b.2(b). AFM images of asphalt AAD after 4 days of water exposure, (i) 25µm^2 and (ii) 5µm^2.

<u>Year Four Work Plan</u>

The rate of debonding due to moisture at the binder-aggregate or filler interface is one of the factors that controls the overall rate of moisture damage within the asphalt mixture. For year four we plan to pursue Subtask M2b.2 on the measurement of rate of debonding at the asphalt binder-solid interface using ATR-FTIR spectroscopy. Another objective of this subtask is to validate the hypothesis that the rate or kinetics of debonding at the binder-aggregate interface is largely dictated by the work of adhesion between these two materials (in addition to extrinsic properties such as temperature, geometry etc). A literature review to investigate available methods to determine the rate of moisture transport at the interface (or the rate of debonding) was conducted. Findings from the literature indicate that it is possible to evaluate the rate of moisture transport at the polymer film-solid interface using spectroscopic techniques. For example, Linossier et al. (1999) used a double sided ATR cell to track rate of movement of water at the polymer film-solid interface as well as the diffusion of water through the polymer film. Figure M2b.3 illustrates the schematic of the process used by these authors and others to determine rate of moisture transport through interfaces.

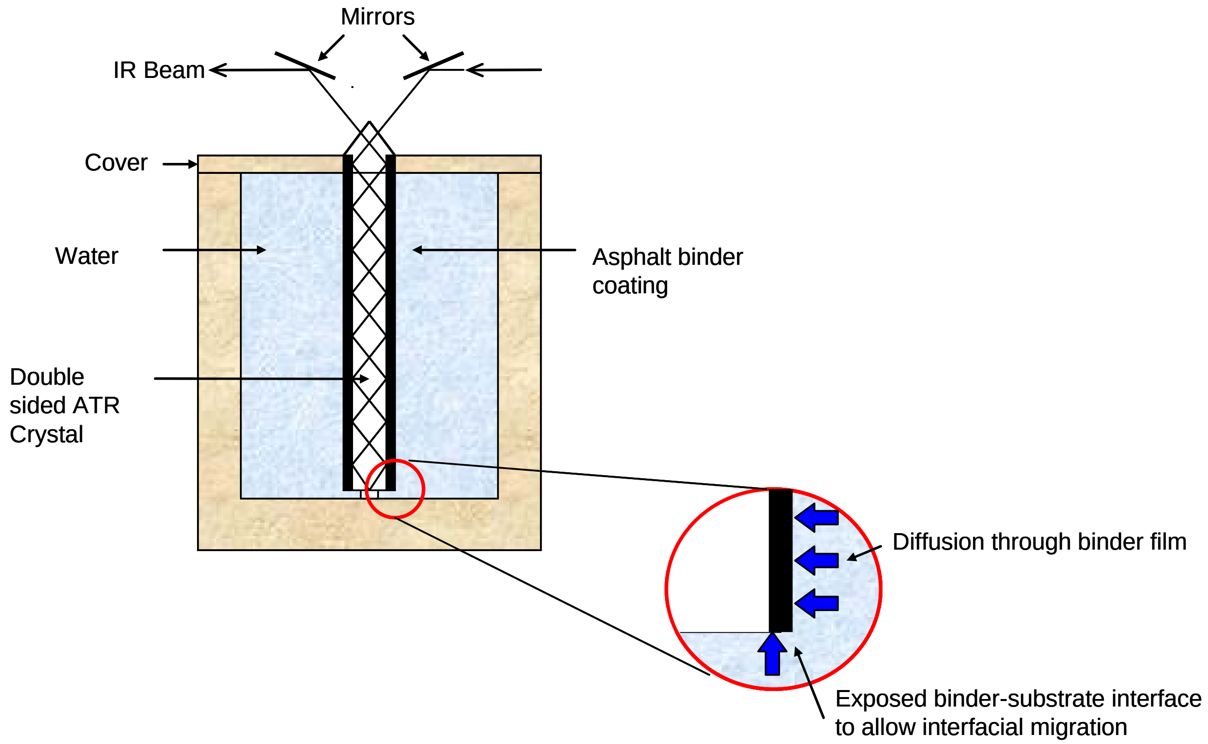


Figure M2b.3. FTIR set up to determine diffusion and interfacial coupled moisture transport.

After preliminary tests it was determined that it may not be feasible to create thin aggregate slices and measure changes at the aggregate-binder interface using the attenuated transmission mode with the FTIR. However, infrared transparent crystals such as ZnSe and KBr will be substituted for aggregates and tested with different asphalt binders. The test procedure will allow simultaneous diffusion of water through the bulk and the interface. Results from this test procedure combined with the diffusivities measured earlier can be used to determine the rate of diffusion of moisture at the binder-solid interface.

One of the objectives of the subtask M2b.1 as detailed in the second year work plan was to measure the influence of overhead pressure on the diffusivity of water through asphalt binders. As described in the second year work plan there are limitations on the amount of pressure that can be applied in the ATR cell. Further work to address this particular objective of this subtask will depend on practical considerations to create overhead pressure in the ATR cell.

Table for Decision Points and Deliverables

Date	Deliverable	Description
12/31/09(1)(2)	Journal Papers (Two)	Measurement of diffusion of water through thin films of asphalt binders
6/30/10(1)	Draft Report	
9/31/10(1)	Final Report	
09/30/11	Journal Paper	Kinetics of debonding at the binder-aggregate interface
12/31/11	Draft Report	
03/31/12	Final Report	

(1) These deliverables have been delayed by approximately 6 months from the original schedule due to the challenges in developing the test method. However, the deliverables will now also include a component on determining the hysteresis in diffusion.

(2) Vasconcelos, K.L., Bhasin, A., and Little, D.N. "Measurement of water diffusion in asphalt binders using the FTIR-ATR technique", *Transportation Research Record,* TRB, National Research Council, Accepted for presentation at the 89th annual meeting and under review for publication in TRR.

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

Major Findings and Status

The development of the protocol for measuring the bond strength of binders using a modified PATTI device has been completed. A final procedure has been developed in which the rate of loading, conditioning time, and metal stub have been defined and carefully evaluated. The results show clear potential for the capability of the test to measure the effect of binders and moisture conditioning. A detailed report will be submitted at the end of Year 3 of the project. Since the main objective of this work element is complete, the research team is proposing combining this work element with the M1a work element. The Year 4 work plan for the combined work elements appears under work element M1a.

Year Four Work Plan

Subtask M2c-1: Evaluate load and deflection measurements using the modified PATTI test

Completed.

Subtask M2c-2: Evaluate effectiveness of the modified PATTI test for detecting modification

Major tasks completed and remaining activities are combined with work element M1a.

Subtask M2c-3: Conduct testing

Major tasks completed and remaining activities are combined with work element M1a.

Subtask M2c-4: Analysis and interpretation

Major tasks completed and remaining activities are combined with work element M1a.

Subtask M2c-5: Standard testing procedure and recommendation for specifications

Standard procedure has been developed. Recommendations for specifications will be completed as part of work element M1a, subtask M1a-6.

CATEGORY M3: AGGREGATE SURFACE

Work Element M3a: Aggregate Surface Characterization

Major Findings & Status

The main tasks in this work element are,

(1) characterization of the chemical composition of the surfaces of reference minerals and aggregates through electron beam spectroscopes, including electron microprobe, backscatter electrons and electron-dispersive spectroscopy (EDS),

(2) characterization of the surface energies of reference minerals and aggregates through the universal sorption device and microcalorimetry,

(3) quantification of surface (upper 14 nm) atomic species and chemical state with an x-ray photoelectron spectroscope (XPS), and

(4) surface topography characterization with scanning electron microscopy (SEM).

The results from this work element will be used to populate the database of aggregate and mineral properties.

Surface energy measurements for pure minerals such as quartz, microcline, labradorite, biotite, andesine, microcline, albite, augite, hornblende, hematite, siderite, dolomite, and calcite have been collected using the universal sorption device. The components of surface energy were calculated on replicates of the samples. In addition, surface energy measurements for six different aggregates were also carried out along with microprobe analysis for WDS quantitative analysis. A detailed list of the status of surface characterization for each of the selected aggregates is presented and updated in each quarterly report.

Year Four Work Plan

The plan for year four is to continue analysis of minerals and aggregates. The information generated from this sub-task will serve as an input for other subtasks on materials characterization and modeling.

Table for Decision Points and Deliverables

The database will be populated for aggregates that are received and testing on an ongoing basis through the end of this project.

CATEGORY M4: MODELING

Work Element M4a: Micromechanics Model (TAMU)

Major Findings and Status

Lattice Micromechanical Model

The plan for Year 3 includes: (a) incorporating viscoelastic fracture in the lattice modeling; (b) capturing the change in time dependence during the scale-up of the lattice modeling; and (c) developing a framework and associated experimental plan for linking continuum damage to fracture. Viscoelastic fracture, as well as rate-dependent damage, is now incorporated into the lattice model in an elegant manner with the help of the work potential-based viscoelastic continuum damage (VECD) model. Change in the time dependence during the scale-up process turned out to be significantly more involved than expected, and extensive experimentation is underway to understand this phenomenon. Once this work is completed, an appropriate model will be developed and incorporated into the lattice modeling framework.

With respect to linking continuum damage to fracture, a decision has been made to first understand the micromechanical characterization of damage prior to localization so that a more quantitative understanding can be attained by examining the propagation and coalescence of microcracks. A preliminary model form has been recently developed. This model will be enhanced and verified through experimental data, which will form the basis for linking continuum damage to fracture.

Cohesive Zone Micromechanical Model (TAMU)

During the third year researchers at TAMU worked on applying the micromechanical model developed during the previous year to investigate the role of different material properties and characteristics of asphalt mixtures on the initiation and development of moisture-induced damage.

Details of the model can be found in the quarterly reports of years 2 and 3, and in the bibliography included in such reports. In summary, the model is able to couple the effect of moisture diffusion with the mechanical performance of an asphalt mixture by means of two different mechanisms:

1. Reduction of the linear viscoelastic relaxation modulus of the asphalt matrix (also called Fine Aggregate Matrix, FAM) as a function of the amount of moisture present in the material (i.e., moisture-induced cohesive deterioration); and
2. deterioration of the mechanical and fracture properties of the asphalt matrix-aggregate interfaces as a function of the amount of moisture that reaches the interfacial zones (i.e., moisture-induced adhesive deterioration).

Although other modes of moisture transport are strongly related to the development of some moisture damage mechanisms, this model focuses exclusively on the effects of moisture diffusion. Moisture diffusion is crucial when investigating the effects of moisture in the microstructure of asphalt mixtures because it induces two main damage mechanisms: 1) it modifies the material properties of the asphalt matrix of the microstructure; and 2) it constitutes the main driving source of moisture that reaches the aggregate-binder interface; the presence of moisture in these zones undermines the quality of the adhesive bond between the two materials.

The micromechanical model gives special attention to the deterioration processes occurring at the aggregate-asphalt matrix interfaces (i.e. adhesive damage). This mechanism, that consists of the breakage of secondary bonds due to the presence of water at the interface (Hefer et al. 2005), is a favorable thermodynamic process that results of the preference of the aggregate surface to be covered by water instead of asphalt binder (Bhasin 2006). The nucleation, initiation and propagation of adhesive fracture at the aggregate-asphalt matrix interfaces were modeled by means of the cohesive zone modeling (CZM) technique.

The model was implemented in the finite element software Abaqus® using a moisture-mechanical sequentially coupled scheme. Cohesive zone elements, herein called *adhesive elements*, were embedded between each coarse aggregates and the asphalt matrix. The adhesive elements were assigned material properties representing the fracture characteristics of the interfaces.

During the third year, the applications of the coupled model focused on investigating:

1. The influence of different physical and mechanical material properties of the two main constitutive phases of the mixture (i.e., fine aggregate matrix, FAM, and coarse aggregates) on the moisture-related mechanical performance of asphalt mixtures.
2. The role of the air void phase on the moisture-related mechanical performance of asphalt mixtures.

Influence of material properties and loading conditions on the mechanical response of asphalt mixtures subjected to moisture diffusion

Figure M4a.1 presents the microstructure used for the parametric analysis and its implementation in finite elements. Details of the geometry of the sample as well as the physical and mechanical properties used for the constitutive phases can be found in the April 2009 quarterly report or in Caro et al. (2010a) and Caro (2009). The material properties of the FAM and of the aggregates were modified to analyze the relative impact of each property. The mechanical/fracture properties of the adhesive elements, i.e., those embedded between the coarse aggregates and the FAM, were made a function of the individual properties of the aggregates and the asphalt matrix. The impact of different environmental conditions and different loading rates were also investigated in this study.

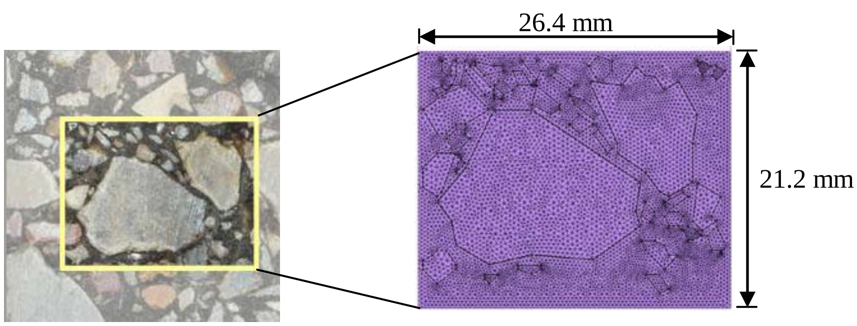


Figure M4a.1. Microstructure used in the parametric analysis and its corresponding finite element implementation.

A total of 24 microstructures resulted from combining the different material properties of the constitutive components (all of them with the geometry illustrated in figure M4a.1). The microstructures were subjected to different moisture diffusion conditions and to a mechanical loading scheme. The mechanical scheme consisted in applying two loading-unloading cycles under a displacement-controlled scheme at different displacement rates changing from 0.1 to 0.025 mm/s. The microstructures were subjected to such a mechanical scheme in two conditions: 1) dry state, and 2) after being subjected to a moisture diffusion conditioning process. The reduction of the maximum force supported by the mixture from the dry case to the moisture-conditioned case was used as an indicator of moisture susceptibility.

The results showed that, in general, all mixtures were highly susceptible to the combined deterioration caused by moisture and mechanical loading. The data also showed that the moisture diffusion coefficients of the materials, particularly the moisture diffusion of the asphalt matrix, play the most significant role in the development of damage. For example, it was found that a difference of one order of magnitude in the diffusion coefficient of the FAM reduced the maximum force experienced by the mixture at a given displacement by up to 3.7 times compared to a similar dry mix. The results also suggest that a difference of two orders of magnitude in this property reduced the maximum force of resistance of the mixtures from 1.2 to almost 2 times in comparison with similar dry mixes. Besides, it was observed that mixtures containing more resistant adhesive bonds between the aggregates and the asphalt matrix were less susceptible to the deleterious effects of moisture.

Details of the model, the model properties and the results obtained from the simulations can be found in Caro et al. (2010b).

Influence of the air void phase on the moisture-related mechanical response of asphalt mixtures

The internal air void structure of asphalt mixtures plays a main role on the development of moisture-related deterioration processes. However, this phase is usually considered to be part of the fine aggregate matrix (FAM) of the mixture and its actual contribution to damage is usually overlooked.

Within this context, researches at TAMU decided to use the micromechanical model to investigate the influence of the air void phase on the mechanical response of asphalt mixtures subjected to moisture diffusion. Two different probabilistic-based approaches were used to accomplish this objective. In the first approach, a volumetric distribution of air void sizes measured using X-Ray Computed Tomography (CT) in a dense-graded asphalt mixture was used to generate probable void structures in a microstructure of an asphalt mixture. In the second approach, a stochastic modeling technique based on random field theory was used to generate probable air void distributions of the mixture. In this second approach, the influence of the air void was accounted for by making the physical and mechanical properties of the asphalt matrix dependent on probable void distributions. Although both approaches took into consideration the characteristics of the air void phase on the mechanical response of the mixtures subjected to moist environments, the former explicitly introduced the air phase within the microstructure while the latter indirectly included its effects by modifying the material properties of the bulk matrix.

Figure M4a.2 presents the 50mm by 50mm representative volume element (RVE) that was selected in both approaches, as well as its finite element implementation. The mixture was composed by 231 coarse aggregates embedded in the fine aggregate matrix.

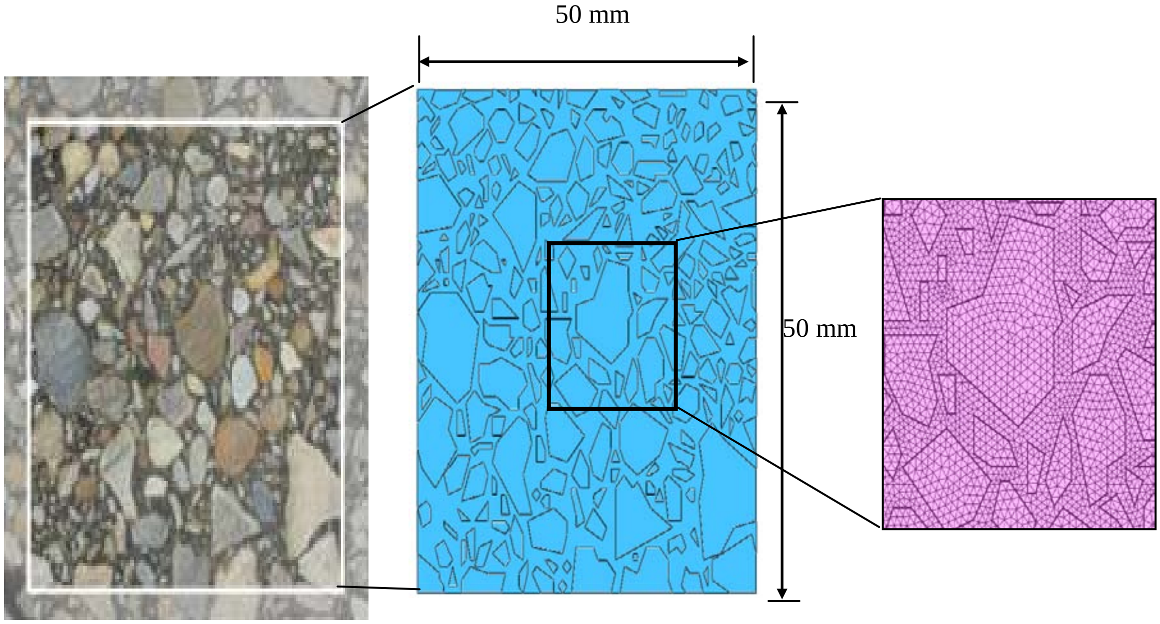


Figure M4a.2. Microstructure model used in the parametric analysis and its corresponding finite element implementation.

In both approaches, the microstructures were initially subjected to a load-controlled mechanical test in *dry* condition. The mechanical test was similar to the one used in the parametric analysis described previously in this section, and it consisted in loading and unloading the material at a rate of 0.16 N/s during a total of 30 seconds. Similar microstructures were subjected to a 10 days moisture diffusion period, after which the microstructures (in *wet* condition) were subjected to the same mechanical loading scheme previously described. The total energy dissipated, *DE*, by the microstructures in *dry* and *wet* conditions (i.e., area within the load-displacement curves in the right hand side of figure M4a.4) and the overall stiffness of the mixtures, *K*, (i.e., maximum load divided by maximum displacement in the same figure) were used to study the impact of the air void phase on the mechanical responses of the mixtures.

In the first approach, circular voids were randomly generated using a log-normal probabilistic density function of the air voids sizes obtained from a dense-graded asphalt mixture by means of the X-Ray CT technique. The location of the air voids within the microstructure was also randomly determined. Three different levels of total air voids content were considered in the analysis: 4%, 7% and 10%. In order to include the uncertainty associated with the location and sizes of air voids, at each level of total air void content, 10 different sets of air voids were generated. Figure M4a.3 shows one example of the air voids structures generated at the three levels of air voids content.

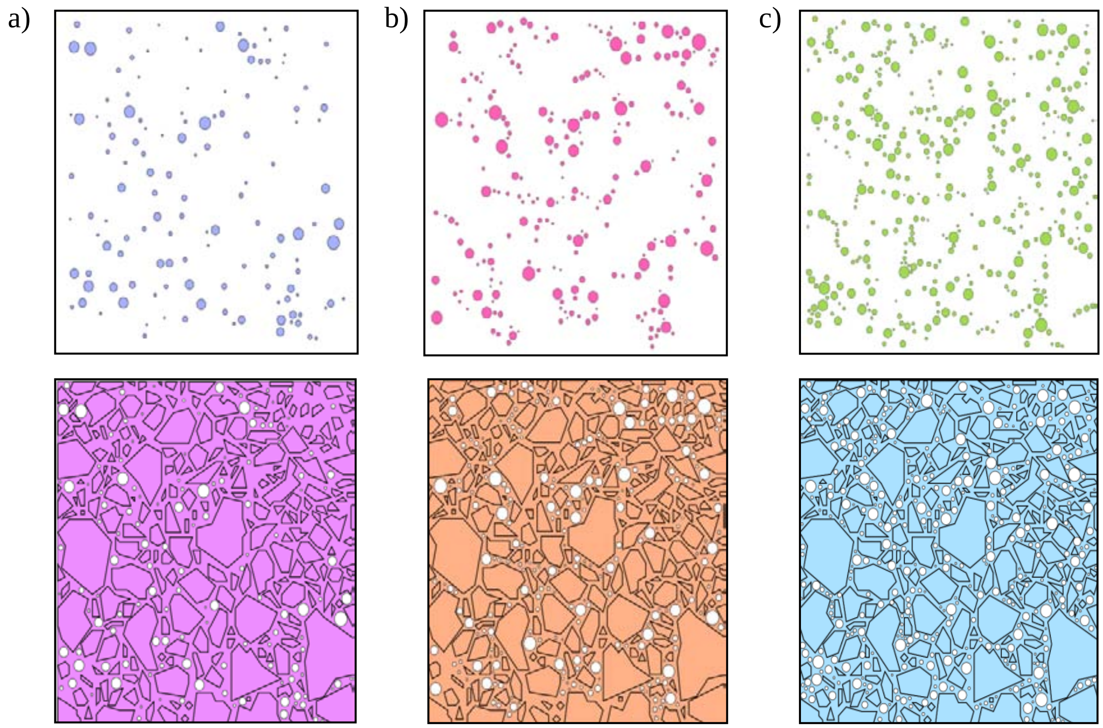
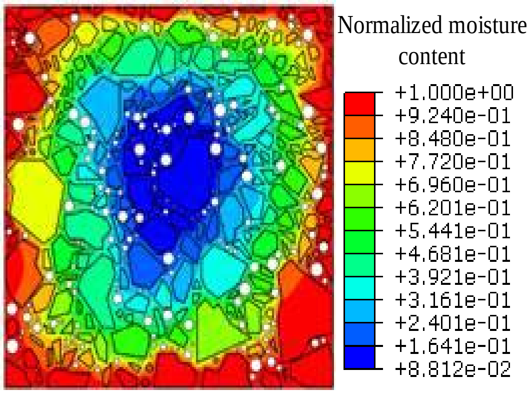


Figure M4a.3. Randomly created void structures and their correspondent microstructure models at three levels of air voids content: a) 4%, b) 7% and b) 10%.

The results from the study showed that the air void phase highly influences the mechanical performance of asphalt mixtures. Mixtures with large amounts of air voids presented larger values of total dissipated energy and smaller values of stiffness. Besides, at any fixed level of total percent of air voids, the energy dissipated by a microstructure in wet state was always larger than the energy dissipated by the mixture in dry condition. It was also observed that a polynomial function of third order or higher can be used to describe the relationship between the amount of air voids (when this value is in a range of 0% to 10%) and the expected mechanical performance of the mixture (i.e., reduction of stiffness or increase in the total dissipated energy).

In the second approach, a new methodology based on random field theory was developed to indirectly include the effects of the air void phase on the moisture-related mechanical response of the mixtures. A discrete-Gaussian random field theory proposed by El-Kadi and Williams (2000) was used to incorporate the effects of air voids on the material properties of the FAM. In order to do so, the FAM phase was divided into 100 equal-size sections and each section was assigned its own physical and mechanical material properties according to probable air void spatial variability and internal distributions (figure M4a.4).

a) b)



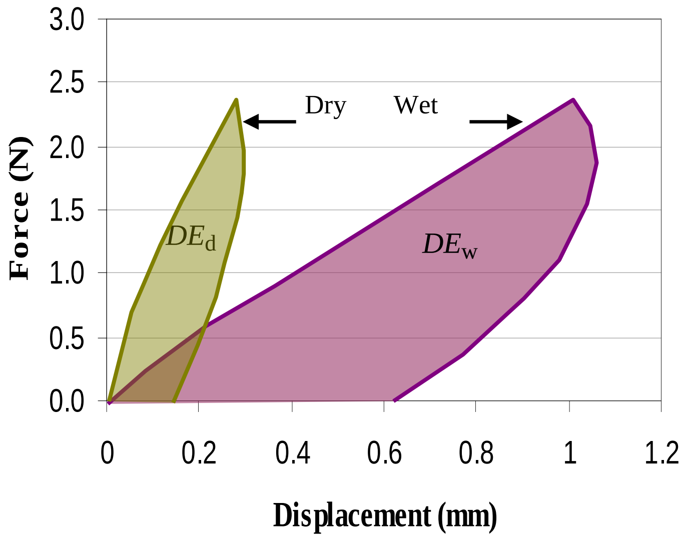


Figure M4a.4. a) moisture diffusion profile after 10 days of moisture conditioning (10% air voids), and b) typical force-displacement curve obtained for a structure containing 7% air voids content (*DE*: dissipated energy).

The stochastic methodology had into account the spatial variability of the total air voids within an asphalt layer in the field (i.e., the total air void contents obtained from different core fields at different locations are different), as well as the internal distribution of the air voids within the mixture (i.e., the total air void content within a field core changes with depth). Three different cases of air void content variability in the field were studied: asphalt layers with coefficient of variation (COV) of the air void content of 10%, 20% and 30%. Figure M4a.5 presents a typical realization of the air void random field. After each section of the FAM is assigned its own material properties, the microstructures were subjected to a similar moisture-diffusion and mechanical loading schemes as those used in the first approach (i.e., probabilistic addition of air voids in the microstructure).

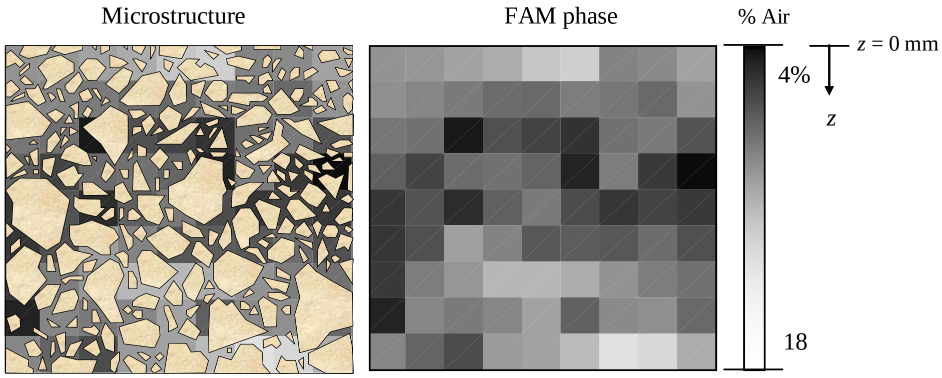


Figure M4a.5. Example of a stochastic realization of the air void random field within the FAM phase.

The results showed that an increase in the variability of the air voids content within the asphalt mixture in the field is associated with an increase in the variability of the total dissipated energy (*DE*) and the reduction of the stiffness of the mixture (*K*). In fact, it was observed that the COV of *DE* and *K* in the asphalt mixture is between 25% and 30% of the magnitude of the COV representing the spatial variability of field air void contents. This range was found to be close to reported data on the relationship between the air void variability and the expected mechanical response of the mixtures in the field.

Details of the stochastic approach, the material properties and the moisture diffusion and loading schemes used in the model, as well as the main results obtained from the simulations can be found in Caro (2009) and in Caro et al. (2010c).

The studies conducted during the third year proved the efficiency of the coupled micromechanical model to investigate the effect of moisture diffusion on the mechanical performance of asphalt mixtures.

Besides the results summarized in the previous paragraphs, the main products that resulted from the research conducted during the third year include the following journal papers:

- Caro, S., Masad, E., Bhasin, A., and Little, D. (2010). "Coupled micromechanical model of moisture-induced damage in asphalt mixtures." *Journal of Materials in Civil Engineering (ASCE)*, (in press).
- Caro, S., Masad, E., Bhasin, A., and Little, D. (2010). "Micromechanical modeling of the influence of material properties on moisture-induced damage in asphalt mixtures." *Construction and Building Materials*, doi:10.1016/j.conbuildmat.2009.12.022.
- Caro, S., Masad, E., Bhasin, A., Little, D., and Sanchez-Silva, M. (2010). "Probabilistic modeling of the effect of air voids on the mechanical performance of asphalt mixtures

subjected to moisture diffusion." *Journal of the Association of Asphalt Paving Technologists (AAPT)*,(in press).

- Caro, S., Masad, E., Sanchez-Silva, M., and Little, D. (2010). "Stochastic micromechanical modeling of asphalt mixtures subjected to moisture diffusion processes." *International Journal for Numerical and Analytical Methods in Geomechanics* (submitted for evaluation).

<u>Year Four Work Plan</u>

Lattice Micromechanical Model

Lattice Modeling: Experimental work related to change in the time dependence during scale-up will continue, followed by the development and incorporation of the model into the lattice modeling framework. The important effect of air voids will be included in the lattice model. Furthermore, the lattice model will be extended so that it can model damage and fracture under cyclic loads. The lattice model will be verified by correlating its results with experimental observations.

Continuum Damage to Fracture: The preliminary model for the micromechanical description of damage will be finalized. The model will be extended to incorporate the effects of viscoelasticity and crack coalescence, eventually leading to a macroscopic model of the macrocrack. An appropriate experimental program will be developed and implemented through this effort.

VECD-Aging and Moisture Study: The NCSU research team intends to work with the TAMU and WRI researchers during Year 4 to develop the framework that incorporates the effect of aging and moisture damage into the VECD model. A white paper describing the research approach will be developed in the beginning of Year 4 and will be submitted to TAMU, WRI, and FHWA for their review and inputs.

Cohesive Zone Micromechanical Model

The two main tasks for the following year are:

- Incorporate the influence of moisture diffusion and the air void phase on the adhesive and cohesive fracture mechanisms within the numerical cohesive model that is currently under development by the research group at University of Nebraska, UNL (under the direction of Dr. Yong Rak Kim). This proposal will combine the results and experiences gained at TAMU in moisture induce-damage and the comprehensive micromechanical damage model developed at UNL.
- Use the experimental results on the fracture characteristics of aggregate-asphalt binder systems (work element F.1a.) to calibrate the interface fracture properties required to accurately model adhesive deterioration in the numerical coupled model.

Table for Decision Points and Deliverables

Date	**Deliverable**	**Description**
05/31/10	Decision Point	Complete the experimental investigation into the change in time dependence during the up-scaling process.
07/31/10	Decision Point	Incorporate air voids and cyclic loading into the lattice modeling.
07/31/10	Journal Paper	Write the journal paper on multiscale lattice modeling.
10/31/10	Decision Point	Incorporate the model for change in the time dependence into the lattice modeling framework.
06/01/10	Decision Point	Finalize the computational modeling framework for continuum damage to fracture. Establish the database for the VECD model and fracture mechanics tests for two HMA mixtures.
10/31/10	Journal Paper	Write the journal paper on continuum damage to fracture process.

Cited References

Bhasin, A. (2006). "Development of methods to quantify bitumen-aggregate adhesion and loss of adhesion due to water," Ph.D. dissertation, Texas A&M University, College Station, Texas.

Caro, S. (2009). "A coupled micromechanical model of moisture damage in asphalt mixtures: Formulation and applications," Ph.D. dissertation, Texas A&M University, College Station, Texas.

Caro, S., Masad, E., Bhasin, A., and Little, D. (2010a). "Coupled micromechanical model of moisture-induced damage in asphalt mixtures." *Journal of Materials in Civil Engineering (ASCE)*, (in press).

Caro, S., Masad, E., Bhasin, A., Little, D., and Sanchez-Silva, M. (2010b). "Probabilistic modeling of the effect of air voids on the mechanical performance of asphalt mixtures subjected to moisture diffusion." *Journal of the Association of Asphalt Paving Technologists (AAPT)*,(in press).

Caro, S., Masad, E., Sanchez-Silva, M., and Little, D. (2010c). "Stochastic micromechanical modeling of asphalt mixtures subjected to moisture diffusion processes." *International Journal for Numerical and Analytical Methods in Geomechanics*, (submitted for evaluation).

El-Kadi, A. I., and Williams, S. A. (2000). "Generating two-dimensional fields of autocorrelated, normally distributed parameters by the matrix decomposition technique." *Ground Water*, 38(4), 523-532.

Hefer, A. W., Little, D. N., and Lytton, R. L. (2005). "A synthesis of theories and mechanisms of bitumen-aggregate adhesion including recent advances in quantifying the effects of water." *Journal of the Association of Asphalt Paving Technologists (AAPT)*, 74, 139-196.

Work Element M4b: Analytical Fatigue Model for Mixture Design

As indicated in the detailed Year 2 work plan, the analytical fatigue model for specimens subjected to moisture damage will be the same as the model being developed under work element F2b. Major findings and Year 4 work plan are described jointly with work element F2b.

Work Element M4c: Unified Continuum Model

Major Findings & Status

The development of the TAMU model in formulating temperature-dependent damage and healing laws is presented in work element F3c. However, the development of the TAMU continuum model for capturing the effect of moisture on the degradation of the adhesive and cohesive bond strength is presented in this section. To model the effect of moisture on bond strength degradation two physical mechanisms are considered. The first mechanism is due to the effect of the moisture on bond degradation within the mastic itself (cohesive damage, ϕ_c^M); whereas, the second mechanism is related to the diffusion of the moisture at the interface of the mastic and aggregate leading to the bond strength degradation at the interface (adhesive damage ϕ_a^M). These two mechanisms may ultimately lead to erosion of the mastic film due to water imposed by passing traffic (scouring effect). Moisture damage is modeled using the effective (undamaged) configuration concept which makes the numerical implementation very easy. Hence, various damage laws which are linear/nonlinear functions of moisture content are investigated for modeling both cohesive moisture damage and adhesive moisture damage. These continuum-based moisture damage laws are implemented in the finite element code Abaqus using the user material subroutine UMAT. Each damage law is then used to predict the available experimental data in order to verify the moisture damage model and determine the associated material parameters. An attempt is made to relate these material parameters in the moisture damage model with the fundamental properties of the aggregate-mastic interface and the mastic. Furthermore, the developed moisture damage model is coupled with the viscoelastic, viscoplastic, and viscodamage model developed in work element F3c. This will allow one to investigate the effect of moisture on the viscoelastic, viscoplastic, and damage response of asphalt mixes when subjected to realistic loading conditions. A parametric analysis is conducted to verify that the model captures the main effects of moisture on the response of the asphalt mixtures. In another parametric study the effect of moisture damage on permanent deformation and rutting in asphalt layers subjected to traffic loading while moisture-conditioned is studied.

Year Four Work Plan

The focus of the year four work plan will be on calibrating and validating the moisture damage model. A systematic procedure will be developed for identifying the material parameters associated with the moisture damage model based on well-designed experiments at TAMU. Furthermore, the experimental verification of the moisture damage component of the unified continuum damage model and the constitutive model itself will be initiated by conducting the tests outlined in table F3c.2 after subjecting the specimens to different levels of moisture conditioning. The validated moisture law will be employed in predicting pavement distresses in the presence of the moisture based on the unified viscoelastic, viscoplastic, and viscodamage model.

Another issue that will be investigated is expressing the moisture damage laws as a function of relative humidity instead of the moisture content. In reality, moisture content in asphalt layers is extremely difficult to predict, whereas relative humidity are much easier to predict. Therefore, including relative humidity is crucial for realistic applications of the moisture damage model for predicting the effect of weather on the performance of asphaltic layers.

Table for Decision Points & Deliverables

Date	**Deliverable**	**Description**
02/31/10	Journal Paper	Submit a paper on integration of the continuum moisture damage model into the unified continuum damage model
04/15/10	Journal Paper	Submit a paper on the calibration and validation of the moisture damage model
07/31/10	Journal Paper	Submit a paper on the effect of moisture damage on rutting
10/31/10	Decision Point	Finalize the calibration and validation of the moisture damage model and its integration into the unified continuum damage model

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.

Table of Decision Points and Deliverables for the Moisture Damage Program Area

Work Element	Date	Deliverable	Description
M1a-1	04/10	Presentation	Presentation at ETG or technical conference.
M1a-1	08/10	Journal Paper	TRB or AAPT paper submission summarizing findings on moisture susceptibility characterization of aggregate-binder interface using PATTI and DSR.
M1a-1	09/10	Presentation	Presentation at the Binder or Mixture ETG.
M1a-1	01/11	Presentation	Presentation on correlation between moisture susceptibility of mixtures and results from PATTI.
M1a-1	01/11	Journal Paper	Paper to a technical journal on the effect of modifiers on moisture damage.
M1a-1	03/11	Final Report	Final Report on work element.
M1b-1	9/30/09[(1)]	Journal Paper	Use of micro calorimeter to measure total energy of adhesion
M1b-3	05/30/10	Decision Point	Validate methods
M1b-3	10/31/09	Draft Report	Report on findings from subtasks M3a-1
M1b-3	11/30/10	Final Report	Final Report on findings from subtasks M3a-1
M1b-3	12/20/10	Journal Paper	Organic-aggregates interactions
M2a-1	9/30/11	Journal Paper	Surface properties of saturated asphalt binders
M2b	12/31/09[(1)(2)]	Journal Papers (Two)	Measurement of diffusion of water through thin films of asphalt binders
M2b	6/30/10[(2)]	Draft Report	
M2b	9/31/10[(2)]	Final Report	
M2b	09/30/11	Journal Paper	Kinetics of debonding at the binder-aggregate interface
M2b	12/31/11	Draft Report	
M2b	03/31/12	Final Report	
M4a	05/31/10	Decision Point	Complete the experimental investigation into the change in time dependence during the up-scaling process.
M4a	07/31/10	Decision Point	Incorporate air voids and cyclic loading into the lattice modeling.
M4a	07/31/10	Journal Paper	Write the journal paper on multiscale lattice modeling.
M4a	10/31/10	Decision Point	Incorporate the model for change in the time dependence into the lattice modeling framework.
M4a	06/01/10	Decision Point	Finalize the computational modeling framework for continuum damage to fracture. Establish the database for the VECD model and fracture mechanics tests for two HMA mixtures.
M4a	10/31/10	Journal Paper	Write the journal paper on continuum damage to fracture process.
M4a	10/31/10	Journal Paper	Write the journal paper on continuum damage to fracture process.

[1] See specific section for detail on publications.
[2] These deliverables have been delayed by approximately 6 months from the original schedule due to the challenges in developing the test method. However, the deliverables will now also include a component on determining the hysteresis in diffusion.

Table of Decision Points and Deliverables for the Moisture Damage Program Area (con't)

Work Element	Date	Deliverable	Description
M4c	02/31/10	Journal Paper	Submit a paper on integration of the continuum moisture damage model into the unified continuum damage model
M4c	04/15/10	Journal Paper	Submit a paper on the calibration and validation of the moisture damage model
M4c	07/31/10	Journal Paper	Submit a paper on the effect of moisture damage on rutting
M4c	10/31/10	Decision Point	Finalize the calibration and validation of the moisture damage model and its integration into the unified continuum damage model

Moisture Damage Year 4

		Year 4 (4/10-3/11)											
		4	5	6	7	8	9	10	11	12	1	2	3
Adhesion													
M1a	**Affinity of Asphalt to Aggregate - Mechanical Tests**												
M1a-1	Select Materials												
M1a-2	Conduct modified DSR tests												
M1a-3	Evaluate the moisture damage of asphalt mixtures	P				JP					P		
M1a-4	Correlate moisture damage between DSR and mix tests												
M1a-5	Propose a Novel Testing Protocol										JP		F
M1a-6	Standard Testing Procedure and Recommendation for Specifications						P						
M1b	**Work of Adhesion**												
M1b-1	Adhesion using Micro calorimeter and SFE												
M1b-2	Evaluating adhesion at nano scale using AFM												
M1b-3	Mechanisms of water-organic molecule competition												
M1c	**Quantifying Moisture Damage Using DMA**				JP				D				F
Cohesion													
M2a	**Work of Cohesion Based on Surface Energy**												
M2a-1	Methods to determine SFE of saturated binders												
M2a-2	Evaluating cohesion at nano scale using AFM												
M2b	**Impact of Moisture Diffusion in Asphalt**												
M2b-1	Diffusion of moisture through asphalt/mastic films			D			F						
M2b-2	Kinetics of debonding at binder-aggregate interface												
M2c	**Thin Film Rheology and Cohesion**												
M2c-1	Evaluate load and deflection measurements using the modified PATTI test												
M2c-2	Evaluate effectiveness of the modified PATTI test for Detecting Modification												
M2c-3	Conduct Testing												
M2c-4	Analysis & Interpretation												
M2c-5	Standard Testing Procedure and Recommendation for Specifications	see Subtask M1a-6											
Aggregate Surface													
M3a	**Impact of Surface Structure of Aggregate**												
M3a-1	Aggregate surface characterization			JP				P					
Modeling													
M4a	**Micromechanics model development**						JP						
M4b	**Analytical fatigue model for use during mixture design**												
M4c	**Unified continuum model**						JP			DP		M&A	
M5	**Moisture Damage Prediction System**												

LEGEND

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

Moisture Damage Year 2 - 5

		Year 2 (4/08-3/09)				Year 3 (4/09-3/10)				Year 4 (04/10-03/11)				Year 5 (04/11-03/12)			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Adhesion																	
M1a	**Affinity of Asphalt to Aggregate - Mechanical Tests**																
M1a-1	Select Materials		DP														
M1a-2	Conduct modified DSR tests		P		P												
M1a-3	Evaluate the moisture damage of asphalt mixtures				DP		P			P	JP		P				
M1a-4	Correlate moisture damage between DSR and mix tests						P		P								
M1a-5	Propose a Novel Testing Protocol				P				P, D				JP, F				
M1a-6	Standard Testing Procedure and Recommendation for Specifications										P						
M1b	**Work of Adhesion**																
M1b-1	Adhesion using Micro calorimeter and SFE						JP										
M1b-2	Evaluating adhesion at nano scale using AFM							JP									JP, F
M1b-3	Mechanisms of water-organic molecule competition				JP												
M1c	**Quantifying Moisture Damage Using DMA**										JP	D	F				
Cohesion																	
M2a	**Work of Cohesion Based on Surface Energy**																
M2a-1	Methods to determine SFE of saturated binders														JP		
M2a-2	Evaluating cohesion at nano scale using AFM							JP									JP, F
M2b	**Impact of Moisture Diffusion in Asphalt**																
M2b-1	Diffusion of moisture through asphalt/mastic films						JP	D	F	D	F						
M2b-2	Kinetics of debonding at binder-agreagte interface																
M2c	**Thin Film Rheology and Cohesion**																
M2c-1	Evaluate load and deflection measurements using the modified PATTI test	DP	JP	D	F												
M2c-2	Evaluate effectiveness of the modified PATTI test for Detecting Modification			D	DP,F												
M2c-3	Conduct Testing						JP										
M2c-4	Analysis & Interpretation				P				D								
M2c-5	Standard Testing Procedure and Recommendation for Specifications					D				**see Subtask M1a-6**							
Aggregate Surface																	
M3a	**Impact of Surface Structure of Aggregate**																
M3a-1	Aggregate surface characterization									JP		P					
Models																	
M4a	**Micromechanics model development**				JP				JP		JP			D	DP	F, SW	
M4b	**Analytical fatigue model for use during mixture design**															M&A,D	F
M4c	**Unified continuum model**								JP		JP	DP	M&A	D	DP	F, SW	
M5	**Moisture Damage Prediction System**																

LEGEND

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

Work planned

Work completed

Parallel topic

PROGRAM AREA: FATIGUE

CATEGORY F1: MATERIAL AND MIXTURE PROPERTIES

Work Element F1a: Cohesive and Adhesive Properties

Subtasks F1a-1: Critical review of the literature
F1a-2: Development of test method
F1a-3: Thermodynamic work of adhesion and cohesion
F1a-4: Mechanical work of adhesion and cohesion
F1a-5: Evaluate acid base scales for surface energy calculations

<u>Major Findings & Status</u>

Literature review

Literature review was conducted with emphasis in two different areas. The first area of emphasis was to investigate test and analytical methods to determine the practical work of cohesion for different binders and the work of adhesion between binders and standard surfaces. In addition to the review, the methods to measure practical work of adhesion were discussed in person by Drs. Little and Masad from Texas A&M with Drs. Aiery and Kinloch from the University of Nottingham and Imperial College in the United Kingdom. This discussion was part of the "Collaborating for Success through People" program sponsored by the United Kingdom. Researchers from the Imperial College, London, led by Dr. Kinloch, have pioneered the development of several industry standards that are used to determine the practical work of adhesion and cohesion for different polymeric adhesives.

The second area of emphasis for the literature review was to document the relationship between practical (or measured) and ideal (thermodynamic or based on surface free energy) work of fracture. This review was based on the work of other researchers with materials other than asphalt binder on this topic for the last three decades. The following is a brief summary of the findings from this review.

The ideal work of fracture, W_A, quantified using the laws of thermodynamic and the practical work of fracture, W_P, determined from mechanical tests, are never equal. In fact, the latter can be several orders of magnitude larger than the former, independent of the type of failure (i.e. cohesive failure within the material or adhesive failure at the interface of adhesive joints). Factors contributing to such differences based on experimental and numerical data reported in the literature are as follows.

During the measurement of W_P, materials dissipate energy due to irreversible processes such as viscous and plastic deformation. These energy contributions make the value of W_P larger than W_A. The range of this difference strongly depends on the characteristics of the materials (e.g. time-dependent and yielding properties), and on the experimental conditions at which W_P is measured. In the case of viscoelastic materials, it was found that W_P is a function of the rate of loading, temperature and rate of crack growth. In the case of brittle materials, that have minimal energy dissipation potential due to irreversible processes such as viscous or plastic deformation during mechanical tests, the values of W_P are larger than the values of W_A determined using surfaces free energy. This was mostly attributed to the differences between the true fracture area that includes micro-branches and the nominal fracture surface area, or due to other irreversible phenomena, such as hardening orientation. These results show that it is not possible to eliminate all irreversible processes that can arise during mechanical testing. In other words, W_P will always be different from the W_A even for ideally perfect brittle-elastic materials.

However, the most important conclusion that was extracted from the detailed literature review was that even thought W_A is not equal in magnitude to W_P, these two values are strongly related. Figure F1a.1 illustrates one example from the literature that demonstrates the correlation between the ideal (x-axis) and practical work of cohesion (y-axis). This means that any small modification in the ideal work of fracture will have a significant impact on the practical work of fracture. In other words, materials with larger values of W_A will naturally show larger values of W_P during mechanical testing. This observation has been verified by the recent work that has been conducted at Texas A&M University in which W_A values for asphalts and aggregate-asphalt systems have been successfully used to estimate the resistance to fatigue cracking and moisture damage in asphalt mixtures.

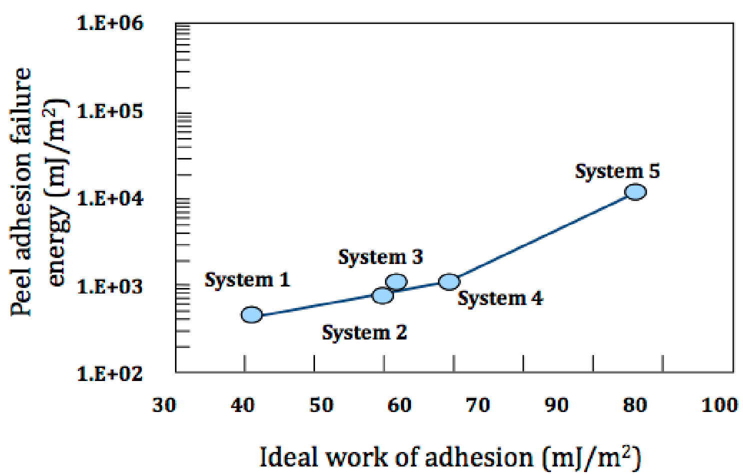


Figure F1a.1. Practical vs. ideal work of adhesion (from Okamatsu et al. 2001).

The findings from the aforementioned white paper were discussed in person with Dr. Kinloch and his colleagues from the Imperial College, London and Dr. Scarpas and his colleagues from TU-Delft. The proposed white paper was further improvised during a joint discussion at TU-Delft with Dr. Scarpas and his group. Findings from the white paper have also been summarized in the form of a technical paper accepted for publication in the Journal of Association of Asphalt Pavement Technologists.

Results comparing practical and ideal work of cohesion and adhesion

The two main objectives of this task are i) to establish the relationship between practical work of adhesion or cohesion with ideal work of adhesion or cohesion, respectively and ii) to generate basic input such as the traction-separation behavior between binder/mastic-aggregate interface for inputs in the modeling effort. A test method was developed to measure these properties. Thin film specimens were created using a DSR and tested in a 5kN universal testing machine. High resolution imaging was used to measure deformation during the test. Details of the test method have been presented in previous quarterly reports and have also been summarized in a forthcoming technical paper. The summary of findings and conclusions are reiterated here.

- A range of sample thicknesses was tested to observe the effect of film thickness on the displacement and failure mode of the samples. It was found that as the sample thickness increased, the effective surface free energy of failure decreased, the maximum tensile force at failure decreased, and the displacement at failure increased (figure F1a.2).
- In general, a higher surface energy yields a higher value of fracture energy (figure F1a.3.). However, there are other material factors besides surface energy that can contribute to the fracture energy of the thin asphalt film.

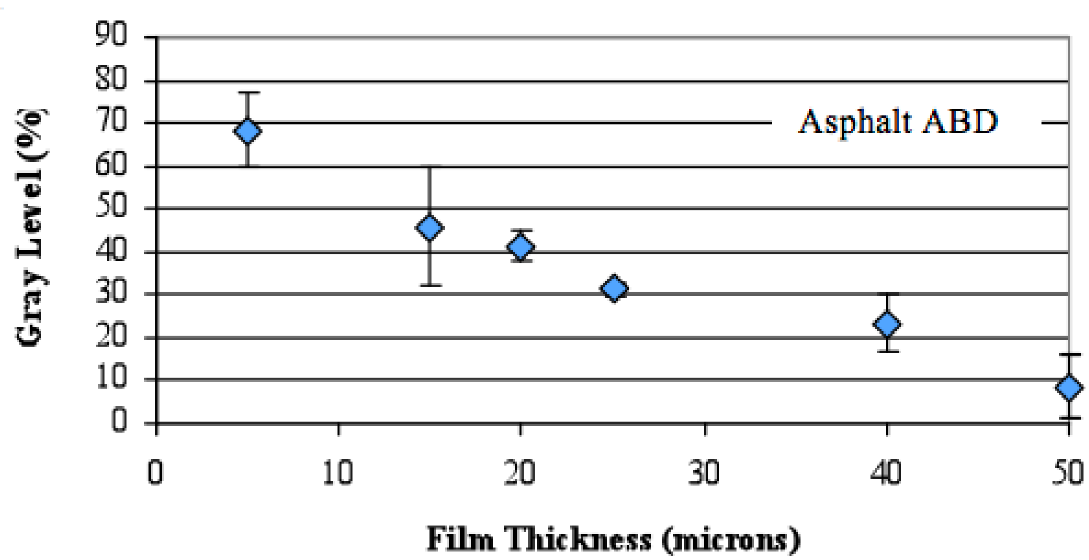


Figure F1a.2. Typical results to demonstrate influence of film thickness on tensile strength and mode of failure in asphalt binders.

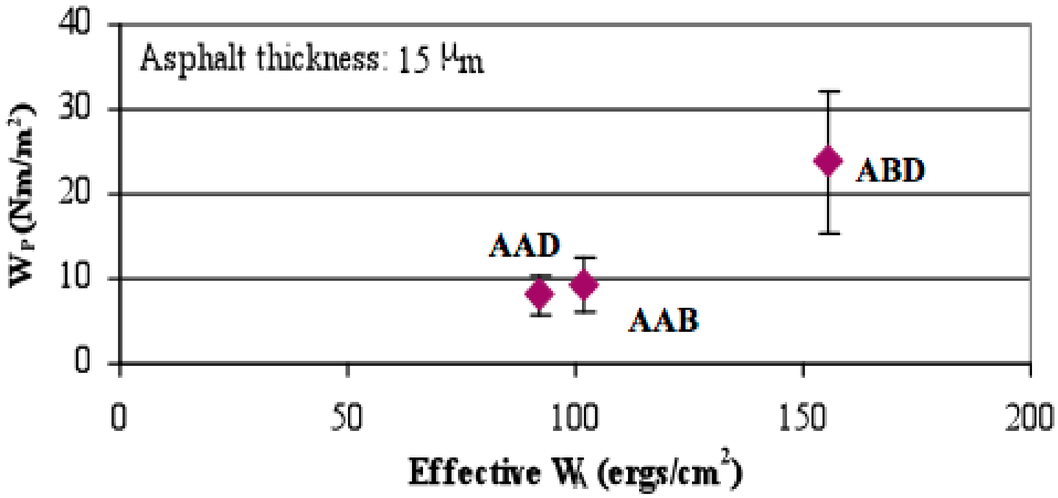


Figure F1a.3. Typical results to demonstrate relationship between practical and ideal work of cohesion for different asphalt binders at a given film thickness.

Significant Problems, Issues and Potential Impacts on Progress

The data analysis to compute the displacement of the thin asphalt film for the duration of the pull-off test requires a substantial time requirement. This pushed back the start of testing with aggregate substrate. However, a more efficient version of the software is being developed that should reduce the analysis time by at least half.

Year Four Work Plan

All tests utilizing the asphalt-stainless steel substrate were completed last year. The remaining testing to complete consists of asphalt binder with aggregate substrate. Two aggregates with different lithologies and different observed moisture resistance were chosen. There are three sets of tests to be run with each asphalt-aggregate combination in order to fully characterize the combination. Table F1a.3 displays the matrix of tests to be run with each aggregate substrate.

Table F1a.3. Testing matrix for asphalt-aggregate pull-off tests.

Testing Matrix																		
Replicate	Asphalt	Film Sweep - 45 Tests					Master Curve - 81 Tests									Moisture Conditioning - 27 Tests		
		0.01 mm/sec @ 23°C					Loading Rate - Temperature Combinations - 30μm									0.01 mm/sec @ 23°C & 30μm		
		Film Thicknesses (μm)					0.01 mm/sec			0.02 mm/sec			0.05 mm/sec			Conditioning Time		
		5	10	30	50	100	10°C	23°C	36°C	10°C	23°C	36°C	10°C	23°C	36°C	12 hrs	24 hrs	48 hrs
1	AAB																	
2																		
3																		
1	AAD																	
2																		
3																		
1	ABD																	
2																		
3																		

The first set of tests to be conducted will be an asphalt binder film sweep ran at a single loading rate and temperature. The asphalt film will range from very thin, producing an adhesive failure, to relatively thick, producing cohesive failure. This set of data will enable the researchers to determine the relationship between the ideal work of fracture, determined with surface free energy, and the corresponding practical work of fracture measured from the experimental test.

The second set of tests to be conducted consists of changing the loading rate and temperature of samples with a single film thickness. Three different loading rates each with three different temperatures will be used. Because asphalt binder is a viscoelastic liquid, its properties are affected by both loading rate and temperature. Through this set of tests, the master curve can be generated. These tests will allow researchers to determine the effect of loading rate and temperature on the dissipated energy of system.

The final set of tests to be conducted will look at how moisture affects the practical work of fracture of the asphalt-aggregate combination. The asphalt aggregate samples will be submerged under water at room temperature for various times. One loading rate, temperature, and film thickness will be used in conjunction with 3 moisture conditioning times. This set of data will enable the researchers to determine the relationship between the ideal work of fracture in the presence of water, determined with surface free energy, and the corresponding practical work of fracture measured from the experimental test.

<u>Table for Decision Points and Deliverables</u>

Date	**Deliverable**	**Description**
12/31/08[(1)]	Journal Paper	A review of practical and thermodynamic work of cohesion and adhesion
09/30/09[(2)]	Journal Paper	Comparing practical and thermodynamic work of adhesion and cohesion
6/30/10[(3)]	Draft Report	
09/30/10[(3)]	Final Report	
[(4)]	Journal Paper	On the acid-base scale of surface energy components

(1) A white paper documenting this review has been prepared and submitted to FHWA.

(2) Masad, E., Howson, J., Bhasin, A., Caro, S. and Little, D.N. “Relationship of Ideal Work of Fracture to Practical Work of Fracture”, Journal of the Association of Asphalt Paving Technologists, Vol. 79 (In Press).

(3) These deliverables will be presented approximately 6 months later from the original plan due to delays in the development of the test method. The revised Gantt chart will reflect this.

(4) This deliverable is being eliminated with the corresponding subtask. The revised Gantt chart will reflect this.

References

Okamatsu, T., Y. Yasuda, and M. Ochi, 2001, Thermodynamic Work of Adhesion and Peel Adhesion Energy of Dimethoxysilyl-Terminated Polypropylene Oxide/ Epoxy Resin System Jointed with Polymeric Substrates. *Journal of Applied Polymer Science,* 80(11): 1920-1930.

Marek, C. R., and Herrin, M. (1958). "Tensile Behavior and Failure of Thin Films of Asphalt." *Proc. Association of Asphalt Paving Technologists*, 37, 386-421.

Work Element F1b: Viscoelastic Properties

Subtask F1b-1: Viscoelastic properties under cyclic loading

Major Findings & Status

A method to calculate the nonlinear viscoelastic and damage parameters based on the Schapery's nonlinear viscoelastic model was developed. This method was extended to dynamic loading in a fatigue test by considering the nonlinear parameters as a function of stress or strain amplitudes applied in the DMA. Damage is quantified by changes in the nonlinear parameters at an applied stress or strain level. This analysis method was used to analyze DMA test results at various stress amplitudes, strain amplitudes and frequencies. Table F1b-1.1 summarizes the three important components of this methodology.

Table F1b-1.1. Methodology to characterize fatigue damage by incorporating the non linear viscoelastic response of the material.

	Procedure	**Purpose**
Step 1	Identify the limiting stress or strain amplitude that generates nonlinear viscoelastic response without causing damage	This information will also be used to select a suitable magnitude of stress or strain amplitude for the specific material to ensure that incremental crack growth occurs with each consecutive cycle
Step 2	Model and monitor **the change in** the nonlinear viscoelastic **parameters with increasing number of load cycles** during the fatigue test	A change in the nonlinear viscoelastic parameters with increasing number of load cycles indicates accumulation of damage. Therefore, this change can be used to quantify the accumulated fatigue damage in the test specimen
Step 3	Model and monitor **the change in** the nonlinear viscoelastic **parameters within each cycle** during the fatigue test	A change in the nonlinear parameters within each cycle can be modeled and monitored to determine the type of damage that is being accumulated during the fatigue load test and also to accurately partition the dissipated energy due to damage versus nonlinear viscoelastic dissipated energy

Significant progress was made in Steps 1 and 2 during years 1 and 2 of this project. In year 3 of the project, a detailed investigation was carried out for Step 3 of this study. A summary of the findings is presented below.

Step 1 (Years 1 and 2): The limiting stress or strain amplitude that generates nonlinear viscoelastic response without causing damage was determined by conducting stress or strain sweeps. The stress or strain sweeps were conducted by subjecting the specimen to a minimum number of load cycles at each increment of the strain or stress amplitude. The optimal parameters for increments and the minimum number of load cycles that are required to obtain the desired information were determined by conducting several trials. For a strain amplitude sweep, the slope or change in the torque amplitude versus number of load cycles was recorded at each strain amplitude. Similarly, for a stress amplitude sweep, the slope or change in the displacement amplitude versus number of load cycles was recorded at each stress amplitude. Figure F1b-1.1 illustrates typical results from stress sweep test. From figure F1b-1.1, the limit stress amplitude that generates nonlinear viscoelastic response without cause damage is close to 4.5E+04 Pa.

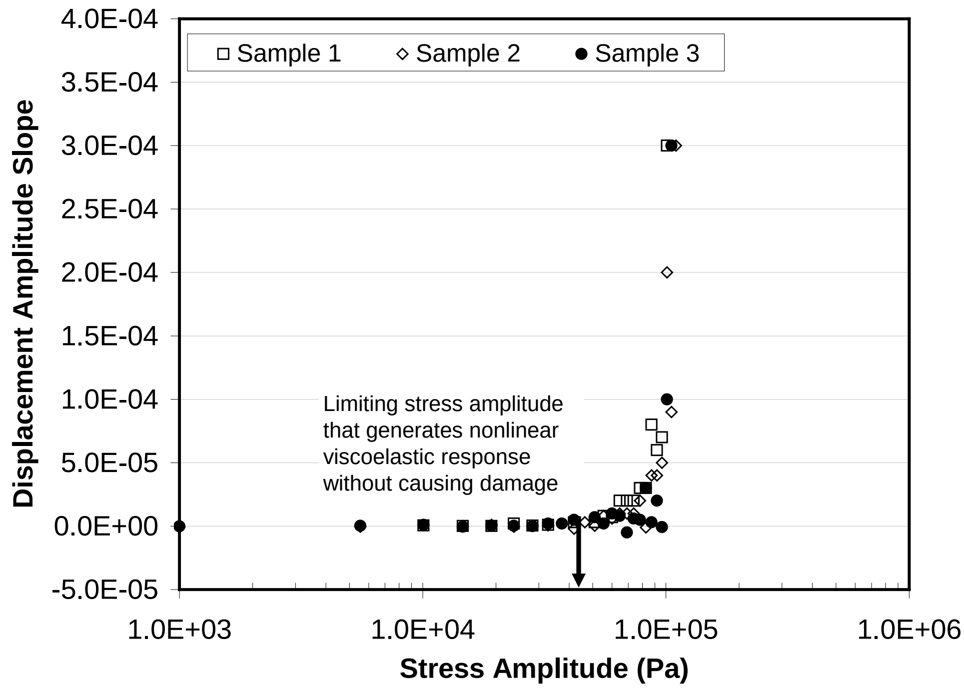


Figure F1b-1.1. Displacement amplitude slopes.

Step 2 (Years 1 and 2): Two different approaches were used to characterize damage evolution in fine aggregate matrix specimens subjected to cyclic loading. The first approach was to use crack growth index albeit with the improved correction for non-linear viscoelastic properties as described in step 1. The second approach was to use Schapery's non-linear viscoelastic parameters as described below as a measure of damage. Recall that damage and non-linear viscoelastic response have a similar manifestation.

Preliminary results from the test and data analysis protocols that were developed support the following conclusion. When FAM specimens are tested within a certain range of stress amplitude or strain amplitude, the results from the controlled stress mode of loading are equivalent to the results from the controlled strain mode of loading (F1b-1.2).

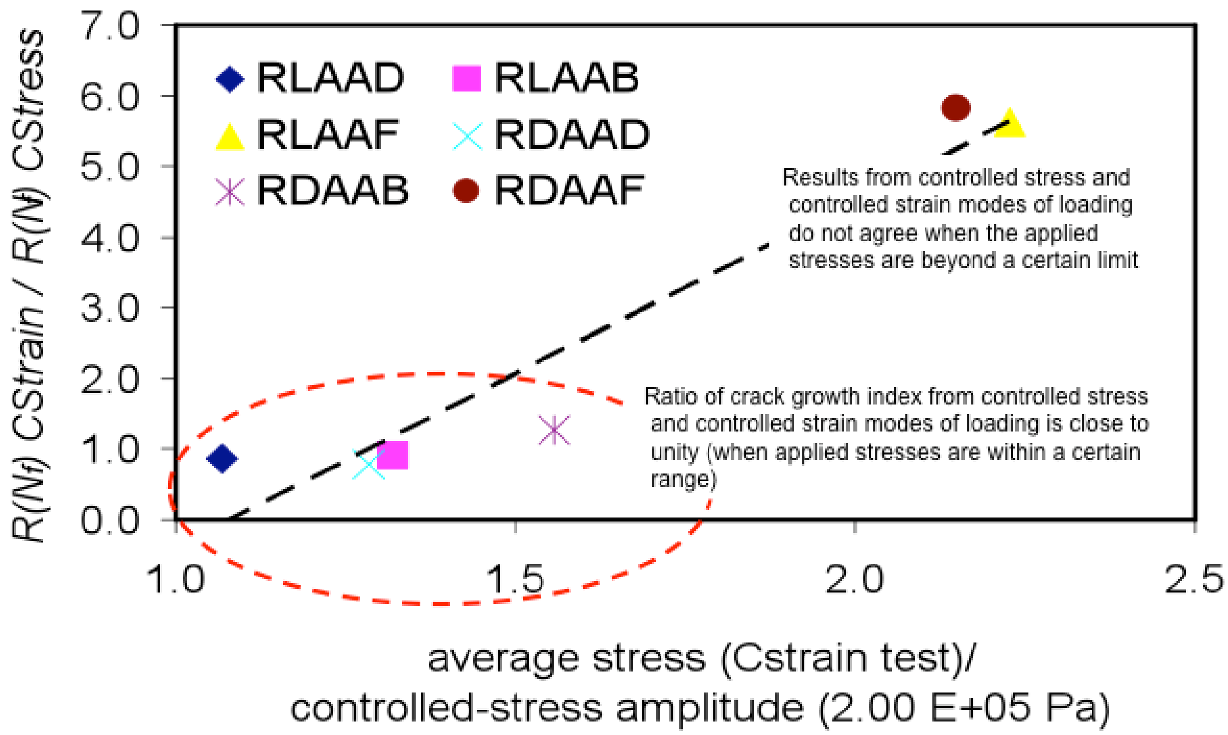


Figure F1b-1.2. Illustration of the uniformity of results from controlled stress and controlled strain modes of loading within a certain stress range.

The details of the findings from Steps 1 and 2 were documented in journal publications that are currently in press. A detailed technical report is currently being prepared.

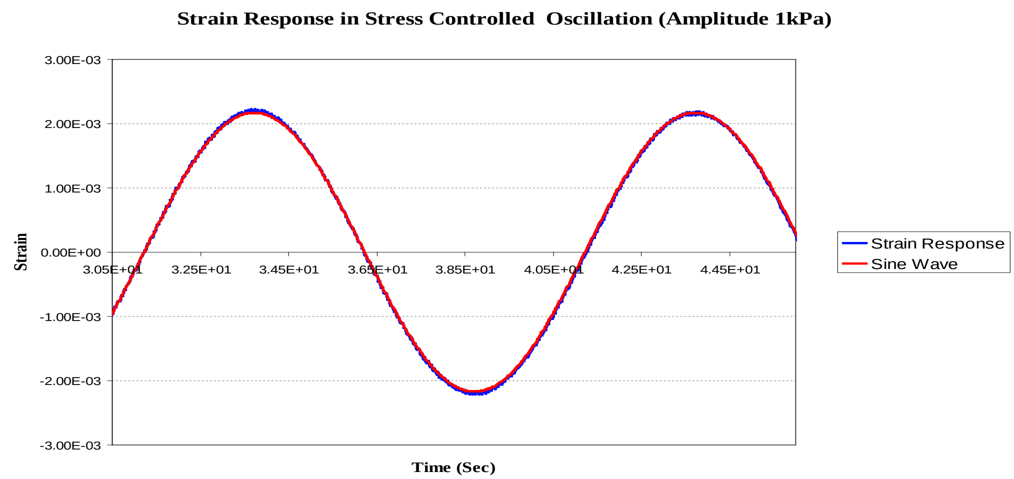
Step 3 (Year 3): The main objective of step 3 was to develop an analytical solution to characterize the response of non-linear viscoelastic materials subjected to dynamic loading. This step is important because the researchers hypothesized that during each load cycle only specific portions of the load cycle contribute to damage. Also, in order to obtain an accurate estimate of the dissipated energy due to fatigue damage, the non-linear viscoelastic response and response due to damage must be accurately modeled and accounted for at each and every point within the load cycle.

The modeling effort was primarily geared towards FAM. However, pending the fabrication of FAM specimens using the selected core materials, researchers decided to evaluate the model using asphalt binder. Different types of binders were tested under torsion using the DMA. Binders with different PG grades were selected in order to ensure a broad spectrum of mechanical properties. Most of these binders were polymer modified and were tested in torsional shear using DMA. The cone and plate geometry was used in order to have a uniform stress-strain distribution.

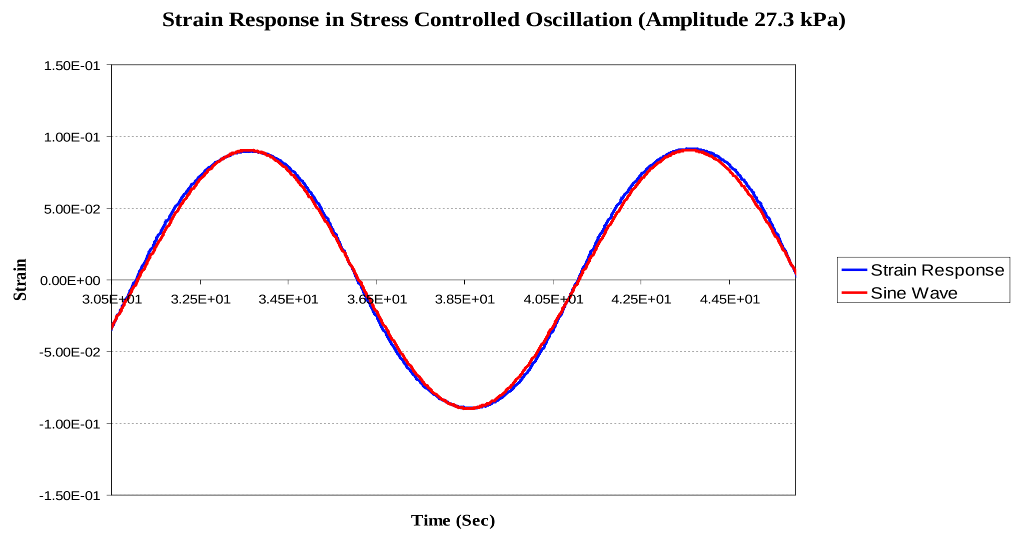
The hypothesis behind this effort is briefly described here. When a time dependent material is subjected to a cyclic sinusoidal load the steady state response also follows a sinusoidal response for a linear material. However, when the stress levels are high and the response is non-linear the steady state response deviated from a sinusoidal curve and there exists a non-uniform phase angle throughout the loading cycle. By conducting stress sweep test on binders, it was observed that the response at low stress levels exactly follows a sine wave, as expected (figure F1b-1.3a). However, when the amplitude was increased the strain response was symmetric but did not follow a sine wave (figure F1b-1.3b). A further increase in the stress amplitude resulted in an asymmetric response with an amplitude that changed with each load cycle (figure F1b-1.3c). In summary the following three stages could be observed:

1. At low stress levels the strain response perfectly followed a sinusoidal curve and the amplitude of the response did not change with increasing number of cycles.
2. At intermediate stress levels the strain response deviated from a sinusoidal curve (indicating non-linear behavior) but the amplitude did not change with increasing number of cycles.
3. At high stress levels the strain response deviated from a sinusoidal curve (indicating non-linear behavior) and the material response changed with increasing number of cycles (indicating significant change in the material properties with increasing number of cycles).

a)



b)



c)

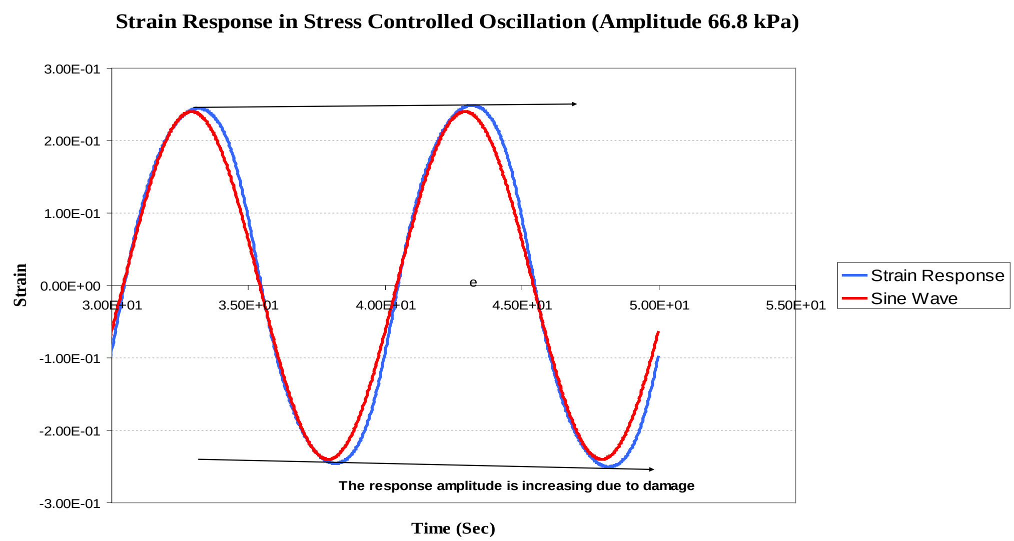


Figure F1b-1.3. Strain response under stress controlled oscillation.

The non-linear response of the viscoelastic materials can be captured using the model proposed by Schapery. However, it is also important to determine the nature of non-linearity to ensure that the aforementioned model is versatile and not dependent on the test procedure. Further investigations were carried out to determine the sources of non-linear response in asphalt materials. A review of literature suggests that for non-Newtonian fluids a normal force may result (first normal stress difference is non zero) when the specimen is subjected to shear due to large deformations or Weissenberg effect. Based on some preliminary test data, it was hypothesized that the presence of a normal force leads to interaction non-linearity and consequently reduced torsional stiffness. For example, figure F1b-1.4 illustrates this response for a certain polymer. The presence of interaction non-linearity in asphalt binders was further explored in this subtask.

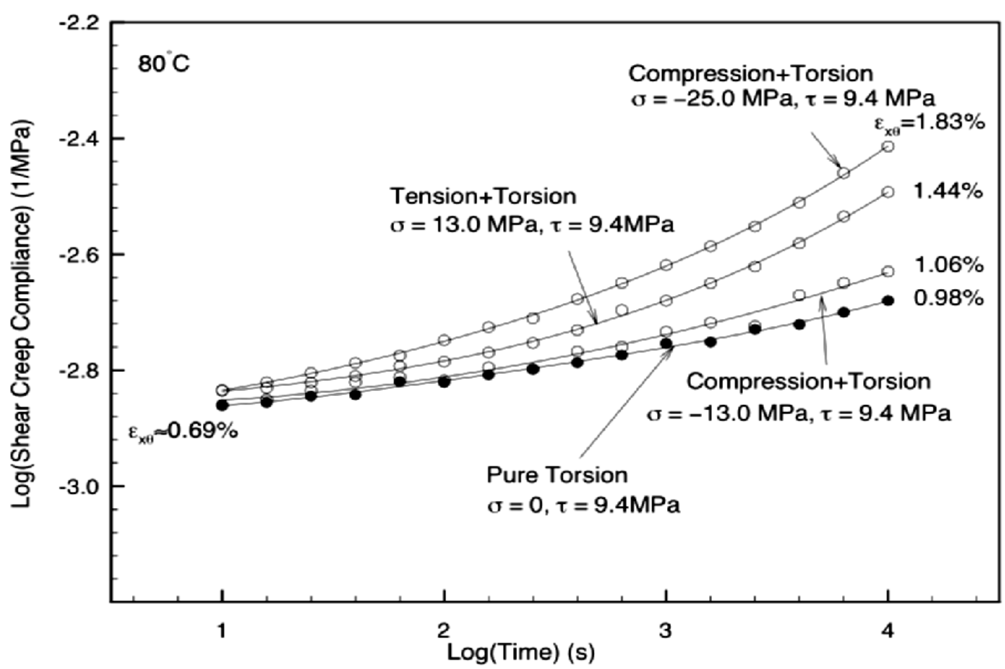


Figure F1b-1.4. Shear creep compliance curves for pure torsion and torsion with superimposed tension or compression for PMMA. Change in creep compliance with multiaxial load test illustrates interaction nonlinearity (Lu and Knauss 1999).

The following approach was used to validate this hypothesis. Repeated creep-recovery tests were conducted at different stress levels on asphalt binders using the cone and plate geometry. Analysis of the test results indicated that the selected asphalt binder had a linear viscoelastic response up to stresses as high as 20 KPa. However, when the same material was subjected to amplitude sweep (under sinusoidal loading) non-linear response was observed at stress amplitudes as low as 5 KPa. However, close examination of the test data revealed that for the dynamic amplitude sweep test there was a buildup of normal forces (figure F1b-1.5).

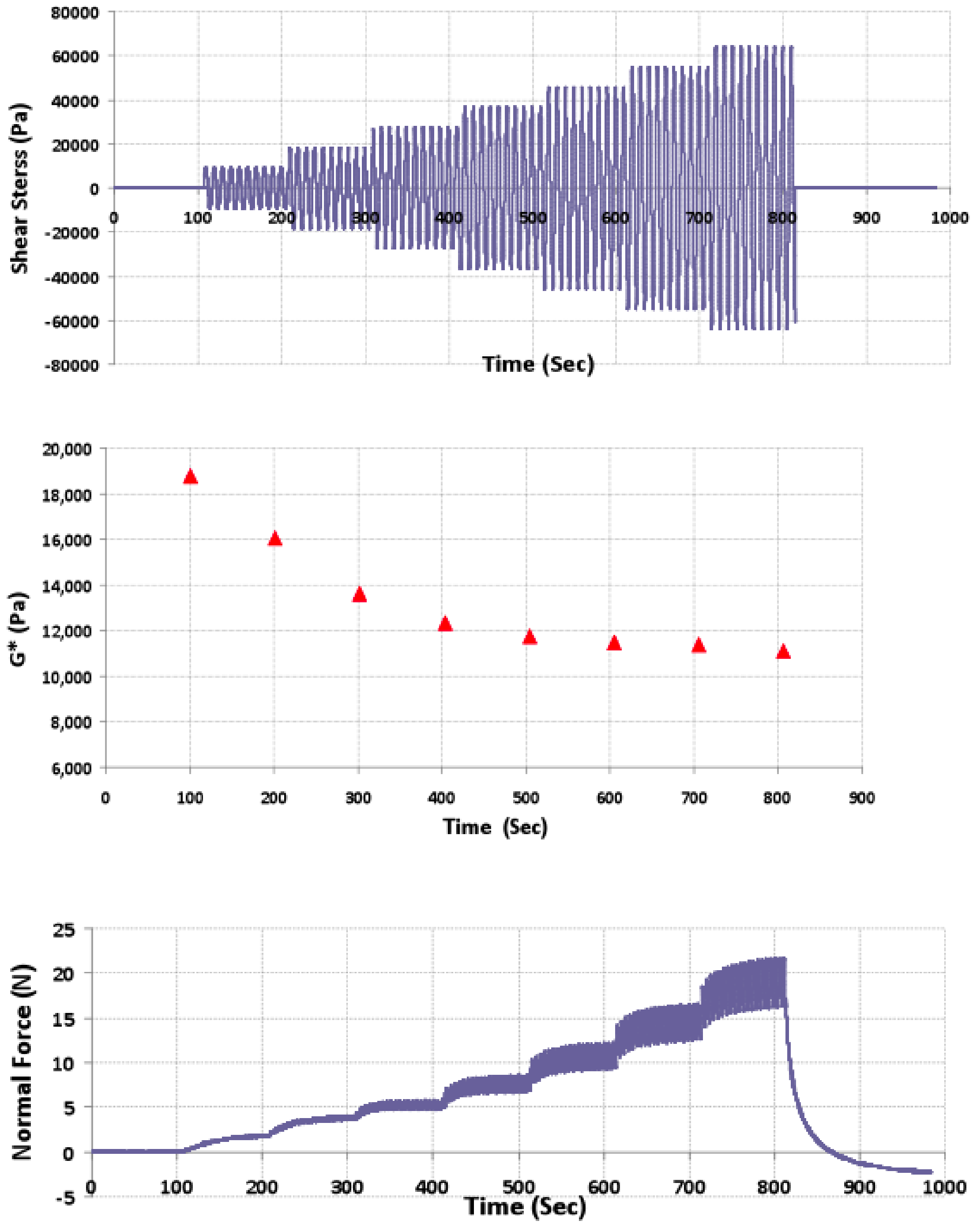


Figure F1b-1.5. Amplitude sweep, change in G* and normal force for a PG grade asphalt binder tested using the DSR with cone and plate geometry.

The next step was to validate the source of the normal force and quantify the amount of non-linearity induced due to the normal force. This was done by comparing the theoretical response expected from a linear viscoelastic material subjected to large deformations to the response measured using the DSR. The theoretical response was obtained using a finite element simulation of the cone and plate geometry (a closed form analytical solution could not be used because of the large deformation and specimen geometry). Figure F1b-1.6 illustrates the finite element analysis of the specimen in cone and plate geometry. Figure F1b-1.7 illustrates the difference between the results obtained from the finite element analysis and the measured values. As expected, the measured G* was smaller than the computed G*. The measured normal force can now be used to explain non-linearity and the difference between the measured and computed G* values.

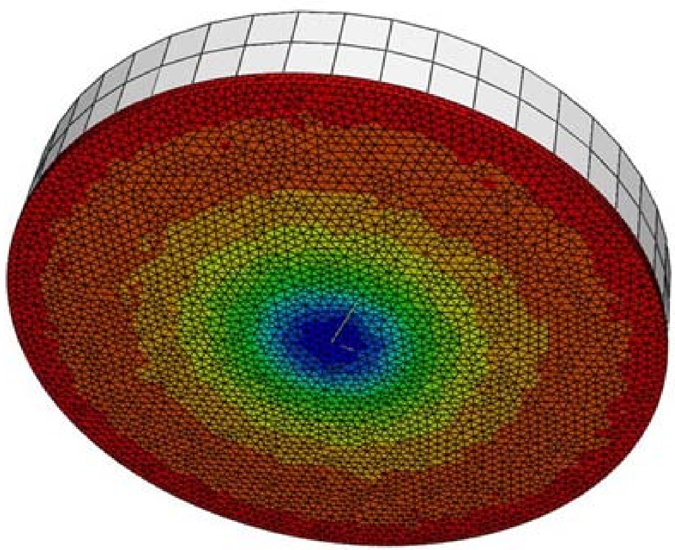


Figure F1b-1.6. Finite element analysis of the cone and plate geometry to determine normal force and G* of a specimen subjected to stress amplitude sweep (colored contours show distribution of normal force).

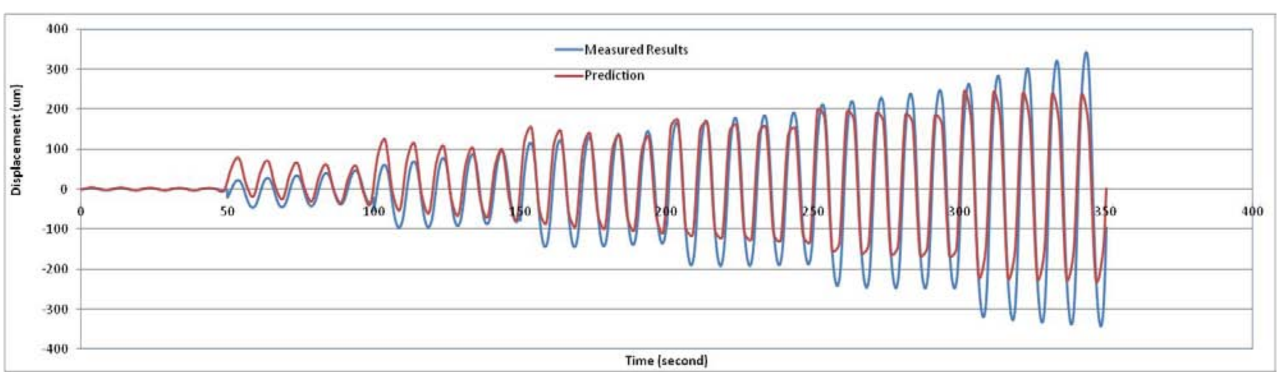


Figure F1b-1.7. Comparison of the computed and measured values of G* to quantify the amount of non-linearity.

Initial test results support the hypothesis that normal force induces a non-linear response in the material. This is also referred to as interaction non-linearity in the literature. We will continue with the investigation and modeling of this form of non-linear response. The expectation is that the findings from this subtask will result in a more robust constitutive model for the time and stress state dependent response for asphalt materials.

Year Four Work Plan

The first objective of the fourth year work plan for this subtask is to complete the aforementioned task of quantifying the non-linear response of asphalt binders. This will involve: (a) validating the source of non-linearity as discussed above, (b) based on the validation, identifying an appropriate constitutive equation that incorporates the stress state of the material and (c) establishing a methodology to determine the parameters in the constitutive equation. The basic approach to accomplish this objective is described above.

The second objective of the year four and five work plan is to evaluate the fatigue cracking response of the asphalt materials (binder and FAM) when subjected to torsional shear and normal loading. The following factors will be considered for this portion of the sub-task.

Materials and geometries:

i) asphalt binders subjected to torsion,
ii) thin films of asphalt binders subjected to direct tension,
iii) thin films of asphalt mastics subjected to direct tension, and
iv) FAM specimens

Type of loading:

i) creep-recovery tests
ii) repeated cyclic tests until failure (similar testing will be conducted for work element F1d on healing by incorporating a dwell time after each cycle during the repeated load test).

Table for Decision Points and Deliverables

Date	Deliverable	Description
3/30/10[1]	Draft Report	Use of non-linear viscoelastic properties to characterize fatigue damage and delineate non-linear viscoelastic response from damage
12/31/08[2]	Journal Paper	
06/30/10[1]	Mathematical model	
06/30/10[1]	Final Report	
06/30/10	Journal Paper	The non-linear viscoelastic response of a material subjected to dynamic loading
09/30/10	Journal Paper	The non –linear viscoelastic response of thin films subjected to dynamic loading
09/30/11	Journal Paper, Model, Draft Report	Characterization of damage in thin films subjected to dynamic loading
03/31/12	Final Report	

(1) A draft for all these deliverables is complete and is under review by the research team. The delivery dates have been revised from the original schedule to allow completing the review.

(2) Branco, V.C., Masad, E., Bhasin, A., and Little, D.N. “Fatigue Analysis of Asphalt Mixtures Independent of Mode of Loading”, *Transportation Research Record No. 2057*, 147-156.

Bhasin, A., Branco, V. C., Masad, E., and Little, D. N. (2009). "Quantitative Comparison of Energy Methods to Characterize Fatigue in Asphalt Mixtures." *Journal of Materials in Civil Engineering*, 21(2), 83-92.

Masad, E., Branco, V. C., Little, D. N., and Lytton, R. L. (2008). "A Unified Method for the Dynamic Mechanical Analysis of Sand Asphalt Mixtures." *International Journal of Pavement Engineering*, 9(4), 233-246.

References:

Branco, V. C., 2008, "A Unified Method for the Analysis of Nonlinear Viscoelasticity and Fatigue Damage of Asphalt Mixtures Using the Dynamic Mechanical Analyzer," Ph.D. Dissertation, Texas A&M University, College Station.

Subtask F1b-2: Viscoelastic properties under monotonic loading

Major Findings & Status

A method was developed to separate the recoverable and irrecoverable responses using creep recovery experimental measurements at various temperatures and stress levels. A schematic of a single creep-recovery test is shown in figure F1b-2.1 for a constant stress loading and unloading condition. Hence, applying Schapery’s nonlinear viscoelastic model to represent the recoverable response, the creep and relaxation strain can be expressed as:

$$\varepsilon^{c}(t)=\varepsilon^{rec}(t)+\varepsilon^{irrec}(t)=g_1\,g_2\sigma\;\Delta D\left(t\right)+\varepsilon^{irrec}(t) \tag{F1b-2.1}$$

$$\varepsilon^{r}(t)=\varepsilon^{rec}(t)+\varepsilon^{irrec}(t_a)=\left[g_2\sigma\;\Delta D\left(t\right)-g_2\sigma\;\Delta D\left(t-t_a\right)\right]+\varepsilon^{irrec}(t_a) \tag{F1b-2.2}$$

where ε^{c} is the total creep strain, ε^{r} is the total relaxation strain, ε^{rec} is the recoverable strain, ε^{irrec} is the irrecoverable strain, t_a is the loading time shown in figure F1b-2.1. The Prony series is used to represent the transient compliance ΔD as follows:

$$\Delta D^{\psi^t}=\sum_{n=1}^{N}D_n\left(1-\exp\left(-\lambda_n\psi^{t}\right)\right) \tag{F1b-2.3}$$

The first step of the analysis procedure is to obtain the Prony series coefficients D_n and λ_n (equation F1b-2.3) from a linear viscoelastic response. This study assumed the material behavior at the lowest stress level is linear viscoelastic response. This analysis uses the strain $\Delta\varepsilon^{r1}$ shown in figure F1b-2.1 which is the recovered strain between t_a and t_b to obtain the Prony series coefficients D_n and λ_n. The expression for $\Delta\varepsilon^{r1}\left(t\right)$ can be derived from equations F1b-2.1 and F1b-2.2 such that:

$$\begin{aligned}\Delta\varepsilon^{r1}\left(t\right)&=\varepsilon^{c}\left(t_a\right)-\varepsilon^{r}\left(t\right)\\&=\sigma\left\{\begin{aligned}&\sum_{n=1}^{N}D_n\left[1-\exp\left(-\lambda_n t_a\right)\right]-\\&\sum_{n=1}^{N}D_n\left[1-\exp\left(-\lambda_n t\right)\right]+\sum_{n=1}^{N}D_n\left[1-\exp\left(-\lambda_n (t-t_a)\right)\right]\end{aligned}\right\}\end{aligned} \tag{F1b-2.4}$$

Then the determined Prony series coefficients (D_n and λ_n) are used in equations F1b-2.1 and F1b-2.2 to analyze the experimental measurements at higher stress levels in order to determine the nonlinear viscoelastic parameters g_1 and g_2. At the higher stress levels, the following expression for the recovered strain $\Delta\varepsilon^{r3}\left(t\right)$ from $t=t_1$ to $t=t_b$ (see figure F1b-2.1) can be derived from equation F1b-2.2 and then used to determine the nonlinear parameter g_2, such that:

$$\begin{aligned}\Delta\varepsilon^{r3}\left(t\right)&=\varepsilon^{r}\left(t_1\right)-\varepsilon^{r}\left(t\right)\\&=g_2\sigma\left\{\begin{aligned}&\sum_{n=1}^{N}D_n\left[1-\exp\left(-\lambda_n t_1\right)\right]+\sum_{n=1}^{N}D_n\left[1-\exp\left(-\lambda_n (t_1-t_a)\right)\right]-\\&\sum_{n=1}^{N}D_n\left[1-\exp\left(-\lambda_n t\right)\right]+\sum_{n=1}^{N}D_n\left[1-\exp\left(-\lambda_n (t-t_a)\right)\right]\end{aligned}\right\}\end{aligned} \tag{F1b-2.5}$$

Once the nonlinear parameter g_2 is obtained, the expression for the recovered strain $\Delta\varepsilon^{r2}(t)$ which can be derived from equations F1b-2.1 and F1b-2.2 and then used to fit the experimental measurements from $t = t_a$ to $t = t_1$ (see figure F1b-2.1) in order to obtain the nonlinear parameter g_1, such that:

$$\Delta\varepsilon^{r2}(t) = \varepsilon^c(t_a) - \varepsilon^r(t)$$
$$= \sigma \left\{ \begin{array}{l} g_1 g_2 \sum_{n=1}^{N} D_n \left[1 - \exp(-\lambda_n t_a)\right] - \\ g_2 \sum_{n=1}^{N} D_n \left[1 - \exp(-\lambda_n t)\right] + g_2 \sum_{n=1}^{N} D_n \left[1 - \exp(-\lambda_n (t - t_a))\right] \end{array} \right\} \quad \text{(F1b-2.6)}$$

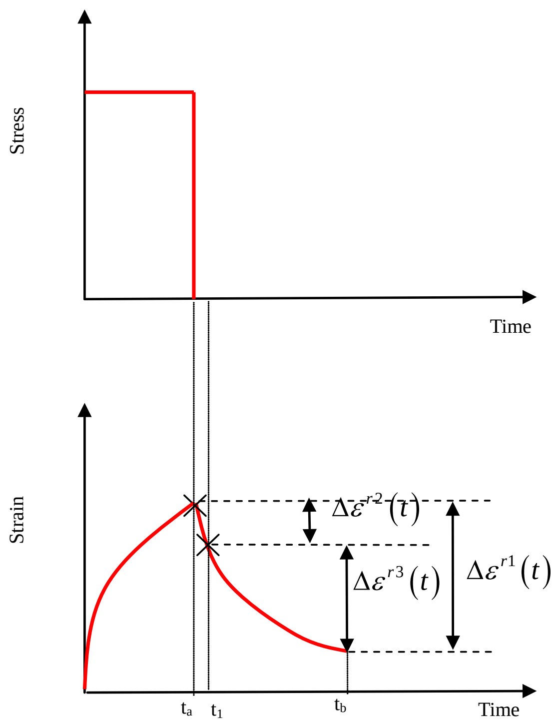


Figure F1b-2.1. A schematic of single creep and recovery test.

Year Four Work Plan

The method for separating the nonlinear viscoelastic and viscoplastic components will be used in the analysis of the ALF experimental data and the experimental measurements that will be conducted during the fourth year. Then, this systematic framework will be used for the identification of the material constants associated with the viscoelastic and viscoplastic models that are part of the unified continuum damage model. Therefore, this framework will support the calibration and validation of the other mechanistic models of moisture damage, mechanical damage, healing, and aging. Future plans for the continuum model are presented in task F3c.

Work Element F1c: Aging

Major Findings & Status

Year three produced significant improvements in modeling pavement temperature as a function of time and depth, and in our ability to use that temperature model to calculate binder aging in pavements over time in a way that includes oxygen diffusion resistance in the binder. A presentation and a journal paper were presented for each of these models and they provide details of the methods and their capabilities of predicting both temperature and binder oxidation in pavements. Both of these capabilities are essential for modeling and predicting pavement performance.

Additionally, methods for testing laboratory mixture specimens and field cores have been developed. While these methods and procedures have taken considerably longer than anticipated, the results are excellent and data acquisition is progressing. The methods are significant improvements over previous methods in both quality of data obtained and in the speed with which the data may be obtained. Because of this latter feature, we believe that getting back on schedule will be achieved this year. This testing protocol will provide data for the purpose of developing a fundamental understanding of the effect of binder oxidation on mixture fatigue resistance properties, including binder healing.

Year Four Work Plan

Subtask F1c-1: Critical Review of Binder Oxidative Aging and Its Impact on Mixtures

This work element is ongoing. New information obtained in year 4 on binder oxidation rates in pavements and the impact of binder oxidation on mixture properties will be evaluated from the perspective of existing and new literature. Of particular current interest is a review of literature articles on oxidation reactions as they might explain the fast-rate oxidation kinetics that are being determined in the laboratory.

Subtask F1c-2: Develop Experimental Design

A 63 page experimental plan was previously completed and submitted. The Year 4 effort will continue to carry out this plan.

Subtask F1c-3: Develop a Transport Model of Binder Oxidation in Pavements

A transport model has been developed and, following preliminary evaluation with available pavement cores, is ready for a more complete calibration and validation. This effort will continue in Year 4 with field cores from the WRI test pavements in Arizona, Kansas, Nevada, Minnesota, and Wyoming, and the binder, recovered from several depths. Because of the delays in improvements to the mixture testing equipment and protocols, the work of this subtask lags behind the year three plan.

Parallel to comparisons of model calculations with field aging will be collaborative efforts with the several mixture modeling efforts of the ARC. The objective will be to provide links between the transport oxidation model and the mixture modeling that can be used to enhance pavement performance prediction as it is affected by binder oxidative hardening. A key element of this linkage will be to develop the connections between binder physical properties and their changes due to oxidative hardening and mixture properties that reflect durability performance. This connection likely will depend upon an improved fundamental understanding of the relationships between binder properties and mixture performance, especially the non-linear properties of cracking and fatigue. These collaborative efforts between the aging modeling effort and other members of the ARC have been initiated.

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

This subtask will comprise a major effort of the F1c task in year 4. Details were given in the experimental plan. The effort was summarized in the Year 3 plan in tables F1c.1 and F1c.2. While conducting this subtask has been delayed due to the equipment and test development described elsewhere, tests are now underway.

Subtask F1c-5: Polymer Modified Asphalt Materials

<u>Background and Motivation</u>

Polymer modification of asphalt binders provides enhancement of binder properties by providing an elastic polymer network interacting with asphalt. The interaction of the polymer modifier and the base asphalt binder appear to be critical in establishing the beneficial effects and these interactions need to be better understood. This interaction has been shown to be reduced by oxidative aging of polymer-modified binder (polymer network damage due to polymer oxidative degradation or a reduction in interactions with the asphalt binder), to the point that the modified binder eventually behaves like the aged unmodified binder. Understanding the changes of this interaction with oxidation is an important issue that impacts the evaluation and selection of polymer modifiers.

<u>*Part 1: Characterization of SBS and Base Asphalt Interactions*</u>

The objective of this work is to develop protocols that enable the characterization of Styrene-Butadiene tri-block copolymer (SBS) and base asphalt interaction. SBS is a polymeric material having contractile properties that is commonly used as an asphalt modifier. Modified bitumen is characterized primarily by its mass fraction polymer, poly-styrene/poly-butadiene ratio, and the nature of the polymer structure formed in the asphalt (linear, branched, or star-like). Three techniques for characterizing and evaluating polymer modification follow.

Imaging: Fluorescent Microscopy and Confocal Microscopy

Sharp contrast in fluorescence of base asphalts and polymer modifier make it possible to observe polymer structure in asphalts. Thus, fluorescence microscopy and confocal laser scanning microscopy can be used to obtain qualitative information on polymer-asphalt morphology, to characterize polymer networks and SBS-base asphalt structural interaction. Comparing the chemical structure of poly-styrene and poly-butadiene, it is not difficult to assume that poly-styrene might play a role as anchor point for this copolymer due to its high affinity with aromatic components of asphalt, while poly-butadiene blocks provide chains in polymer network structure. The interplay of these two components will determine, to some extent, the polymer network structure formed and the interaction of polymer network to asphalt.

This study involves several tasks. 1): Observe individual morphology features of polystyrene and poly-butadiene in the base asphalt. 2): Analyze the network structure of SBS polymer with different polystyrene/polybutadiene ratios to understand their separate roles in polymer network formation. 3): Based on information obtained tasks 1 and 2, develop an improved understanding of how to evaluate polymer networks by observing their structural features.

FTIR Spectroscopy: Quantitative Characterization of Polymer

FTIR is the most important means to characterize polymers. In the IR region, each group has several patterns of vibration (stretching, bending, etc.) that lead to a number of characteristic absorption bands. The absorbance of these bands is proportional to their content based on the Lambert–Beer law. Recently, several attempts have been made to characterize bound polystyrene and bound polybutadiene in asphalt by measuring films that formed by casting sample-toluene solution on Sodium Chloride mono-crystal disks or by measuring sample-carbon disulfide solution in transmission cells. Considering the complexities of the structures (i.e. butadiene unit has 1,4-cis, 1,4-trans and 1,2-vinyl microstructure while isoprene unit has other additional 3,4-microstructure), those general methods (with external calibration) based on only absorption of polybutadiene at 966 cm^{-1} and polystyrene at 699 cm^{-1} still need further validation.

In this study, we aim to establish a FTIR method to quantify polystyrene and polybutadiene content in asphalt material. Asphalt mixed with different mass fractions (from 1-5 percent) of polystyrene and polybutadiene will be prepared. By measuring their FTIR spectra, hopefully, we can establish reliable standard curves (methods) that give quantitative information of polymer content based on those absorption bands. Asphalt with different SBS content and SBS with different polystyrene/polybutadiene ratios will be prepared to evaluate and improve those standard curves.

Rheology: Characterization of Polymer Effectiveness

Effect of polymer modifier on binder rheological properties can be specified by comparing rheological properties of the base binder and its SBS blends. Indexes such as the ratio of the limiting viscosity (or DSR function $G'/(\eta'/G')$) of the polymer modified binder to the limiting viscosity (or DSR function) of the base binder will give an indication of the polymer effectiveness in the asphalt. The DSR function would be the preferred function in the event that a low shear rate limiting viscosity does not exist for the polymer modified asphalt. This function also appears to be particularly relevant to mixture fatigue because it includes both the stress building (deformation) elastic modulus and the stress relieving (flow) property, the viscosity.

Part 2: Characterization of Changes in asphalt-polymer Interaction with Oxidation

The objective of this work is to study deterioration of polymer-asphalt interactions due to oxidation using the characterization methods described above. An improved understanding of this issue will enhance the cost-effective evaluation and selection of polymer modifiers. From binder kinetics studies, we are obtaining a number of base asphalts and their corresponding SBS modified binders oxidized at different temperatures for different times. These samples are ready for analysis of polymer-asphalt interaction based on the characterization methods developed. Some preliminary study results are shown in figure F1c-5.1 and figure F1c-5.2. Figure F1c-5.1 shows changes of polybutadiene content, indicated by its peak area at 966 cm^{-1}, at different temperatures with oxidation. Figure F1c-5.2 shows changes of DSR function index (ratio of DSR function of polymer modified binder over DSR function of base binder) at different temperatures with oxidation. With the characterization methods described in the previous section, we will obtain data to answer questions such as how polymer degrades with oxidation, and what are the degradation kinetics.

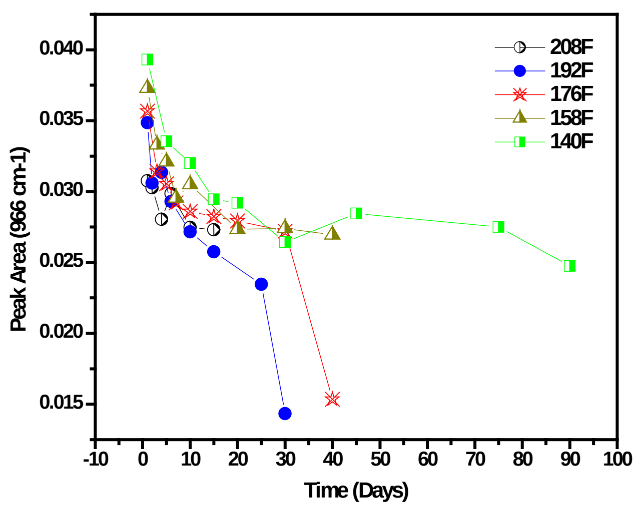


Figure F1c-5.1. Changes of polybutadiene content (absorption at 966 cm^{-1}) of SEM 70-22 with oxidation.

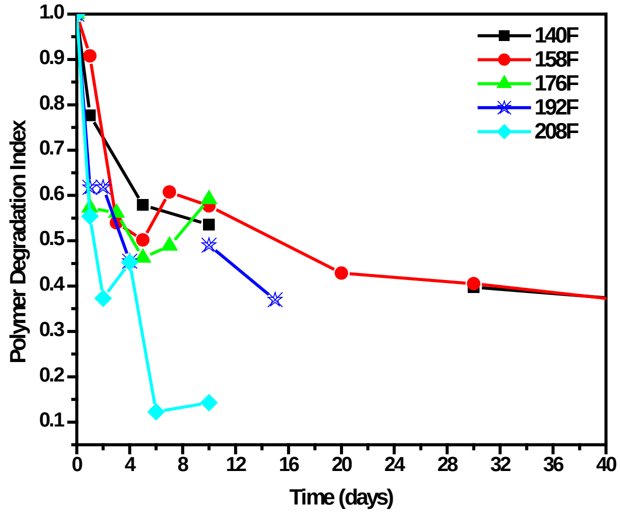


Figure F1c-5.2. Changes of DSR function index of SEM 70-22 with oxidation.

Table for Decision Points and Deliverables

Date	Deliverable	Description
07/10	Presentation	Present early results on binder oxidation and fatigue (F1c-4)
01/10	Presentation, Journal Paper	Present field comparison of oxidation model (F1c-3, F1c-4). Submit for publication 8/10.
01/10	Presentation, Journal Paper	Results on binder oxidation and fatigue (F1c-4). Submit for publication 8/10.
03/10	Draft Report	Draft Report on findings to date from subtasks F1c-4.

Work Element F1d: Healing (includes Subtask F1d-1 thru F1d-5 and F1d-8)

Subtasks F1d-1: Critical review of the literature
F1d-2: Material selection
F1d-3: Experiment design
F1d-4: Test methods to measure properties related to healing
F1d-5a: Testing of materials and validating healing model
F1d-8: Coordinate form of healing parameter with continuum damage model

Major Findings & Status

The major findings from the previous years are as follows:

- Documenting a synthesis of self-healing properties and mechanisms based on a detailed literature review (Years 1 and 2)

- Development of a micro-mechanics model for self-healing of cracks in asphalt binder and partial validation using molecular simulations (Years 1 and 2)
- Development of a test method to determine intrinsic healing properties of asphalt binders (Years 1 and 2)
- Measurement of intrinsic healing of asphalt binders at different temperatures (Year 3)
- Development of an experiment design to determine wetting characteristics of asphalt binders in sand-asphalt or FAM mixtures (Year 3)

A summary of these findings is presented below followed by the Year 4 work plan.

Synthesis of self-healing properties and mechanisms (Years 1 and 2)

A detailed literature review was conducted to identify the methodologies adopted to quantify healing and its effect on the fatigue cracking of asphalt mixtures. The review also included literature related to the investigation and modeling of healing mechanism for viscoelastic materials other than bituminous materials. The review concentrated on laboratory tests to determine healing, field validation to provide proof of healing, and fundamental mechanisms related to the healing process. The literature review was presented in the 2nd quarterly report and was also summarized as a book chapter (Little and Bhasin 2007).

Micro-mechanics model for self-healing and partial validation (Years 1 and 2)

A micro mechanics and materials science based model to describe healing in asphalt binders was developed. This model comprises the following steps related to the healing process*:*

- wetting of the two faces of a nano crack,
- instantaneous strength gain due to interfacial cohesion between the crack faces, and
- long-term strength gain due to diffusion and randomization of molecules from one face to the other.

Wool and O'Connor (1981) described the net macroscopic recovery, *R*, or healing in a material as a process in which crack faces wet each other and a wetted crack interface gains strength or heals over time. Mathematically, this is expressed as a convolution integral of the intrinsic healing function, R_h (*t*), and the wetting distribution function, φ (*t*, *X*), as follows:

$$R = \int_{\tau=-\alpha}^{\tau=t} R_h(t-\tau)\frac{d\phi(\tau)}{d\tau}d\tau \qquad \text{(F1d.1)}$$

The convolution integral implies that the rate at which a crack regains its ability to carry load or heal is the net effect of: i) the rate at which the two cracked surfaces wet and ii) the rate at which a wetted crack surface regains strength due to cohesion and inter- molecular diffusion.

The first step in the healing process, i.e., wetting of the two faces of a nano crack, is represented by a wetting distribution function φ (*t, X)* as described in the convolution integral (equation

F1d.1). The second and third steps of the healing process, i.e., strength gain due to interfacial cohesion and inter diffusion of molecules between the wetted surfaces is represented by the intrinsic healing function $R_h(t)$ as described in the convolution integral (equation F1d.1). A modified form of the Avrami equation was used along with a simple DSR based test method to characterize the intrinsic healing function of different asphalt binders.

Kim et al. (1990) proposed the use of two parameters to quantify molecular characteristics related to self healing: the methylene to methyl hydrocarbon or MMHC ratio and the methylene to methyl group ratio or CH_2/CH_3. These parameters can be computed provided that the exact molecular structure is known or these can be estimated using FTIR (Fourier Transform Infra-Red) spectra. Kim et al. (1990) demonstrated a good correlation between these parameters and the healing index for select asphalt binders. As a part of this study, the molecular dynamics was used to determine the efficacy of using MMHC and/or CH_2/CH_3 ratio as a measure of self-diffusivity and consequently to investigate its correlation to intrinsic healing of asphalt binders. This study was motivated with the expectation that the findings would:

i) improve the knowledge and understanding of the relationship between molecular characteristics and self-healing in asphalt binders,
ii) provide support for the use of parameters such as MMHC and CH_2/CH_3 ratio as indices of molecular morphology that can be used to estimate self-diffusivity and concomitant intrinsic healing characteristics of asphalt binders, and
iii) illustrate the utility of molecular simulations to investigate mechanisms at the molecular scale and describe how they ultimately influence the engineering performance of asphalt binders.

Results based on the molecular dynamics reinforce the findings proposed by Kim et al. For a more detailed discussion of the above findings please refer to Bommavaram et al. (2009), Bhasin et al. (2008), and Little and Bhasin (2007).

Test method to determine intrinsic healing properties (Years 1 and 2)

The strength gained over time, $R_h(t)$, was quantified in terms of the shear modulus measured using a DSR. The reasons for using shear modulus as a measure of strength are as follows: i) it can easily be measured using the DSR which is usually available in asphalt laboratories, and ii) it can be measured by applying very small stress or strain (0.001%) to the specimen without disrupting the healing process that occurs at the crack interface.

The test procedure involved the use of two short cylindrical specimens of the same asphalt binder. Bringing the circular faces of the two specimens into intimate contact with each other created an idealized and completely wet crack interface. This was referred to as the “two piece” specimen. The intrinsic healing, expressed as the gain in shear modulus, was determined over time for this idealized created crack interface. The increasing value of G^* measured over time provides a quantitative measure of the rate of healing across this interface. In order to obtain the dimensionless intrinsic healing function, $R_h(t)$, the values of G^* recorded over time were normalized using the value of G^* for an intact specimen with the same geometry.

Temperature dependence of intrinsic healing in asphalt binders (Year 3)

Intrinsic healing of asphalt binder can be determined using the DSR based test method as described above. Based on the hypothesis for the healing mechanism it is expected that the intrinsic healing of asphalt binders would be temperature dependent. In order to validate this hypothesis and quantify the rate of intrinsic healing, healing was determined at three different temperatures using the DSR. This testing was recently completed and the data are being analyzed.

Experiment design to determine wetting characteristics of asphalt binder (Year 3)

The rate of wetting of asphalt binders is one of the two important components of the healing model. In order to validate the model presented in the form of equation F1d.1 the rate of wetting and rate of intrinsic healing must be known for a given material. The DSR based test method may be used to determine the rate of intrinsic healing. However, the rate of wetting cannot be measured directly. Based on this limitation, two options were explored to validate the healing model.

The first option was to control the rate of wetting experimentally by performing a strain-controlled test in direct tension mode on sand-asphalt mixtures. In this case the rate of deformation from the peak strain to zero strain can be assumed to represent the rate of crack closure for mode I cracks formed during the fatigue cracking process. Notwithstanding the accuracy of this assumption, one confounding factor in this approach was the stress reversal as the crack is forced to close. Stress reversal from tension to compression is expected for time dependent materials subjected to cyclic loading in a displacement-controlled mode. This stress reversal would invalidate the use of intrinsic healing rates that are not measured with the specimen subjected to a compressive stress state. Based on preliminary test results and feedback collected during the FHWA Models Expert Task Group meeting in San Antonio we have decided not to pursue this option to validate the healing model.

The second option to validate the healing models is to back calculate the rate of wetting using experimental data and intrinsic healing properties of the binder with equation F1d.1. We are currently conducting preliminary tests to validate this approach. A deconvolution process can be used to back-calculate the wetting function. The model will be validated using a randomized series of loading and rest periods. A preliminary experiment design to accomplish this was developed; this experiment design will be finalized and reported in the forthcoming quarterly reports.

<u>Year Four Work Plan</u>

During years four and five the focus will be on the following three aspects of the healing model.

1. Validation of the healing mechanism using synchrotron experiments

Texas A&M and ARC have been offered a unique opportunity to use the Canadian Light Source Synchrotron located at the University of Saskatchewan to perform key experiments related to the process of healing. The use of beam time from the synchrotron will not cost the ARC project.

The objective of this experiment is to determine the rate at which intrinsic healing occurs across an artificially created crack interface. The integrity of the material and amount of healing is quantified in terms of the mass density of the material. The hypothesis here is that the mass density at the interface of a crack would be zero (point of singularity). However, as the material heals over time the average mass density across the interface should approach a value that is similar to the bulk mass density.

The following is the outline for the experiments that will be conducted. Two specimens of the asphalt binder will be prepared on solid substrates (figure F1d.1). The faces of these two specimens will be used to represent two faces of an ideally fractured bulk material. These two faces will be brought into intimate contact with each other and the mass density will be monitored across the interface over time (figure F1d.2).

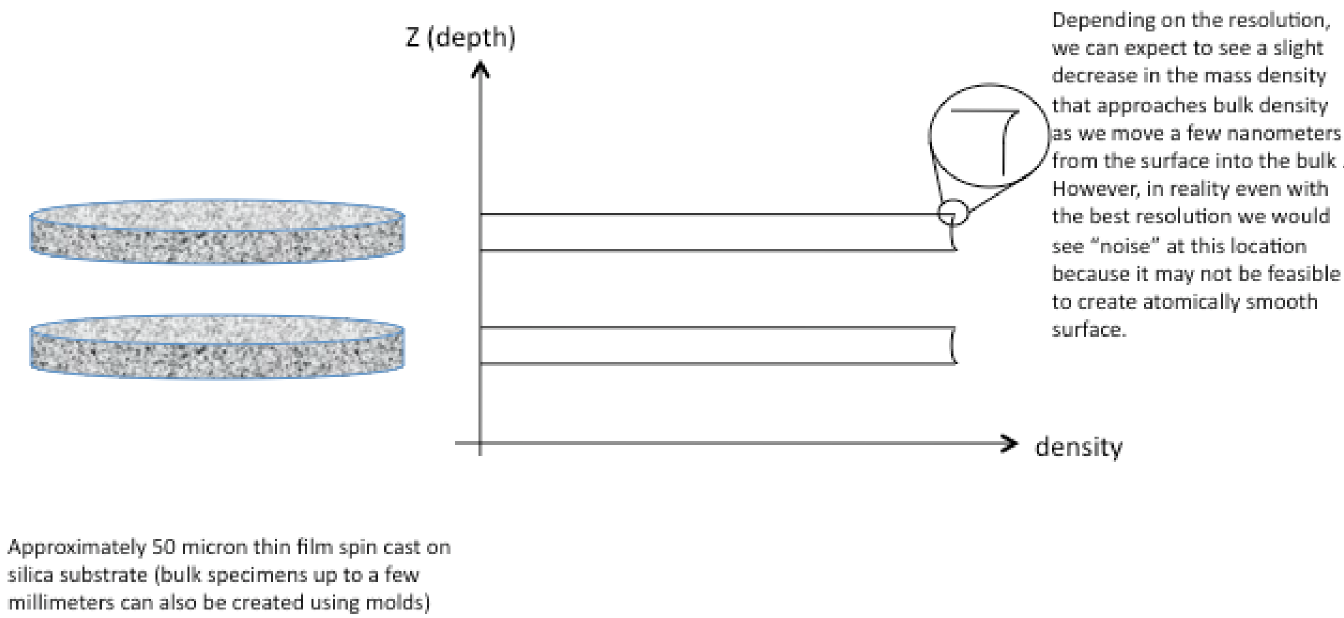


Figure F1d.1. Schematic of the specimens and expected density profile.

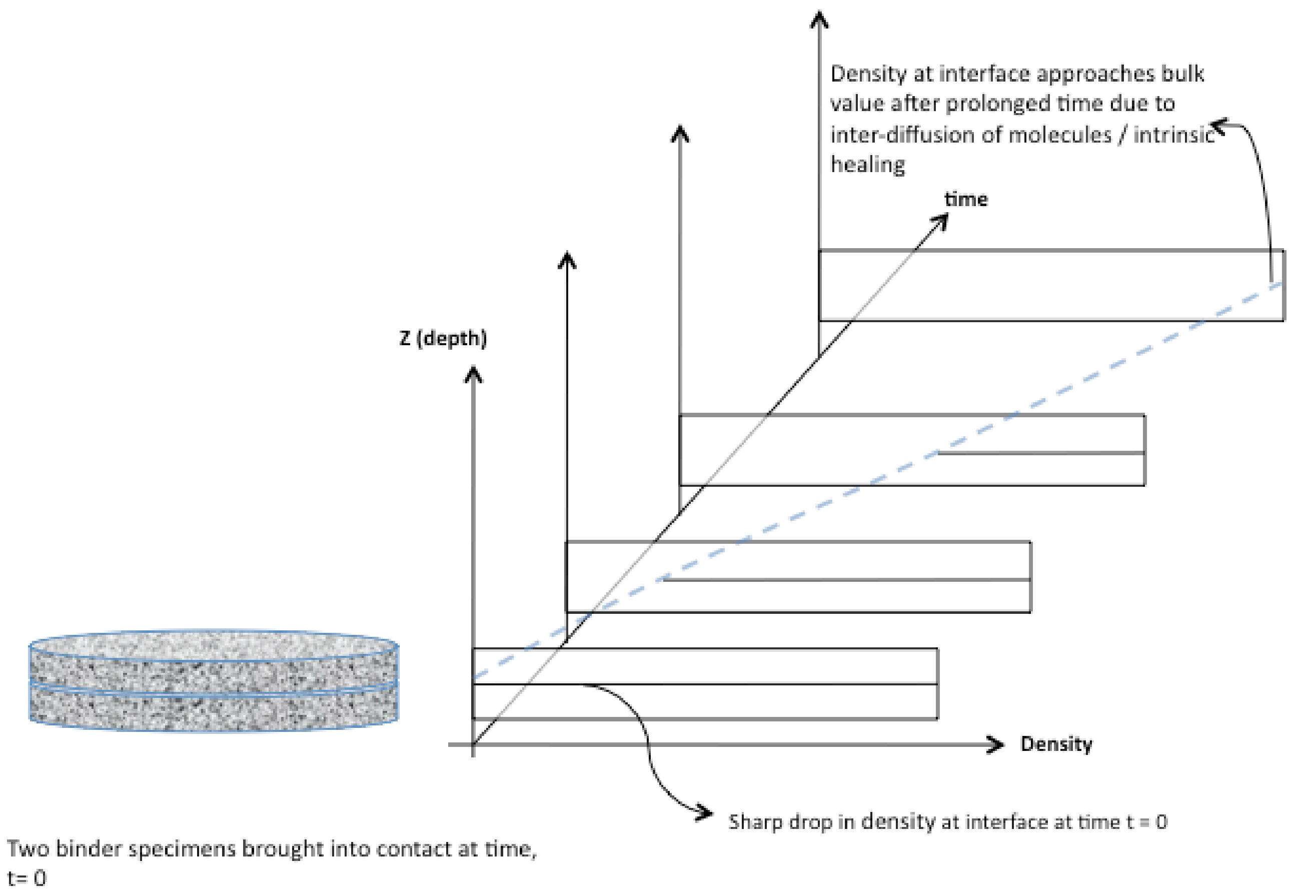


Figure F1d.2. Measurement of density across the interface over time.

2. *Determining the wetting function for the healing model for sand-asphalt or FAM mixtures and validating the model using randomized loading and rest periods*

As described in equation F1d.1, there are two critical components for the micro-mechanical healing model. First is the rate of intrinsic healing of asphalt binders. These properties can be measured using the DSR based test method. Second, is the rate of crack wetting in a mixture that is undergoing fatigue cracking. The rate of crack wetting can be determined using material properties with the model for crack wetting that was originally developed by Schapery as shown in equation F1d.2 below.

$$\frac{d\phi(tX)}{dt} = \dot{a}_b = \beta\left[\frac{1}{D_1 k_m}\left\{\frac{\pi Wc}{4(1-v^2)\sigma_b^2\beta}D_0\right\}\right]^{-\frac{1}{m}} \qquad \text{(F1d.2)}$$

In equation F1d.2, W_c is the work of cohesion; ν is the Poisson's ratio; σ_b represents the stresses at the crack surfaces; $\dot{a}_b$ is crack closing speed; β is the healing process zone; D_0, D_1, and m are creep compliance parameters which can be obtained by fitting $D(t) = D_0 + D_1 t^m$; and k_m is a material constant that can be computed from *m*. Material properties such as the healing process zone cannot be obtained by direct experimental measurements. Therefore, an alternate approach is to back calculate the rate of wetting of asphalt binders in sand-asphalt or full asphalt mixtures using equation F1d.1. In other words, the overall healing of a test specimen will be measured experimentally and the wetting characteristics will be obtained using a deconvolution of equation F1d.1, given that the rate of intrinsic healing is known a priori using the DSR test method.

A preliminary experiment design has been developed to determine the rate of wetting. Preliminary tests are currently being carried out to validate the feasibility of this experiment design. All tests are currently being carried out using the DMA in torsional shear. The final test matrix and approach will be presented in forthcoming quarterly reports. Once the rates of wetting and intrinsic healing are determined, a series of random fatigue cracking and self-healing experiments will be carried out to validate the applicability of this micromechanics model.

3. *Validating the relationship between mechanical properties and wetting characteristics of the sand-asphalt mixture or FAM*

The last and one the most important components of this work element will be to determine the relationship between the rate of wetting and the viscoelastic properties of the material. Rate of wetting for different materials will be obtained from the previous step. The theoretical relationship between the rate of wetting and viscoelastic properties is available in the form of equation F1d.2. The model presented in equation F1d.2 can be partially validated using the results from this subtask.

Subtask F1d-5b: Thermodynamic model for healing in asphalt binders

This is a new subtask that is being added to the work element on healing. The micromechanical model of healing described in F1d-5 addresses the healing of microcracks. As one would glean from a close analysis of the Schapery closure speed model, most of the healing is expected to occur in the β process zone. The size range of these cracks is not exactly defined but one would expect them to range from the nano scale to a few millimeters. Work by Kringos, Schmets, Pauli and Scarpas (2009) has relied upon Atomic Form Microscope (AFM) surface topography of asphalt binders that show the evidence of phase separation within the bitumen. They postulate that if the mechanical properties, specifically stiffnesses, of the phases are significantly different then the interfaces between the phases serve as natural stress inducers. They used their finite element model CAPA 3-D to demonstrate this. The result of the TU Delft study was to demonstrate the presence of crazing that occurs among the phases at the interfaces. Kringos et al. described thermodynamic considerations and a constitutive formulation that could explain how a reversal of the crazing process could occur with the input of thermal energy and/or mechanical energy back into the system. This results in healing at a smaller length scale than the model presented in this section. The ARC team applauds the excellent work and approach being developed by the TU Delft team.

In fact, as described in the Year 2 and Year 3 work plans, ARC has designed AFM experiments aimed at investigating the properties of different phases of the bitumen at TAMU. This work has demonstrated differences in the viscoelastic properties of the phases, and this work will be continued at an accelerated rate in year 4. Two Ph.D. level students working jointly under the supervision of Professors Rajagopol in the Mechanical Engineering Department of TAMU and Dallas Little have been trained in thermodynamic and mechanics by Professor Rajagopal for the past year and one half to address this problem. In year four they will complete the task of defining the viscoelastic properties between the phases of the asphalt binder using the AFM. Professor Rajagopal is well recognized as an expert in mechanical models based on thermodynamic natural configurations and will supervise the development of a healing model or healing parameter to address healing from this length scale. We believe we can synergistically work with our colleagues at TU Delft who have made significant development in modeling healing at this length scale, and we plan to seek their advice and collaboration in each step of this approach in order to properly recognize their excellent work and optimize the results. In fact Professors Scarpas and Little are working together on synchrotron experiments with Dr. Alexander Schmets, who has already taken steps using Spin Echo Small Angle Neutron Scattering (SESANS) to investigate whether the phase appearance at the surface of the binder identified through AFM is in fact a surface phenomenon or a bulk phenomenon.

Table for Decision Points and Deliverables

Date	**Deliverable**	**Description**
12/31/08[1]	Journal Paper	Test method to determine intrinsic healing properties of asphalt binders
09/31/10[2]	Journal Paper	Test method to determine wetting characteristics of asphalt binders
06/30/10	Draft Report	Material properties related to self-healing in asphalt binders
09/31/10	Final Report	
09/30/09[3]	Journal Paper	Validating the micro-mechanics model for self-healing in asphalt binders
09/30/10	Journal Paper	Validating the micro-mechanics model for self-healing in fine aggregate matrix specimens
06/30/11	Model and Draft Report	A model and test methods to characterize healing in asphalt materials
09/30/11	Journal Paper and Final Report	

(1) Bommavaram et al. (2009)

(2) The due date for this has been revised and changed in the Gantt chart to accommodate changes in the experiment design

(3) Bhasin et al. (2010)

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Little, D. N., and A. Bhasin, 2007, Exploring Mechanisms of Healing in Asphalt Mixtures and Quantifying its Impact. *Self Healing Materials*, S. van der Zwaag, ed., Springer, Dordrecht, The Netherlands, 205-218.

Schapery, R. A., 1989, On the Mechanics of Crack Closing and Bonding in Linear Viscoelastic Media. *International Journal of Fracture,* 39: 163-189.

Wool, R. P., and K.M. O'Connor, 1981, A Theory of Crack Healing in Polymers. *Journal of Applied Physics*, 52: 5953.

Subtask F1d-6: Evaluate Relationship Between Healing and Endurance Limit of Asphalt Binders

Major Findings and Status

In Year 3, the research team collected data that show reasonable variation in time sweep tests with no rest periods. However, testing binders with the time sweep procedure including multiple rest periods showed poor repeatability. The research team used the reduced cycles concept for analysis of mixture fatigue for binder time sweep data. The endurance limits calculated from this analysis were compared with Accelerated Load Facility (ALF) fatigue results. It was observed that binders with a higher endurance strain limit have shown higher ALF fatigue life.

The experimental program for the calculation of endurance limits of binders using time sweep tests at two strain levels (5% and 7%) was completed in Year 3. Further analysis using the reduced cycles procedure for the time sweep experimental results will be performed in Year 4.

Issues Identified During the Previous Year and Their Implications on Future Work

This subtask has been delayed due to the high variability of the time sweep test procedure with rest periods. The research team plans to modify the testing procedure or define new approaches for healing characterization to address the poor repeatability.

Year 4 Work Plan

After reviewing current literature on healing of binder, the research group plans to characterize healing using the concepts of ratio of dissipated energy change (RDEC) and plateau value (PV) proposed by Shen et al. (2009). Preliminary results presented by the authors showed promising results in terms of calculation of healing rates (HR) of different types of binders. Table F1d-6.1 presents the experimental matrix proposed for healing characterization of binders following the procedure described by Shen.

Table F1d-6.1. Proposed time sweep healing tests of asphalt binders.

Variables	Factors	Description
Binder	1	FH 64-22
Rest Periods	4	0, 1, 2 and 4 seconds
Modification	3	Styrene-butadiene-styrene (SBS), Elvaloy, polyphosphoric acid (PPA)
Strain Level	2	2.5% and 4% (low and high level)
Replicates	2	To determine repeatability of testing
Total	**48**	

The research group will also investigate the relationship between the linear viscoelastic properties of binder with its healing properties by means of modeling the cyclic loading of simplified viscoelastic mechanical models such as the Burgers model.

Table for Decision Points and Deliverables

Date	Deliverable	Description
09/10	Journal Paper	Submit a conference paper summarizing the results from healing characterization of binders.
01/11	Presentation	Provide an update on results from healing characterization of asphalt binders at TRB, ETG or similar venue.

Cited References

Shen, S., H. Chiu, and H. Huang, 2009, Characterization of Fatigue and Healing for Asphalt Binders. *ASCE Journal of Materials in Civil Engineering* (accepted for publication).

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

Major Findings and Status

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

In the later stages of fatigue cracking, the failing sections of pavement are often observed to form distinct crack patterns (i.e., alligator crack pattern) usually localized in the traffic wheel path, and often occurring later in the life of the pavement. By comparison, in investigations relating to metal fatigue, pattern forming cracking has been successfully correlated to the microstructure which develops in these materials during casting (Cappelli et al. 2008, Bian and Taheri 2008) corresponding to grain boundaries at the meso, micron and nanometer scale. Occurrence of grain boundaries may be a result of the heterogeneous nature of a material (Cappelli et al. 2008; Bian and Taheri 2008). Thus, this same idea (i.e., grain boundary formation) can be applied to paving materials if such pattern forming phenomena were to be observed (Robertson et al. 2005, 2006).

Neat asphalts and SARA fractions separated from neat asphalts from the comparative performance sites at Rochester Minnesota and Arizona (*Fundamental Properties of Asphalts and Modified Asphalts, III Quarterly Report,* September 2009) were imaged with AFM (intermittent-contact mode). To briefly summarize, asphalts which were found to be the "lumpiest", when imaged by AFM as thin-films (500-nm to 1000-nm) with the exception of polymer modified asphalt, correlated reasonably well with, thermal and fatigue crack severity.

Figure F1d-7.1 depicts phase-contrast images of the four MN asphalts. The asphalt with the most phase-contrast poly-disperse domains showed more thermal cracking. This figure suggests that micro- and nano-"lumps" in asphalt thin films may be discontinuities in asphalt due to microcrystalline and dendrite-like (bee) wax crystals. It is speculated that asphalts with higher concentrations of paraffin and/or microcrystalline wax form microstructural discontinuities (grain boundaries) possibly in synergy with other material phases, and thus, tend to crack more, either due to thermal, fatigue or other distresses.

Work Plan Year Four

Subtask *F1d-7i:* has been completed. The Year 4 plan is to continue with *F1d-7ii*.

F1d-7i: Conduct image analyses of pre-existing results (AFM imaging data of thermally cycled thin films, Spinodal-Blend Films, and asphalt fraction materials representing the eight SHRP core asphalts).

F1d-7ii: Determine asphalt compositional properties from image analysis data and preparation of a database of results

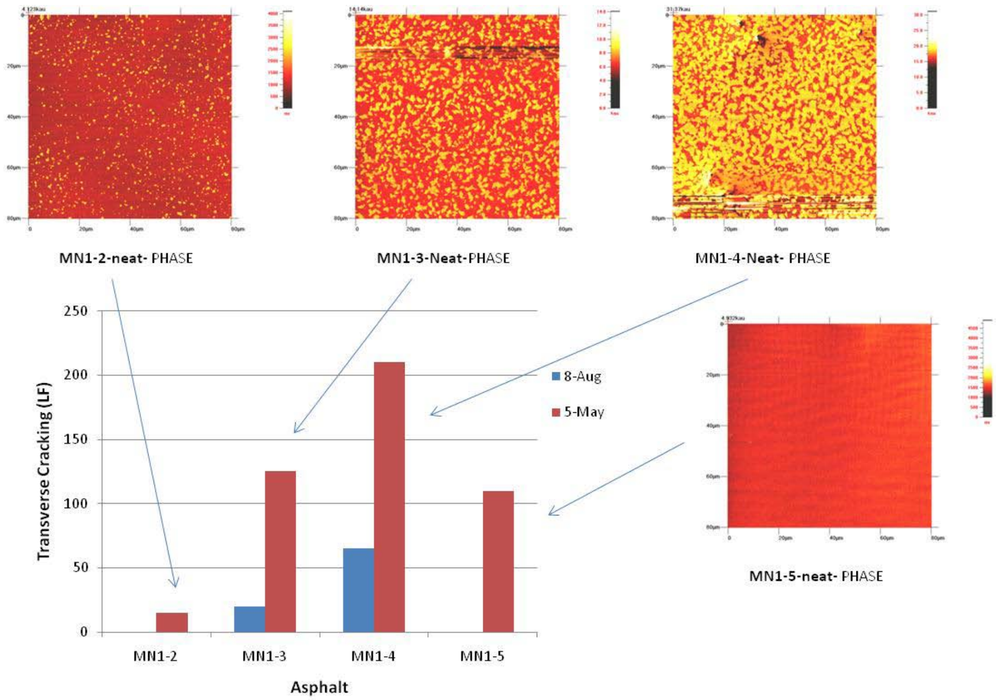

Figure F1d-7.1. AFM Phase-contrast images and a thermal crack severity plot, lowest-to-highest; MN1-2 (polymer), MN1-5, MN1-4, and MN1-4 (high wax).

<u>Cited References</u>

Bian, L., and F. Taheri, 2008, Fatigue Fracture Criteria and Microstructures of Magnesium Alloy Plates. *Materials Science and Engineering A*, 48774–85.

Cappelli, M. D., R. L. Carlson, and G. A. Kardomateas, 2008, The Transition Between Small and Long Fatigue Crack Behavior and its Relation to Microstructure. *International Journal of Fatigue*, 30: 1473–1478.

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

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

CATEGORY F2: TEST METHOD DEVELOPMENT

Work Element F2a: Binder Tests and Effect of Composition

Major Findings and Status

Elasticity is an important material property that directly relates to the ability of materials to recover after deformation. The more elasticity a material exhibits, the more it will return to its original state after being deformed. This ability to recover after deformation is important in pavements, as it ensures that the material can absorb the energy of traffic loading with minimal permanent deformation. There is a general perception that elasticity could add to durability, and there is a tendency for pavement engineers to specify requirements for elastic materials.

Fatigue failure in binders can be measured by using the dissipated energy ratio (DER) concept. The N_{p20} parameter—the number of cycles at which the material exhibits a 20% deviation from the line of equality between DER and number of cycles—appears to offer a good representation for fatigue performance of asphalt binders (Bonnetti et al. 2002; Delgadillo and Bahia 2005).

To investigate the relationship of elastic properties to fatigue resistance in binders, Dynamic Shear Rheometer (DSR) elastic recovery measurements were performed along with time sweep tests on the same set of materials containing different types of modification, and the data obtained from the two tests were compared. Among the conclusions that can be drawn based on the data collected to date are:

- Elastic recovery data measured in the DSR show good correlation with elastic recovery results collected in the ductility bath following the ASTM D6084 procedure. The DSR test procedure mimics the D6084 procedure, in which a constant rate of deformation is imposed until a certain strain is reached, after which load is removed to allow for recovery.
- The elastic recovery values could not be correlated to fatigue results of binders. Therefore, the question of the relevance of elastic recovery to pavement performance remains unanswered. It is critical that this question be answered because if elastic recovery cannot be found to relate to performance, it should not be used in selecting binders.

During Year 3, the research team observed that polyphosphoric acid (PPA)-modified binders respond very differently to the presence of mineral aggregate than other modified binders. Their response seems to be highly dependent on the binder’s chemical composition as well as the chemical properties of the mineral surface. More detailed results and observations are described in the quarterly reports for the F2a work element.

Year Four Work Plan

Subtask F2a-1: Analyze existing fatigue data on PMA

This subtask was completed during Year 2.

Subtask F2a-2: Select virgin binders and modifiers and prepare modified binder

This subtask was completed during Year 2.

Subtask F2a-3: Laboratory aging procedures

This subtask was completed during Year 3.

Subtask F2a-4: Collect fatigue test data

Fatigue data will continue to be collected following the testing matrix described in the Year 3 work plan and subsequent quarterly reports.

Subtask F2a-5: Analyze data and propose mechanisms

The objective of this subtask will be to analyze the collected data from subtask F2a-4. The focus will be on defining mechanisms by which modifiers and aging control fatigue under various conditions. These mechanisms will be used to develop guidelines for selecting modifiers and the tests required to qualify modifiers for improvement of fatigue life.

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

The investigation of rheological properties serves as a tool to classify and rank starting materials. It is also a monitoring tool during the modification and conditioning process. This is accomplished by measuring parameters such as $G^*/\sin(\delta)$—an indication of the rutting resistance of binders—and performing Multiple Stress Creep and Recovery (MSCR) tests on the binders. With this approach the research team can provide important information about how the modification of binders affects not only fatigue but also rutting performance of binders. The rheological properties are investigated for laboratory-aged binders (rolling thin film oven (RTFO)- and pressure aging vessel (PAV)-aged) to cover the entire service temperature range for these materials. This is done with the assumption that aged binders usually have a shorter fatigue life than un-aged binders.

The damage resistance characterization component of the investigation focuses on classifying and ranking different modifiers and/or modification techniques based on their impact on the binder's ability to resist damage. This is mainly focused on fatigue damage, but also uses rutting damage control tests to maintain perspective on improving overall binder properties.

Table for Decision Points and Deliverables

Date	Deliverable	Description
12/10	Presentation	Presentation on the proposed fatigue mechanism.
01/11	Presentation	Presentation on the data analysis performed to date.
01/11	Decision Point	The team will decide which fatigue mechanism is better supported by the experimental data.
03/11	Journal Paper	A journal paper will be submitted for publication describing the proposed fatigue mechanism and the experimental data supporting it.

Cited References

Bonnetti, K. S., K. Nam, and H. U. Bahia, 2002, Measuring and Defining Fatigue Behavior of Asphalt Binders. *Transportation Research Record*, 1810: 33-43.

Delgadillo, R. and H. Bahia, 2005, Rational Fatigue Limits for Asphalt Binders Derived from Pavement Analysis. *Journal of the Association of Asphalt Paving Technologists*, 74: 97-137.

Work Element F2b: FAM Testing Protocol

The reader is referred to work element M1c where a new procedure for preparing FAM specimens were presented.

Year Four Work Plan

The reader is referred to the software development that was presented in work element M1c.

Work Element F2c: Mixture Testing Protocol

The development of the tensile testing process for fatigue properties of mixtures has been completed. The development of the compressive damage testing process for fatigue properties will begin this year.

Work Element F2d: Tomography and Microstructural Characterization (TAMU)

X-Ray Computed Tomography

Major Findings & Status

The current damage functions incorporated in the continuum model (F3c.2) assumes damage distribution to be isotropic. However, it is known that damage directional distribution depends on the stress state and direction. Therefore, it is expected that damage has an anisotropic distribution. In year three, image and analysis techniques that utilized X-ray images of asphalt mixtures are completed and developed to analysis damage directional distribution.

Year Four Work Plan

X-ray CT will be used to scan the test specimens in work element F3c.2, and the developed image and analysis techniques will be utilized to analyze damage directional distribution.

Work Element F2e: Verification of the Relationship Between DSR Binder Fatigue Tests and Mixture Fatigue Performance

Major Findings and Status

In Year 3, significant progress was made regarding the interpretation and modeling of fatigue binder data using the framework of viscoelastic continuum damage (VECD). Previous quarterly reports have shown that modeling damage from the Binder Yield Energy Test (BYET) with VECD works fairly well for unmodified binders. However, it is not appropriate to model the response of modified binders due to strain-hardening behavior. The research team considers the BYET test as a promising procedure for evaluating effects of polymer modification on binder properties and as a possible surrogate for force ductility tests. The test, however, is not found to be effective in modeling and predicting fatigue of binders.

The research team focused its efforts on the development of a new cyclic fatigue testing methodology. The proposed procedure is based on strain sweep test with linear ramping and the calculation of damage growth based on dissipated energy. Preliminary linear amplitude sweep test results were compared to standard time sweep tests. The time and strain sweep tests did not generate the same damage curve due to nonlinearity at high strains in the strain sweep procedure. However, it was observed that the VECD parameters from time and strain sweep are correlated.

Also in Year 3, mixture fatigue data from a Transportation Pooled Fund (TPF) 5(080) was collected for evaluation and validation of the binder fatigue testing procedures. The research team developed a draft standard for the linear amplitude sweep procedure. The standards were submitted to the Binder ETG for review.

The research team proposed to use equation F2e.1 for the calculation of binder fatigue life:

$$N_f = A(\gamma_{\max})^B \quad \text{(F2e.1)}$$

Parameters A and B can be determined from strain sweep testing, and by knowing the strain level of the binder in the pavement structure, the fatigue life (N_f) can be estimated.

Issues Identified During the Previous Year and Their Implications on Future Work

The use of VECD analysis for monotonic tests (e.g., BYET) of polymer-modified asphalts is not adequate due to their strain-hardening behavior. Therefore, the research team will focus its efforts on the linear amplitude sweep test for fatigue characterization.

To reflect actual progress of this work element, the Year 4 and 5-year Gantt charts have been updated to show extended progress and completion dates for subtasks F2e-1 and F2e-2. Also, Gantt charts have been updated to show the planned Draft Report deliverable for subtask F2e-2 will be delivered in May 2010 and the planned Final Report in July 2010.

Year Four Work Plan

F2e-1: Evaluate binder fatigue correlation to mixture fatigue data

The research team will use a comprehensive set of binders to create a database of binder fatigue results. Binder fatigue results will be correlated to actual mixture and pavement fatigue performance. The testing temperature of the binders is selected based on the mixture and pavement fatigue testing conditions. The proposed experimental plan is presented in table F2e.1.

Table F2e.1. Mixture fatigue data and field performance for correlation to binder fatigue results.

	Mix / Pavement Fatigue Data Type		Proposed Binder Testing		
Asphalt Binder	**Laboratory Mix Fatigue Data**	**Pavement Fatigue Data**	**Testing Temp [°C]**	**Alpha Measurement**	**Amplitude Sweep**
70-22 Unmodified	Uniaxial Push-Pull – 19 °C	Accelerated Loading	19	X	XX
Oxidized	Uniaxial Push-Pull – 19 °C	Accelerated Loading	19	X	XX
Crumb Rubber – Terminal Blend	Uniaxial Push-Pull – 19 °C	Accelerated Loading	19	X	XX
Ethylene Terpolymer	Uniaxial Push-Pull – 19 °C	Accelerated Loading	19	X	XX
SBS - Linearly Grafted	Uniaxial Push-Pull – 19 °C	Accelerated Loading	19	X	XX
64-28 Unmodified	Uniaxial Push-Pull – 20 °C	N/A	20	X	XX
64-28 Polyphosphoric Acid	Uniaxial Push-Pull – 20 °C	N/A	20	X	XX
64-34 SemMaterials	Uniaxial Push-Pull – 20 °C	N/A	20	X	XX
76-22 Citgo	Uniaxial Push-Pull – 20 °C	N/A	20	X	XX
64-28 2% Latex Rubber	Uniaxial Push-Pull – 20 °C	N/A	20	X	XX
LTPP 04-B901 [PG 76-10]	N/A	Field Performance	Superpave IT	X	XX
LTPP 09-0902 [PG 64-28]	N/A	Field Performance	Superpave IT	X	XX
LTPP 09-0961 [PG 58-34]	N/A	Field Performance	Superpave IT	X	XX
LTPP 34-0901 [PG 64-22]	N/A	Field Performance	Superpave IT	X	XX
LTPP 34-0961 [PG 76-28]	N/A	Field Performance	Superpave IT	X	XX
LTPP 35-0902 [PG 64-22]	N/A	Field Performance	Superpave IT	X	XX
LTPP 37-0962 [PG 76-22]	N/A	Field Performance	Superpave IT	X	XX
LTPP 89-A902 [PG 52-40]	N/A	Field Performance	Superpave IT	X	XX

SBS = styrene-butadiene-styrene. IT = intermediate temperature.

F2e-2: Selection of testing protocols

The research team will focus its efforts on implementation of the linear amplitude sweep procedure for fatigue characterization of binders. In Year 4, the research team plans to test different materials under different testing conditions to investigate sensitivity of the procedure to factors such as temperature and mode control. A comparison between the proposed test and the currently used time sweep test will also be performed. Table F2e.2 shows the test matrix to be completed by the end of Year 4.

Table F2e.2. Test matrix for comparison of amplitude sweep to time sweep tests.

Binder	Testing Temp	Frequency Sweep	Stress Relaxation	Strain – Controlled Sweep	Stress-Controlled Sweep	5% Time Sweep	7% Time Sweep
64-28 Unmodified	Superpave IT	XX	XX	XX	XX	XX	XX
	5 °C		XX	XX			
64-28 SBS Polymer	Superpave IT	XX	XX	XX	XX	XX	XX
	5 °C		XX	XX			
58-34 Terpolymer	Superpave IT	XX	XX	XX	XX	XX	XX
	5 °C		XX	XX			
64-34 Terpolymer	Superpave IT	XX	XX	XX	XX	XX	XX
	5 °C		XX	XX			

F2e-3: Binder and mixture fatigue testing

Table F2e.3 shows the testing plan for mixture fatigue to be completed in Year 4. A typical mix design with locally available aggregate will be used. The binders used for the mixtures will be characterized using the amplitude sweep test, and their performance will be compared to mixture fatigue testing. For each condition, three replicates will be tested to determine repeatability and perform statistical analysis.

Table F2e.3. Experimental plan for mixture fatigue.

Mixture Fatigue	Cyclic Push-Pull Test	Strain level	600 με
			1000 με
			1400 με
		Frequency	1 Hz
			5 Hz
			10 Hz
	Monotonic Test	Constant Cross-head Rate	12.5 mm/min.
			25.4 mm/min.
			38.1 mm/min.
			50.8 mm/min.

F2e-4: Verification of surrogate fatigue test

Verification of the amplitude sweep and BYET procedures is currently being performed and will continue in Year 4 as more field performance and fatigue mixture data become available. Uniaxial tension-compression mixture fatigue testing results performed by other researchers are also available. Accelerated pavement fatigue tests performed under carefully controlled conditions are also available for validation of proposed procedures. Furthermore, binders used in the construction of field sections monitored by the FHWA's LTPP program are available.

F2e-5: Interpretation and modeling of data

Currently, interpretation and modeling of fatigue data from amplitude sweep tests is based on VECD theory. The research team will perform sensitivity analysis of all parameters involved in the calculation of the damage curves of the materials and on the final performance prediction. The team will also suggest improvements of the current VECD analysis for fatigue testing of binders.

F2e-6: Recommendations for use in unified fatigue damage model

The research team will propose a unified model for fatigue characterization of binders by the end of Year 4. A final standard for binder fatigue characterization following AASHTO format will be finalized.

Table for Decision Points and Deliverables

Date	**Deliverable**	**Description**
05/10	Draft Report	Draft interim report summarizing progress and details of analysis of Linear Amplitude Sweep test.
07/10	Final Report	Final interim report on progress of the Linear Amplitude Sweep test.
07/10	Journal Paper	Summarizing fatigue characterization of binders following amplitude sweep and correlations to mixture fatigue and field performance.
10/10	Draft Report	Comparison of surrogate fatigue tests.
01/11	Final Report	Results of surrogate fatigue test verification.
01/11	Decision Point	Choose most promising fatigue test(s) to continue researching.
01/11	Presentation	Present binder fatigue progress at TRB, ETG or similar venue.
03/11	Model and Algorithm	Automated program for predicting field performance based on laboratory tests.

CATEGORY F3: MODELING

Work Element F3a: Asphalt Microstructural Model

Major Findings & Status

The detailed work plan was prepared as the initial part of the Year 2 Work Plan, which was approved by FHWA in August 2008 then reiterated in the Year 3 Work Plan. The complete work plan is accessible at the ARC website, www.ARC.unr.edu.

As detailed in the plan, a significant portion of the work is in partnership with Virginia Polytechnic and State University (VT), the National Institute of Standards and Technology (NIST), and the University of Rhode Island (URI). There is also significant collaboration with the Technological University of Delft (Delft) in the Netherlands. There was a substantial amount of contractual information and documentation required by the FHWA to establish the subcontracts with these parties which has taken place with all subcontracts presently in place.

The main work accomplished in this Work Element was to establish the big picture for a multiscale chemo-mechanical model of asphalt. The current thinking is described in a contribution to the Proceedings of the First International Workshop on Chemo-Mechanics of Bituminous Materials, which was held in Delft, the Netherlands in June 2009 [Kringos 2009; Greenfield 2009]. In that paper, we described a broad framework for how coupling must occur across length and time scales. The key idea is for a simultaneous "push" (from smaller scales to larger) and "pull" (from larger scales to smaller) within models. Arrows indicating possible "pushes" and "pulls" are shown in figure F3a.1, which was also shown at the September 2009 ETG meeting. The pale arrows in the lower left indicate how molecule-scale simulations can be conducted to yield results for larger lengths at short times, shorter lengths at longer times, or some combinations ("push"). Guidance from rheology and phase structure models ("pull", darker arrow pointing down and to the left) is necessary to formulate the kinds of statistical averaging and simulation that can yield usable parameters. In other words, "pulls" from above help to recognize the "pushes" from below that yield functions and parameters that are found within and/or are useful for the larger scale models.

Not all "pulls" are viable. For example, rheology data can be described within a number of different parameterized models. Some of the models are based on well-defined molecular concepts, such as distributions of relaxation times, while others are described more as resembling curve fits. Only the approaches based on solid fundamentals provide a pathway to connect molecular-scale dynamics results to the rheology model parameters. Another example is that a phase field model can be devised to work (as in many formulations) with a simple double-well potential. Averaging over true molecular-scale simulations doesn't yield such simple results, however. Instead, a means of averaging the thermodynamics function that is simplified into a double-well free energy potential must be found. **Summarizing, the "pull" that can be obtained on the molecular scale as a feed "push" into the mesoscale is important to identify.**

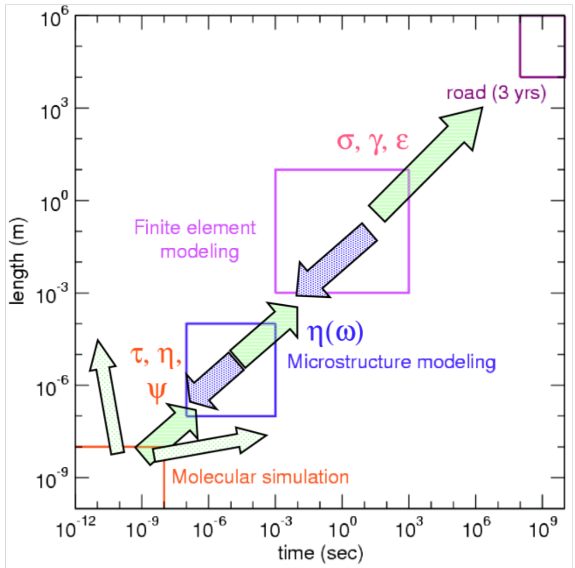

Figure F3a.1. "Push" and "pull" across length and time scales in modeling of asphalt chemical and mechanical properties across wide ranges of length and time scales.

A significant finding occurred when reanalyzing prior simulation results. The presence of a straight-chain C_{22} ordering effect (i.e. **spontaneous wax crystallization**) was recognized in a first-generation model asphalt (Zhang and Greenfield 2007) at 298 and 358 K but not at 400 and 443 K (0 and 85°C but not 127 or 170°C). The ordering occurred over times of 5 to 10 ns (1 ns ≡ 10^{-9} s) within a bulk model asphalt. (Surfaces had been precluded via periodic boundary conditions.) Preliminary information about this exciting event was shared at the Models ETG meeting. Further study is required to understand the crystallizations in detail.

Work Plan Year Four

The bulk of the planned work in this work element is stated in the Year 3 Work Plan which has begun.

In year 4, information refinement and property gathering will continue for asphalts that differ in "molecular type" due to having origins in different crude sources. Identification of these asphalts began in year 3 based on variation in chemical composition (e.g., asphaltene/maltene compatibility, wax content, elemental composition including SARA characteristics), and rheological properties. Molecular "representations" of these "systems" will be refined, and preliminary models representing scaling from molecular to microstructural phase-dependent traits will be derived. Models of wax crystallization phases on molecular and phase field scales will continue to be developed in this year. Two aggregate types will also be identified and molecular mechanics simulations conducted to model interfaces of at least four combinations of asphalt-aggregate systems. During year 4, input parameters derived from molecular to phase-field scales will be implemented into continuum models to simulate the stress concentrations induced by the developing microstructural phases.

Cited References

Kringos, N., 2009 (Editor), *Proceedings: International Workshop on Chemo-Mechanics of Bituminous Materials*, Delft, the Netherlands.

Greenfield, M. L., 2009, Bitumen at the Molecular Level: Molecular Simulations and Chemo-Mechanics, submitted to *Proceedings: International Workshop on Chemo-Mechanics of Bituminous Materials*, Delft, the Netherlands.

Zhang, L. and M. L. Greenfield, 2007, Analyzing properties of model asphalts using molecular simulation. *Energy Fuels*, 21:1712-1716.

Work Element F3b: Micromechanics Model

Subtask F3b-1: Model Development

Major Findings & Status

Work during the 3rd year at the University of Nebraska has continued the development of the micromechanics model and corresponding test protocols and the integration between experimental efforts and computational modeling.

Experimental Modeling Efforts

Experimentally, laboratory tests to obtain key model input parameters such as the linear elastic properties of aggregate particles and linear viscoelastic properties and the cohesive zone (CZ) fracture properties of asphalt matrix phase (referred to as the fine aggregate matrix (FAM) in other related tasks: M1c, F1b, F2b) have been performed. In addition, we have investigated a proper dimension of representative volume elements (RVEs) of typical dense-graded asphalt concrete mixtures subject to damage due to uniaxial tension. The RVE dimension is used as a necessary geometry to accomplish the micromechanical modeling and further efforts such as a two-way couple multiscale modeling which links mixture-level behavior to structure-level performance.

In order to develop a fracture testing system to determine cohesive zone (CZ) fracture parameters of the FAM phase, we have attempted two different specimen geometries: a small-scale tensile fracture test geometry and a semi-circular bending (SCB) specimen geometry. Even if promising results and fundamental insights into the viscoelastic fracture process are obtained from the small-scale tensile fracture test geometry (Aragão et al. 2009), we have investigated the use of SCB geometry, because the SCB testing is very simple to perform, and multiple testing specimens can be easily prepared by a routine process of mixing and Superpave gyratory compacting of asphalt mixtures. The SCB fracture testing was incorporated with the use of a digital image correlation (DIC) system that can monitor the displacement and strain fields on the overall surface of the specimen. The DIC analysis helps characterize fracture behavior more realistically so that the determination of cohesive zone properties can be more effectively performed. The SCB testing system has been advanced with a development of various testing accessories. These efforts enhanced the quality and efficiency of the SCB testing to identify the CZ fracture properties of FAM phase.

Using the improved SCB fracture testing system, we have performed the SCB tests at different loading rates using specimens fabricated with different specimen thicknesses in order to find any meaningful insights into the effects of specimen geometry and loading rates on fracture characteristics of FAM specimens. This effort is to eventually provide an appropriate SCB fracture testing protocol for the characterization of fracture properties. Results from experimental data and coordination with numerical simulations indicated that two-dimensional simulations based on the plane-stress condition can be approximated by using thin SCB specimens such as the ones 25-mm thick. Negligible out-of-plane stresses were observed from 25-mm-thick specimens. A significant rate-dependent fracture process was observed in the SCB fracture tests. A different set of cohesive zone fracture properties was necessary to match with test results, which clearly implied that the fracture process in viscoelastic FAM phase is a rate-dependent phenomenon and must be modeled accordingly. As the loading rates were faster, the cohesive zone strength and the fracture energy necessary to initiate crack growth increased.

In an attempt to identify linear elastic properties of aggregate particles in the mixture, nano-indentation testing has been conducted. A Berkovich-shaped indenter made of diamond was used to make indentations at the nano scale at different locations of very finely polished aggregates (four different types). Test results provided moduli of elasticity of particles. The elastic moduli of aggregates were generally greater than typical values found from handbooks. We have further investigated to find out why the nano-indentation testing produced higher moduli of aggregate particles than typically-known values by incorporating numerical simulations with the test results. Interesting findings have been observed, and the outcomes from this effort will be presented in the 4th year.

Another primary experimental task that we have focused on during the 3rd year is the development of a more articulate and scientific approach in mixing-compaction-production of the FAM phase, which produces key material properties (viscoelastic properties and cohesive zone fracture properties) for the accomplishment of the computational micromechanics modeling. Unlike conventional volumetric systems, we simplified asphalt mixtures as composites which consist of two primary material phases – the elastic phase of aggregates and the viscoelastic phase of FAM, which is composed of asphalt binder, fine aggregates passing sieve No. 16 (1.19 mm), and entrained air voids. The maximum fine aggregate size (1.19 mm) in the FAM phase was selected based on two-dimensional digital image analyses of cross sections obtained from various compacted asphalt concrete samples. The digital images could not properly capture aggregates approximately less than 1.0 mm, which is close to the mesh size of sieve number 16. The mix design of the FAM phase considered binder content that is absorbed into aggregates and that covers aggregates with a fixed binder film thickness. Algebraically, the required binder content to produce the FAM mixture was proposed as the one remaining after excluding binder absorbed in the coarse aggregates and the thin film of binder covering coarse aggregates from the total binder in the bulk asphalt concrete mixtures. This new protocol also incorporated the extraction of small DMA specimens out of Superpave gyratory bulk samples that were compacted with different amounts of FAM mixtures to represent different levels of air voids. Each DMA specimen with a different level of air voids was tested to characterize linear viscoelastic properties which were then incorporated with the micromechanical finite element simulations to predict linear viscoelastic dynamic moduli of the corresponding bulk asphalt concrete mixture. Simulated dynamic moduli from the micromechanical model were then compared to realistic dynamic moduli obtained from bulk asphalt concrete laboratory tests so that the appropriate level of compaction to produce the FAM mixture can be determined. During the 3rd year, we have finished mixing, fabricating FAM specimens with different levels of air voids, DMA testing of FAM specimens, and testing asphalt concrete specimens for the mixture dynamic moduli. Significant findings after performing the micromechanical finite element simulations and comparisons with experimental results will be reported in the 4th year.

To evaluate the proper dimension of RVEs when structural damage is involved in a typical dense-graded asphalt concrete mixture, uniaxial tensile tests were performed by incorporating three types of displacement measurement systems: (i) two-dimensional full-field displacement measurements using the digital image correlation (DIC) technique; (ii) conventional on-specimen LVDTs with a 100-mm gauge length; and (iii) a crosshead LVDT. The combined approaches to characterize strain behavior exhibited the point of localization where significant damage started in the mixture. Before localization occurs, the DIC analysis results indicated that, for the typical dense-graded Superpave asphalt mixtures often used today, approximately 50-60 mm can be effectively used as the minimum dimension of the RVE to characterize mixture properties and performance behavior, while much greater care is necessary after localization due to the significant damage resulting in additional mixture heterogeneities such as cracks. A more detailed description on the research method and results can be found elsewhere (Lee and Kim, TRB Compendium CD, 2010)

Computational Modeling Efforts

For the computational modeling, several activities have been pursued during the 3rd year. First, we continued investigating various CZ models (e.g., Xu and Needleman's exponential model (1993, 1994), the bilinear CZ model (Geubelle and Baylor 1998; Espinosa and Zavattieri 2003), and the nonlinear viscoelastic CZ model proposed by Allen and his colleagues (Allen and Searcy 2001a, 2001b; Kim et al. 2006a, 2006b, 2007)) for a better understanding of features, characteristics, benefits, and limitations of each available CZ model. This review process was to seek a more appropriate application of CZ models to the modeling of asphalt concrete fracture.

Among the CZ models implemented, the bilinear CZ model was further investigated during this year, because it provides computational convenience, and the model is a physically sound and used by many researchers (Geubelle and Baylor 1998; Espinosa and Zavattieri 2003; Song et al. 2006, and many more) for various different materials and their fracture. More specifically, we have conducted studies to investigate the numerical issues associated with the use of intrinsic (initially elastic) and extrinsic (initially rigid) CZ models. For a more equivalent comparison with the bilinear CZ model (for the intrinsic case), a linear softening model was implemented and used for the extrinsic case. In their preliminary studies, we simulated a single-edge notched tension (SENT) test. Eight meshes were designed with varying cohesive element sizes and areas of insertion of CZ elements.

The intrinsic CZ models inherently produced artificial compliance due to a pre-peak region described in the cohesive zone model. However, the artificial compliance was significantly reduced by using the bilinear CZ model, since it can adjust initial slope in the model. As a result, the intrinsic model can be close to the extrinsic linear softening model. It was also true that as the number of CZ elements increased, the compliance likewise increased. When the pre-peak slope is steep enough, the artificial compliance was not significantly sensitive any longer, although it was still recommended to minimize the number of CZ elements, if possible.

On the contrary to the cases using the intrinsic bilinear CZ model, when the extrinsic linear softening model incorporated with the adaptive insertion scheme was applied, simulation results converged and stabilized, as the mesh was finer with an appropriate size of region for the fracture process. This is because the adaptive insertion of CZ elements is governed by stress states in the body, and the stress state is influenced by the local mesh refinement when using the finite element technique because of the discrete characteristics of geometry.

The comparison between the intrinsic model and the extrinsic model revealed that both cases matched well from the initial stage of loading to a certain level before the peak stress. Then, the small difference was observed in the post-peak region of the simulation between the intrinsic and the extrinsic model. The difference observed at the later stage of loading between two CZ modeling approaches seemed reasonable, considering that the way of simulating fracture processes is quite different.

Technical Transfer during the 3rd Year

Journal Papers

- ARAGÃO, F. T. S.; KIM, Y. R.; KARKI, P; and LITTLE, D. N. (2010). Semi - Empirical, Analytical, and Computational Predictions of Dynamic Modulus of Asphalt Concrete Mixtures. Recommended for publication by the Transportation Research Board, TRB, National Research Council, Washington, D.C.
- ARAGÃO, F. T. S.; KIM, Y. R.; LEE, J.; and ALLEN, D. H. (2009). A Micromechanical Model for Heterogeneous Asphalt Concrete Mixtures Subjected to Fracture Failure. Accepted for publication by the Journal of Materials in Civil Engineering (Issue: Multiscale and Micromechanical Modeling of Asphalt Mixes) of the American Society of Civil Engineers (ASCE).

Papers in Scientific Events

- ARAGÃO, F. T. S. and KIM, Y. R. (2010) Modeling of Asphaltic Materials Subjected to Nonlinear Viscoelastic Fracture. Accepted for publication in the Proceedings of the Geo Florida Conference of the American Society of Civil Engineers (Geo Florida 2010), West Palm Beach, FL.
- ARAGÃO, F. T. S.; KIM, Y. R.; LEE, J.; and SOARES, J. B. (2009). A Micromechanical Model for Predicting the Dynamic Modulus of Heterogeneous and Rate-Dependent Asphalt Concrete Mixtures. Accepted for publication in the Proceedings of the IV Simposio Internacional de Avaliacao de Pavimentos e Projetos de Reforco of the Associacao Brasileira de Pavimentacao (ABPV), Fortaleza, Ceara, Brazil.

Presentations in Scientific Events

- ARAGÃO, F. T. S.; KIM, Y. R.; KARKI, P; and LITTLE, D. N. Semi - Empirical, Analytical, and Computational Predictions of Dynamic Modulus of Asphalt Concrete Mixtures. Presented at the 89th TRB meeting, Washington, D.C., January 2010.
- ARAGÃO, F. T. S.; KIM, Y. R.; LEE, J.; and ALLEN, D. H. A Micromechanical Fracture Model for Heterogeneous and Rate-Dependent Asphalt Concrete Mixtures Using the Finite Element Method. Presented at the 10th United States National Congress on Computational Mechanics, Columbus, OH, July 2009.
- ARAGÃO, F. T. S. and KIM, Y. R. Modeling Fracture and Failure of Nonlinear, Inelastic Asphalt Concrete Mixtures. Presented at the 2009 ASCE/ASME/SES Joint Conference on Mechanics and Materials, Blacksburg, VA, June 2009.

Year Four Work Plan

The development of the fracture testing system to determine CZ fracture parameters of the FAM phase will be completed through additional testing and comprehensive analysis of test results. The development of a systematic approach in mixing-compaction-production of the FAM phase will be completed in the 4th year. Advanced image analysis techniques (possibly with coordination of Dr. Amit Bhasin at UTA) and finite element computational simulations of mixtures will be incorporated with mechanical test results of FAM specimens produced from different mixing-compaction procedures to finally develop the best protocol of FAM specimen fabrication.

After a suite of experimental protocols necessary to characterize fundamental material properties and fracture characteristics of mixture constituents (aggregates and FAM phase) has been properly developed, the experimental protocols will then be applied to the testing of common materials (1-2 types of aggregates and 1-2 binders) selected by ARC modeling teams (TAMU, NCSU, UTA, and UNL) for their material properties and fracture characteristics. Test results will then be integrated into the micromechanics model equipped with the CZ fracture module to predict fracture behavior of bulk asphalt concrete mixtures. Model predictions will be compared to laboratory performance test results of asphalt concrete samples. The link between the measured micromechanical properties of mixture constituents and bulk mixture performance can be established through this process. Any necessary calibrations of the model will then be made based on the comparison between model predictions and performance test results. Table F3b-1.1 presents a detailed testing plan pursued by UNL for the characterization of common materials selected.

Table F3b-1.1. A detailed testing plan pursued by UNL for the common materials.

Mixture Constituent	Target Characteristics	Test Methods Employed	Testing Temperatures	Loading Rates	Testing Mode
Coarse Aggregate	Morphology (Shape, Angularity, etc.)	AIMS (Aggregate Image Measurement System)[*]	Room Temperature	N/A	N/A
	Gradation	Sieve Analysis			
	Stiffness	Nanoindentation			Vertical Indentation
FAM Phase	Linear Viscoelastic Properties	DMA Frequency Sweep Testing	0, 10, 20, 30, $40^{o}C$	0.01Hz to 10Hz	Torsional Shear (Cyclic)
	CZ Fracture Characteristics	SCB Fracture Testing	$20^{o}C$	100 to 600 mm/min	Bending (Monotonic)
Air Voids	Volume Fraction and Distribution	X-ray CT Image[*]	Room Temperature	N/A	N/A

Note: [*]testing will be performed by TAMU researchers.

Based on the research outcomes obtained so far, we will start working on the implementation of a cohesive zone model that is capable of accounting for the rate-dependent fracture process in asphaltic materials. This is a fundamental part of our work and is expected to provide important and meaningful insights into the effects of loading rates on the fracture behavior of the asphalt concrete mixtures. Predicting power of the model will also be significantly improved.

In addition to the mixture-level micromechanical modeling effort, we will also pursue the multiscale modeling and analyses for the remaining years. Researchers at the University of Nebraska have developed a multiscale model as a tool to accurately predict performance behavior and damage evolution of general composite structures based on the *two-way couple multiscale algorithm*, which seamlessly links different length scales existing in the composite structures. Multiscale modeling is the way to maximize modeling efficiency by reducing (or minimizing) the amount of laboratory tests and computational costs but still satisfying a sufficient level of predicting accuracy. Computational micromechanics modeling that we have accomplished for this ARC is clearly an advanced technique and has shown extreme versatility in addressing multiple complexities such as mixture heterogeneity, anisotropy, nonlinear inelasticity, and damage growth in multiple forms. However, asphalt materials and structures (i.e., pavements) typically contain thousands of irregularly shaped, randomly oriented aggregate particles, along with numerous potential cracking sites, which would require a highly refined mesh with a huge degree of freedom. The solution for such a problem would require the use of a tremendous amount of computational time and effort, which is rarely feasible with the computing power currently available. Therefore, the multiscale modeling approach has been believed to be a solution to the problem, since it can account for the miscrostructural details but with only a fair amount of computational effort and laboratory tests. The multiscale model allows roadway engineers to clearly understand the mechanical effects of small-scale design variables (such as asphalt film thickness, air voids in the mix, size and distribution of aggregates, mineral additives in the mix, volume fraction of components, mechanical properties of mixture components, etc.) on the overall damage-related responses and performance characteristics of bulk mixtures and structures. Consequently, the clear understanding of small-scale design variables can allow engineers to select mixture constituents in a more appropriate way and to advance the current volumetric mix-design concepts, materials models, and performance models. For the remaining years, we will use the multiscale model to investigate the effects of several key design variables including the mechanical properties of mixture components and geometric characteristics of aggregates (e.g., size, gradation, angularity, and orientation) on the overall fatigue performance of asphalt pavement structures. Parametric analyses of individual design variables and their mechanical sensitivity will be primarily targeted.

Table for Decision Points and Deliverables

All deliverables and decision points for the remaining years (Year 4 and 5) are listed below.

Year	**Date**	**Deliverable**	**Description**
Year 4	July 2010	Journal Paper(s)	Paper(s) related to multiple scale material properties and updated computational modeling of asphalt concrete fracture and fatigue
	January 2011	Presentation(s)	Presentation(s) on multiple scale material properties and updated computational modeling of asphalt concrete fracture and fatigue
	March 2011	Model and Algorithm	Mathematical models developed and computational modules to simulate CZ fracture
Year 5	June 2011	Draft Report	Draft report that describes model development, testing protocols, test results and analyses, integration of test results into the micromechanics model, model simulations, and model calibration/validation
	July 2011	Journal Paper(s)	Papers presenting significant findings from the project
	September 2011	Decision Point	Time to make a decision on parallel paths as to which is more promising to follow
	December 2011	Final Report	Final report that comprehensively describes all activities performed for this project: model development, testing protocols, test results and analyses, integration of test results into the micromechanics model, model simulations, model calibration/validation, and model applications
	January 2012	Presentation(s)	Presentations of any significant findings resulting from the project

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Work Element F3c: Development of Unified Continuum Model

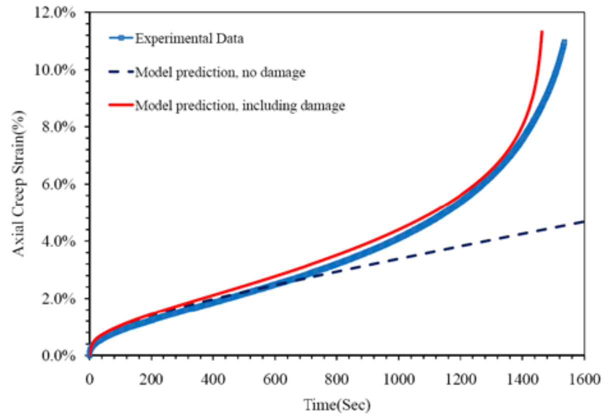
Major Findings & Status

The TAMU continuum model is developed further to include the effects of viscoelasticity, viscoplasticity, mechanical damage, moisture damage, healing, and temperature to describe the response and performance of asphalt mixtures more accurately. The model uses the Schapery-type nonlinear viscoelasticity constitutive law to represent the recoverable component of the strain; whereas, the Perzyna-type viscoplastic constitutive law with a modified Drucker-Prager yield surface capturing the influence of the stress state on material responses is used to represent the irrecoverable component of the strain. Moreover, the model is coupled with damage laws and temperature in order to capture the effect of temperature and the induced micro-cracks and micro-voids during the pavements' service life. Hence, a temperature-dependent viscodamage model is proposed and coupled to the existing viscoelastic and viscoplastic constitutive laws which are also enriched with temperature terms to describe the effect of mechanical damage, and temperature on the behavior of asphalt mixtures. The thermo-viscodamage model is formulated to be a function of temperature, total effective strain, and the damage driving force which is expressed in terms of the stress invariants of the effective stress in the undamaged configuration. The proposed expression for the damage force allows for the distinction between the influence of compression and extension loading conditions on damage nucleation and growth. Furthermore, the effect of the moisture on the strength degradation of asphalt mixes is also modeled using continuum damage mechanics. Hence, different damage laws which are a function of moisture content are investigated.

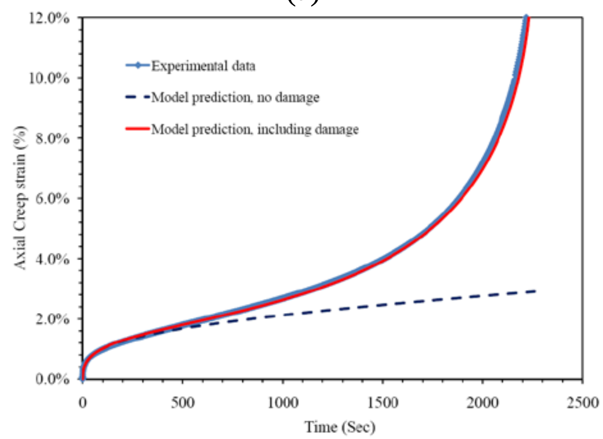
Also, a new configuration (i.e. healing configuration) is proposed in order to incorporate the effect of healing on the response of asphalt mixes subjected to repeated loading with different rest periods. This configuration can differentiate between the healed and unhealed cracks and makes the implementations very simple.

The thermo-viscoelastic-viscoplastic-viscodamage part of the TAMU mode is verified using several laboratory experiments. To this end, a systematic procedure is developed to determine model parameters as well as the temperature coupling terms. Then, the calibrated model is validated through comparing the model predictions with the experimental results for creep, creep-recovery, and constant strain rate tests over a range of temperatures, stress levels, and strain rates. Figure F3c.1 shows the comparison of the creep response between the experimental measurements from the Nottingham experimental database and model predictions when considering damage and no damage. As this figure shows, the model is capable of predicting the creep response of asphalt mixes at different temperatures and stress levels. It also shows the model capability on predicting both the shape of creep response and the time of failure over a range of temperatures and stress levels.

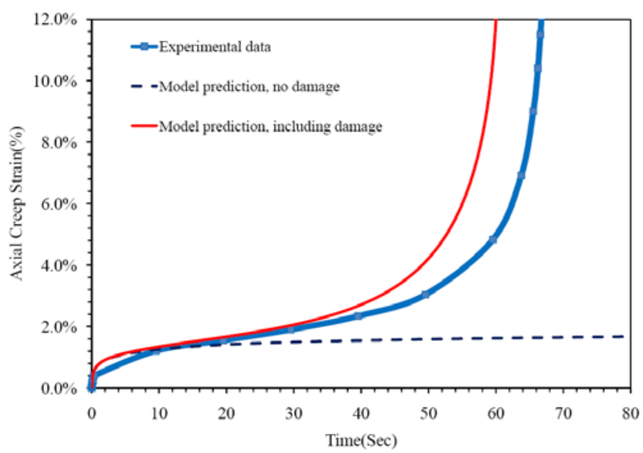
Comparisons between experimental measurements and model predictions are shown in figure F3c.2. The shaded area shows the region that experimental measurements are located whereas the dashed-lines are the model predictions. Figure F3c.2 also confirms the model capability in predicting the behavior of asphalt mixes for different stress paths.



(a)



(b)



(c)

Figure F3c.1. The comparison of the creep response between experimental measurements and model prediction for: (a) $T = 10^o C;\ \sigma = 2500(\text{KPa})$ (b) $T = 20^o C;\ \sigma = 1000(\text{KPa})$ (c) $T = 40^o C;\ \sigma = 750(\text{KPa})$

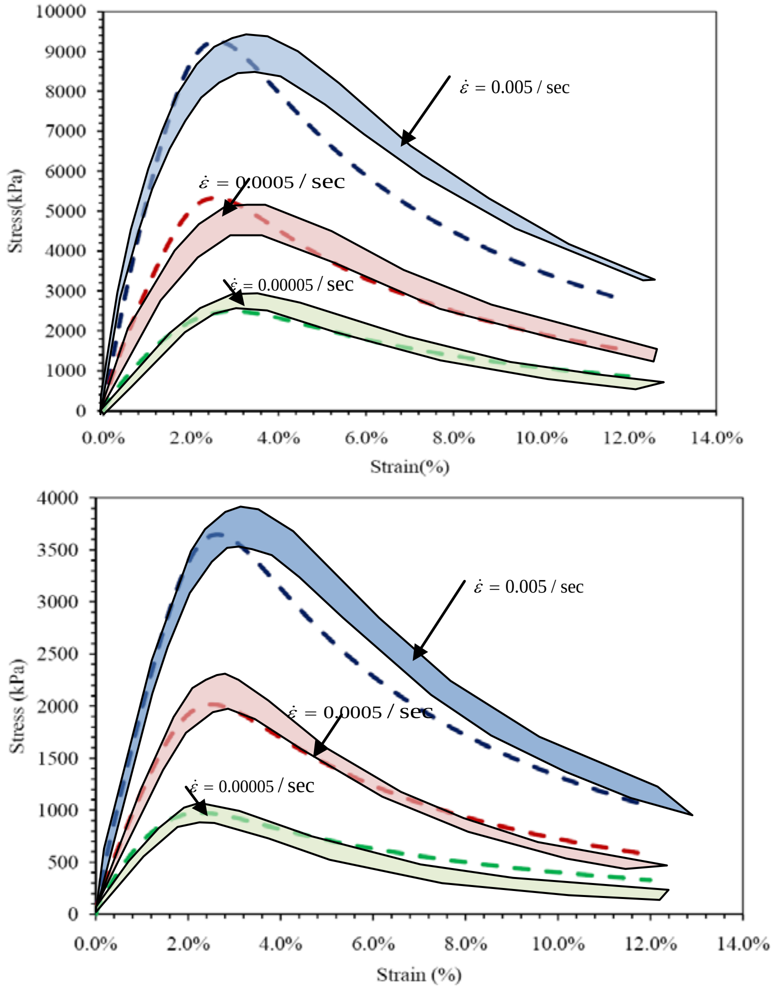
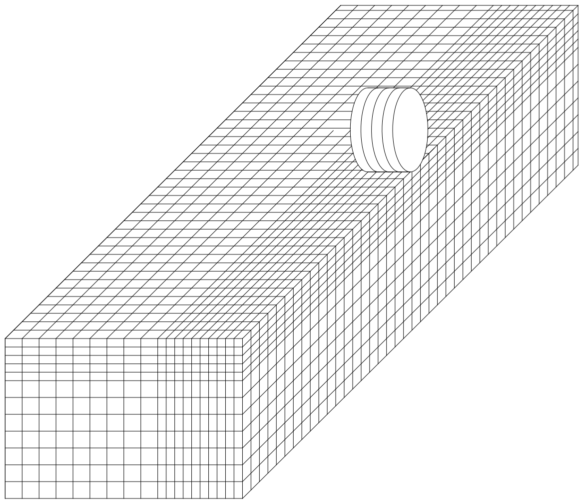


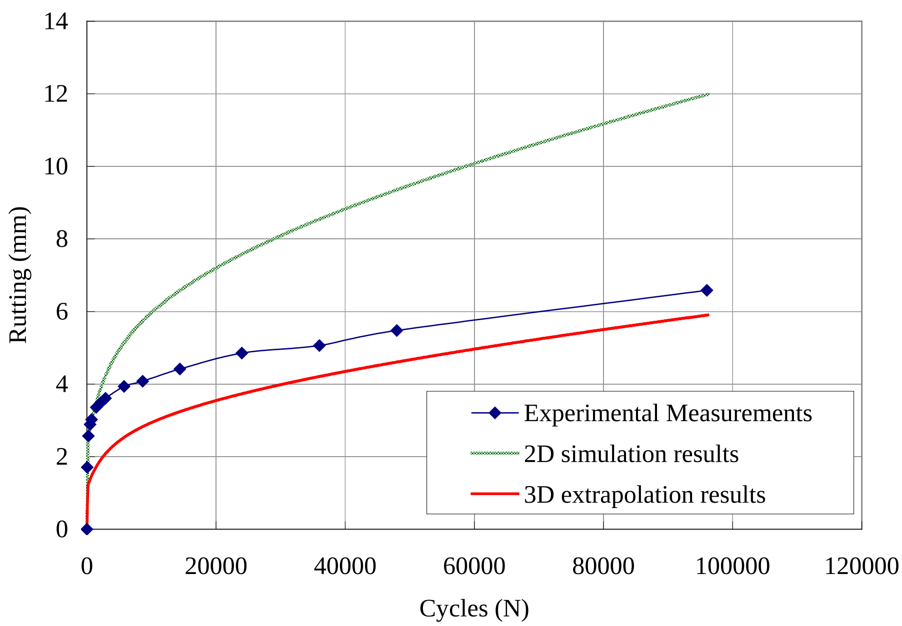
Figure F3c.2. The comparison of the stress-strain diagram between the experimental measurements and the model prediction for the constant strain rate test at:
(a) $T = 10^o C$ (b) $T = 20^o C$

Now, the most challenging task is to accurately simulate the distresses such as rutting in asphalt pavements under realistic loading conditions. However, the complex nature of applied loading, huge number of loading cycles (e.g. millions of loading cycles), and complex behavior of asphaltic materials make the accurate simulation of rutting in pavements very difficult and challenging. From the numerical point of view, it is almost impossible to conduct the 3D simulation of rutting in pavements subjecting to hundreds of thousands loading cycles. Hence, a thorough study on the effect of both different loading modes (e.g. pulse loading, equivalent loading, and moving loading) and type of simulation (2D and 3D) is recently conducted. Based on these studies an extrapolation technique for extrapolating the results of 3D FE analysis subjected to the realistic loading conditions based on the predicted rutting values in 2D simulation is proposed. The proposed extrapolation technique is then used for predicting the rutting in Wheel Tracking Test. The 3D finite element mesh for modeling the Wheel Tracking

Test is shown in figure F3c.3(a). Figure F3c.3(b) shows the comparisons between the experimental measurements from the Nottingham experimental database and the model predictions for a Wheel Tracking Test subjected to 96000 loading cycles. In this figure, the 2D FE simulates the rutting up to 96000 cycles; while the 3D finite element only simulates the rutting up to 1000 cycles. Then, the extrapolation technique is employed to predict the rutting in 3D up to 96000 cycles. Figure F3c.3(b) shows that the final model prediction and experimental measurements are in good agreement.



(a)



(b)

Figure F3c.3. (a) the three dimensional FE mesh for modeling the Wheel Tracking Test (b) comparison of the experimental measurements and model predictions for Wheel Tracking Test; the blue line is the experimental measurements. The green line is the 2D simulation results whereas the red line is the final model predictions based on the extrapolation technique.

A major challenge in using finite element analysis of asphalt pavements is the time it takes to analyze performance under realistic moving loads. Therefore, we have investigated the influence of using mores simplified loading patterns on performance. Five loading modes were simulated in three-dimensional (3D) analysis; and two loading modes were simulated in two-dimensional analysis. The permanent deformation results from these seven loading patterns simulating a wheel tracking test were compared. The geometry of Wheel Tracking Test is sketched in figure F3c.4.

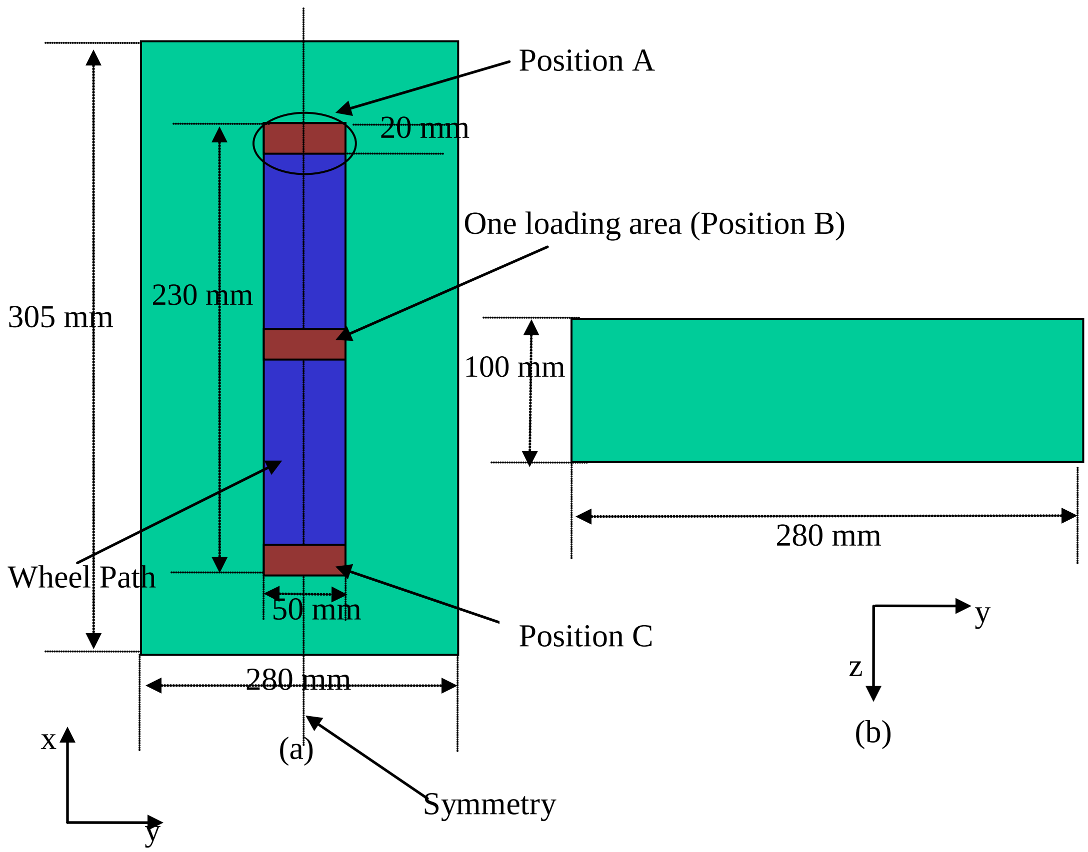


Figure F3c.4. The geometry of Wheel Tracking Test. The Wheel path is shown in blue, while the positions at which the rutting value is measured are shown in brown.

Loading Modes in 2D Simulation

Since in 2D plane strain FE model, the loading is assumed as an infinite stripe bar along the length, only two loading modes can be considered. The first loading mode (Mode 1) is a pulse loading which applies the loading and then removes the loading. The loading scheme is shown in figure F3c.5 (b-2). The second one is the equivalent loading mode (Mode 2). This loading mode represents the equivalent loading time by accumulation of each loading time and then applies the loading as a step loading. The advantage of this loading model is that only one step loading is applied instead of applying huge loading step. The scheme of equivalent loading model is shown in figure F3c.5 (b-1).

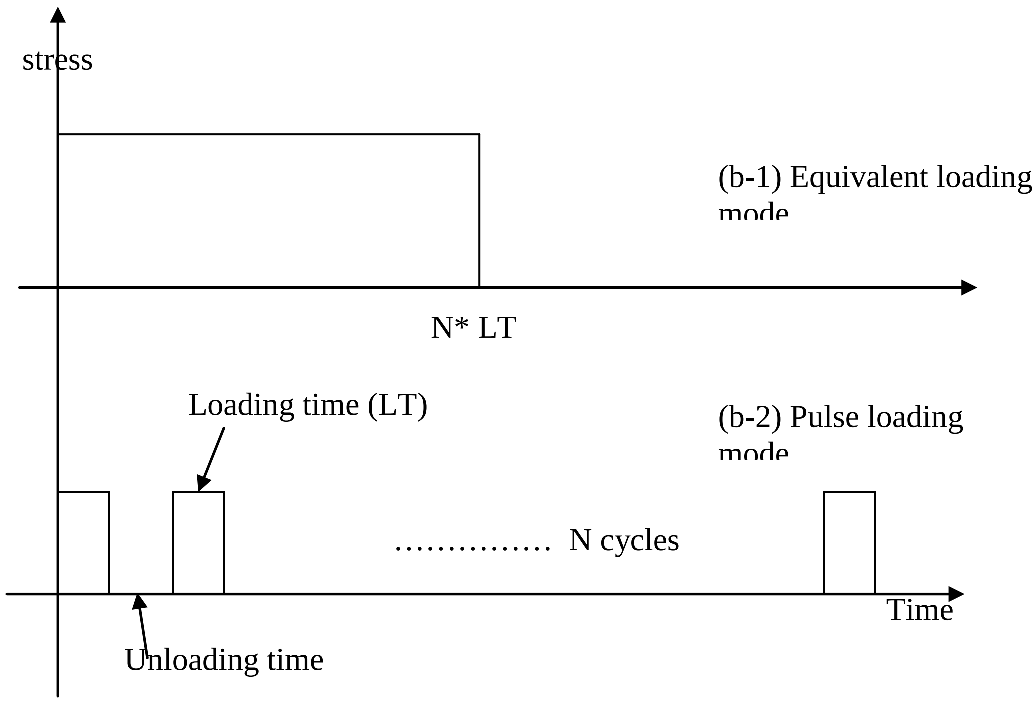


Figure F3c.5. The sketch of equivalent and pulse modes. Pulse loading is substituted by one step equivalent load whose duration is equal to summation of loading times in pulse loading.

Loading Modes in 3D Simulation

The third loading mode (mode 3) uses pulse loading approach and applies the loading on the center of the slab (Position B in figure F3c.4) with one wheel loading area. The forth loading modes (mode 4) employs the equivalent loading approach and one wheel loading area is applied the Position B in figure F3c.4. The fifth loading mode (mode 5) and sixth loading mode (mode 6) employ pulse loading approach and equivalent loading approach, respectively. Both mode 5 and 6 apply the loading over whole wheel path (shown in figure F3c.4). Finally, the last loading mode is a moving load (mode 7) and this mode simulates the moving loading by applying the load on one set of elements (one loading area) at the beginning of wheel path (position A in figure F3c.4) and then it is moved forward to the next set of elements until reach the end of wheel path (position C in figure F3c.4). This loading mode which is sketched schematically in figure F3c.6 simulates actual conditions the most and it is the most time consuming. A table summarizing the loading modes is shown in table F3c.1.

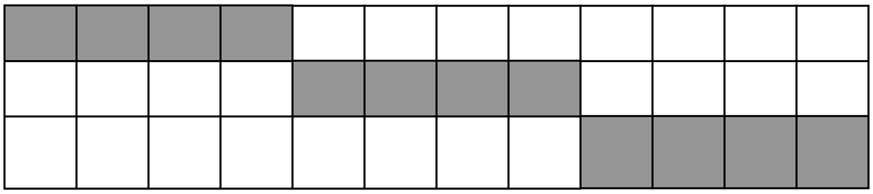
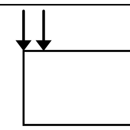
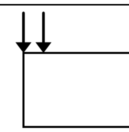
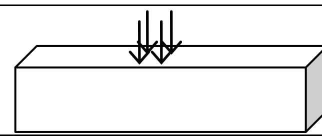
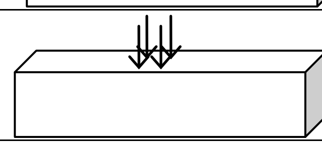
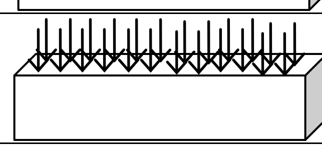
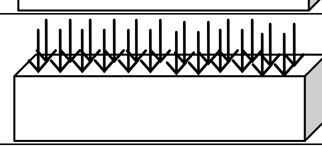
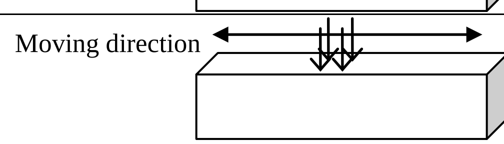


Figure F3c.6. The sketch of moving loading modes. Figure shows the wheel path. The shaded area is the region at which the load is applied when the wheel is moving.

Table F3c.1. The summary of loading modes.

Mode	Loading approach	Loading Area	Schematic representation of loading modes
1 (2D)	Pulse loading	One wheel	
2 (2D)	Equivalent loading	One wheel	
3 (3D)	Pulse loading	One wheel	
4 (3D)	Equivalent loading	One wheel	
5 (3D)	Pulse loading	Whole wheel path	
6 (3D)	Equivalent loading	Whole wheel path	
7 (3D)	Moving loading	One wheel	

Figures. F3c.7 and F3c.8 show the relationships between rutting and number of loading cycles using the ARC nonlinear viscoelastic and viscoplastic material constitutive model at temperatures of 20 and 40 for 3D simulation, respectively. These figures show that applying the loading over the whole wheel path (modes 5 and 6) yields more rutting comparing to the case when the loading is only applied on one loading area (modes 3 and 4). The rutting using moving loading mode (mode 7) is comparable to the loading applied on one loading area (mode 3 and 4). In terms of the effect of pulse (modes 3 and 5) and equivalent loading (modes 4 and 6), the rutting does not have significant difference between pulse and equivalent loading model at high temperature 40 ^{o}C after 600 cycles. However, at lower temperature 20 ^{o}C, the pulse loading and equivalent loading modes have significant difference after about 300 cycles.

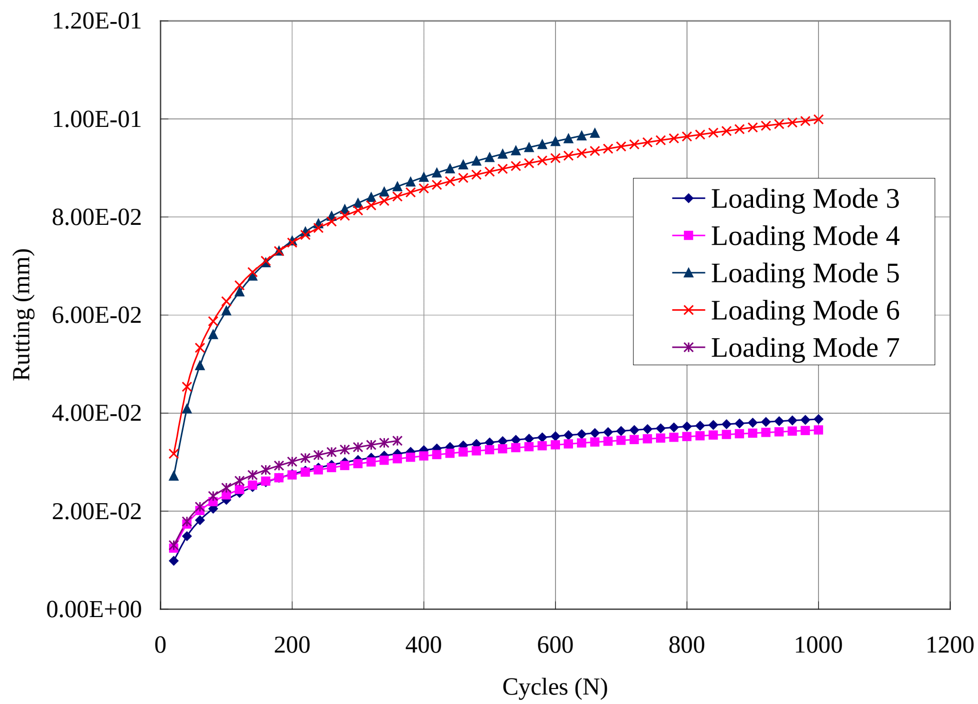


Figure F3c.7. The rutting simulation results in 3D FE analysis at temperature 20 ^{o}C using nonlinear viscoelastic and viscoplastic material constitutive model.

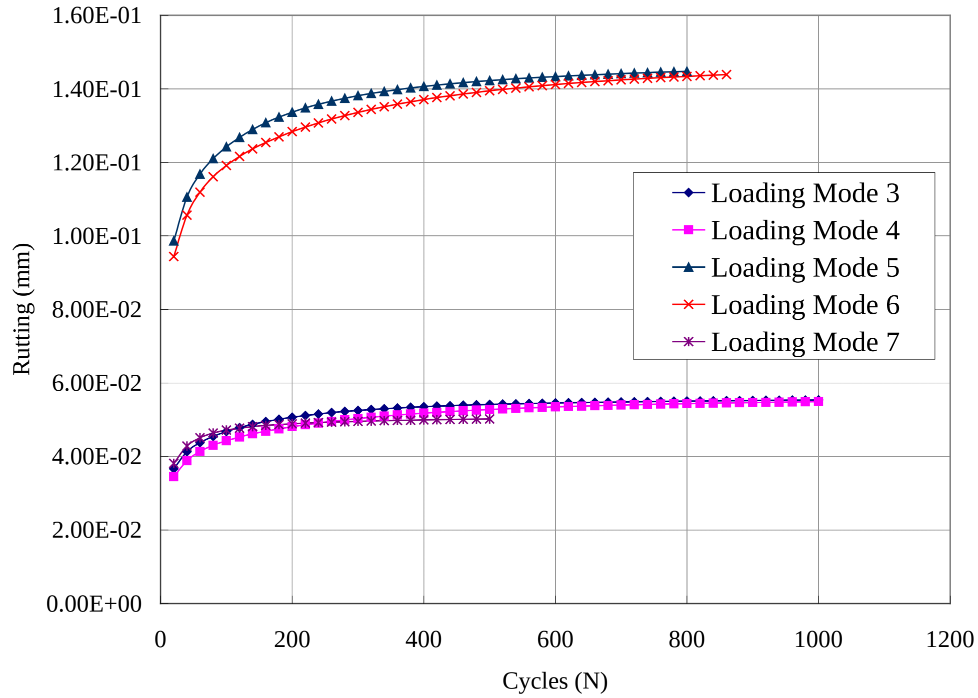


Figure F3c.8. The rutting simulation results in 3D FE analysis at temperature 40 ^{o}C using nonlinear viscoelastic and viscoplastic material constitutive model.

Year Four Work Plan

The year four work plan for the unified continuum damage model will focus on the following tasks:

(1) Extensive calibration and validation of the coupled viscoelastic, viscoplastic, and viscodamage model based on the ALF data. The previous verification efforts focused on laboratory measurements. In the ARC research, we will focus on the calibration and verification of the model using field data and results from full scale testing of pavement sections. The researchers at the University of Nottingham have provided The TAMU team with access to very valuable database of experimental results which include laboratory tests and full scale testing of pavement sections. In addition, we plan to use the data available to the North Carolina State University (NCSU) and the Federal Highway Administration (FHWA) from the Accelerated Loading Facility (ALF). The Nottingham database is summarized in tables F3c.2, F3c.3 and F3c.4. Detailed description of the ALF data is available in the final report of project DTFH61.05.RA.00108, which was submitted by North Carolina State University to the Federal Highway Administration on May 2008. The use of ALF measurements depends on its availability to the ARC.

(2) Integrate the continuum-based healing model into the developed continuum damage model. Moreover, qualitative comparisons between the predictions of the continuum healing model with the micromechanical-based healing model will be conducted.

(3) Investigate the ability of the unified continuum damage model in predicting the cyclic viscoplastic and damage response of asphalt mixes. Based on this task, decision will be made for incorporating kinematic viscoplasticity hardening effects into the unified continuum damage model.

(4) Start the development of the continuum-based aging model to be integrated into the unified continuum damage model. The development of the aging model will be based on insights drawn from available micromechanical experimental and computational studies.

(5) Most of the current modeling efforts include simplistic loading conditions (circular and uniform stress distribution). Some studies have already been made to investigate the effect of 2D/3D simulation of the model under different loading conditions (i.e. pulse loading, equivalent loading, and moving load) on pavement responses under loading. However, more investigations are needed. The TAMU researchers will collaborate with other groups (Dr. Imad Al-Qadi from University of Illinois at Urbana Champaign and Dr. Tom Scarpas from Delft University of Technology) in order to include more realistic loading conditions. The efforts will focus on including nonuniform stress distribution that is supported by experimental measurements of time-pavement contacts.

WORKSHOP ON THE FEATURES AND OPERATIONS OF THE TAMU UNIFIED MECHANISTIC CONTINUUM DAMAGE MODEL

Objective

The objective of this document is to outline the content of a training workshop that the TAMU's ARC researchers will offer during the last quarter of the fourth year of the ARC project. This workshop will present and provide hands-on and training on the theory and use of the unified mechanistic continuum damage model of asphalt pavement performance that is currently under development by the ARC researchers at Texas A&M University. The model is referred to as the PANDA "Pavement Analysis using Nonlinear Damage Approach". The training will be offered using experimental data that the participants will analyze in order to obtain the parameters of the mechanistic model. The feedback from the participants in this workshop will be used to refine the model during the fifth year of the ARC project.

Overview

The ARC will deliver a unified continuum mechanistic damage model in the form of a User MATerial Computational Code (UMAT) subroutine within the well-known commercial finite element software, Abaqus. This model will incorporate several material constitutive relationships to define the behavior (viscoelastic, viscoplastic, mechanical damage, moisture damage, fatigue damage, fracture, aging, and healing) of the asphalt mixture. These constitutive relationships will contribute to the overall ability of the mechanistic model to make reliable predictions of the appearance of important forms of damage to asphalt pavements. The final deliverables of the continuum damage modeling effort will be as follows:

(1) The first part is a computational material code written in the Fortran programming language that is easily linked to the well-known finite element and commercially available software Abaqus. This subroutine – called **UMAT** (i.e. User MATerial computational code) in Abaqus – includes the finite element implementation of state-of-the-art constitutive equations of the ARC continuum damage material model. The developed computational code UMAT will be used to predict the constitutive behavior (viscoelastic response, permanent deformation, fatigue damage, moisture damage, healing, and aging) of the asphalt mixture in an asphalt pavement structure. This computational code can be used to simulate the asphalt mixture behavior under various mechanical and environmental loading conditions.

(2) The second part is a set of geometrical finite element models for different pavement structures that will be prepared within Abaqus software and will be provided along with the computational code UMAT. This set of finite element structural models will include precise and robust finite element meshes, boundary conditions, loading conditions, and two-dimensional versus three-dimensional models. These structural models will be provided as CAE (Computer Aided Engineering) visual files within the Abaqus environment such that the user can choose to directly utilize these files to run performance simulations of a specific pavement structure without the need to create the model. However, the user will also have the flexibility to modify the provided structural models or even create completely new ones.

(3) The third part is a set of documents that include:

- guidelines to estimate or measure the material constants associated with the constitutive equations in UMAT.
- a theory manual which documents the constitutive equations of the continuum damage model included in the developed computational algorithms used to implement these equations in UMAT.
- description of different pavement structures (boundary conditions, method of applying repeated loading).

As shown in Figure 1, in order to run the deliverable computational code UMAT, two software programs are needed: (a) Abaqus, and (b) a Fortran compiler that compiles the UMAT Fortran code which is hidden and the user does not have to deal with it. Therefore, in order to use UMAT successfully those two software programs should be installed on the computer. The software along with the developed UMAT are compatible with any operating system (Windows, Unix) or any computer (PC, Workstation, Beowulf cluster). Moreover, depending on the complexity of the problem, parallel (i.e. many calculations are carried out simultaneously) or unparallel computations can be performed. Therefore, once the user hits the button “RUN” in Abaqus, then Abaqus links to UMAT and UMAT links to Fortran until the simulation is finished. Table 1 includes some of the technical attributes of the TAMU model and the continuum model being developed at NCSU under a different contract with the FHWA.

Description of the Workshop

The workshop will be for two days and it will include formal lectures and interactive training sessions as follows:

1. Description of the material constitutive model (4 hours): this part will include presentations of the theoretical background of the materials models and their components. This will encompass descriptions of the viscoelastic and viscoplastic models as well as the internal state variables and functions that describe aging, healing, mechanical damage, and moisture damage.

2. Numerical implementation of the model (2 hours): this part will include description of the numerical techniques and programming of the material model in UMAT and its linkage to the Abaqus software package.

3. Identification of the model parameters (2 hours): this session will describe the experimental methods that are used to identify the model parameters. In addition, the analytical methods and programs that are used to extract these parameters from the experimental results will be described. Finally, how to input these identified parameters into the UMAT will be described.

4. Structural model (2 hours): this session will include description of the method used to generate pavement structural models in Abaqus, loading conditions and boundary conditions. Discussion of the application of realistic loading conditions will be presented.

5. Interactive session on the use of the mechanistic model (4 hours): this session will include hands-on experience with using the PANDA to predict pavement performance. The training will cover the modules for inputting the model parameters, generate the structural model and predict performance. This session will utilize experimental measurements and data that are used in the ARC for the purpose of the verification of the PANDA. Therefore, the workshop participants will have the chance to examine how changes in the material response and model parameters for a known experimental set (e.g. ALF data) impact the performance of the pavement structure under realistic loading and boundary conditions.

6. Interactive feedback from the participants (2 hour): this session will focus on receiving feedback and suggestions from the participants on how to improve and modify specific aspects of the mechanistic model, tests for identifying the material parameters, and techniques for simulating more realistic loading and boundary conditions, etc.

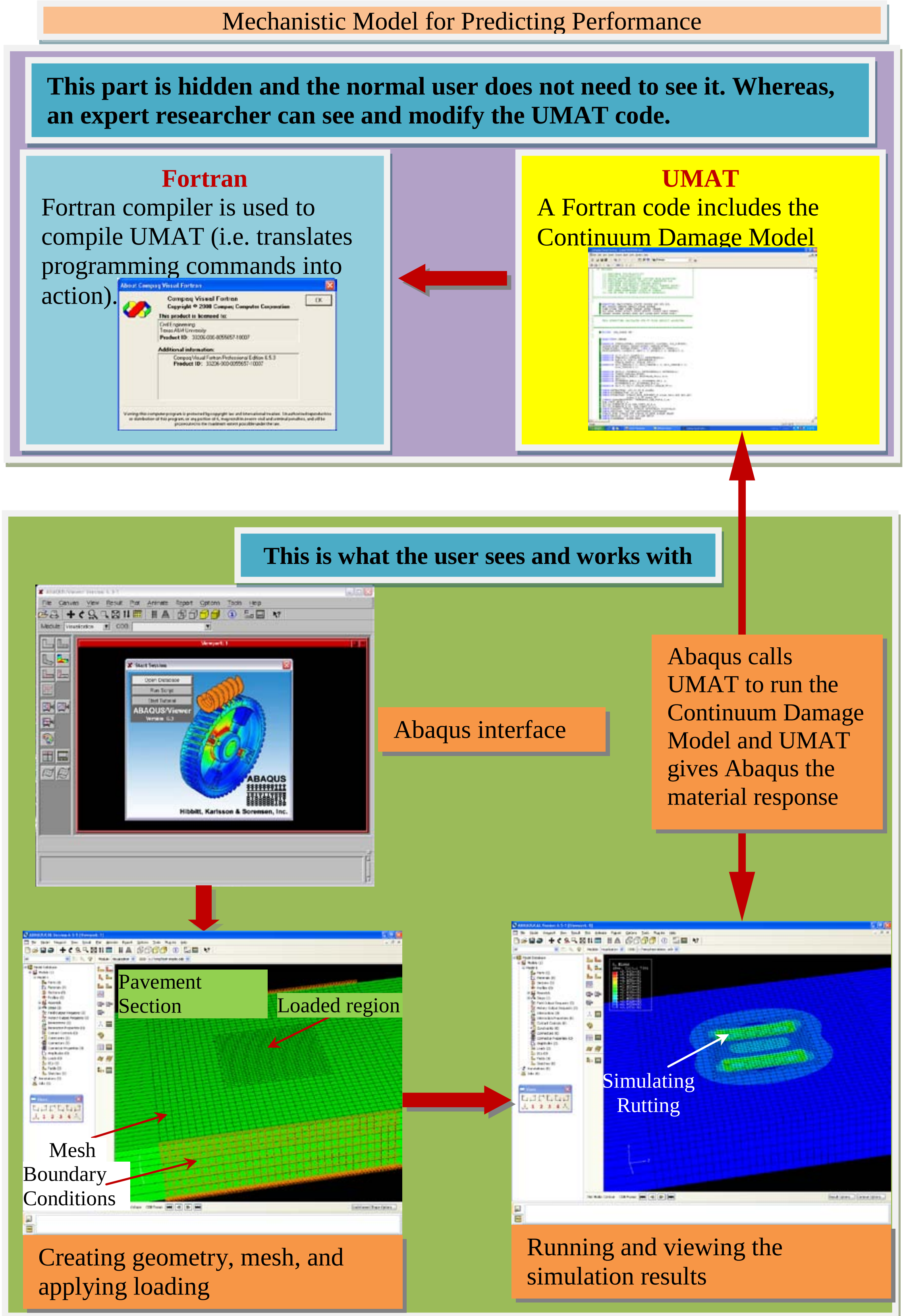


Figure 1: A Procedure to run the ARC deliverable Continuum Damage Model.

Table for Decision Points & Deliverables

Date	Deliverable	Description
02/31/10	Journal Paper	Submit a paper on thermodynamic consistency of the unified continuum damage model
03/31/10	Journal Paper	Submit a paper on evaluation of computational and modeling techniques for predicting rutting and performance of asphaltic layers
04/31/10	Decision Point	Finalize the integration of healing into the continuum damage model
05/31/10	Journal Paper	Submit a paper on integration of the healing model into the unified continuum damage model
6/31/10	Decision Point	Finalize the integration of aging into the unified continuum damage model
7/31/10	Journal Paper	Submit a paper on coupling aging model with the developed unified continuum damage model
10/31/10	Decision Point	Finish the majority of calibration and validation of the unified continuum damage model

Table of Decision Points and Deliverables for the Fatigue Program Area

Work Element	Date	Deliverable	Description
F1a	12/31/08[1]	Journal Paper	A review of practical and thermodynamic work of cohesion and adhesion
F1a	09/30/09[1]	Journal Paper	Comparing practical and thermodynamic work of adhesion and cohesion
F1a	6/30/10[2]	Draft Report	
F1a	09/30/10[2]	Final Report	
F1b-1	3/30/10[1]	Draft Report	Use of non-linear viscoelastic properties to characterize fatigue damage and delineate non-linear viscoelastic response from damage
F1b-1	12/31/08[1]	Journal Paper	
F1b-1	06/30/10[1]	Mathematical model	
F1b-1	06/30/10[1]	Final Report	
F1b-1	06/30/10	Journal Paper	The non-linear viscoelastic response of a material subjected to dynamic loading
F1b-1	09/30/10	Journal Paper	The non –linear viscoelastic response of thin films subjected to dynamic loading
F1b-1	09/30/11	Journal Paper, Model, Draft Report	Characterization of damage in thin films subjected to dynamic loading
F1b-1	03/31/12	Final Report	
F1c	1/10	Presentation, Journal Paper	Present field comparison of oxidation model. Submit for publication 8/10.
F1c	01/10	Presentation, Journal Paper	Results on binder oxidation and fatigue. Submit for publication 8/10.
F1c	03/10	Draft Report	Draft Report on findings to date from subtasks.
F1c	07/10	Presentation	Present early results on binder oxidation and fatigue
F1d	12/31/08[1]	Journal Paper	Test method to determine intrinsic healing properties of asphalt binders
F1d	09/30/10[3]	Journal Paper	Test method to determine wetting characteristics of asphalt binders
F1d	06/30/10	Draft Report	Material properties related to self-healing in asphalt binders
F1d	09/30/10	Final Report	
F1d	09/30/09[1]	Journal Paper	Validating the micro-mechanics model for self-healing in asphalt binders
F1d	09/30/10	Journal Paper	Validating the micro-mechanics model for self-healing in fine aggregate matrix specimens
F1d	06/30/11	Model and Draft Report	A model and test methods to characterize healing in asphalt materials
F1d	09/30/11	Journal Paper and Final Report	

[1] See specific section for detail on publications.
[2] These deliverables will be presented approximately 6 months later from the original plan due to delays in the development of the test method. The revised Gantt chart will reflect this.
[3] The due date for this has been revised and changed in the Gantt chart to accommodate changes in the experiment design.

Table of Decision Points and Deliverables for the Fatigue Program Area (con't)

Work Element	Date	Deliverable	Description
F1d-6	9/10	Journal Paper	Submit a conference paper summarizing the results from healing characterization of binders.
F1d-6	1/11	Presentation	Provide an update on results from healing characterization of asphalt binders at TRB, ETG or similar venue.
F1d-7	4/30/10	Journal Paper	Journal paper on wax microstructure and its relationship to fatigue cracking
F2a	12/10	Presentation	Presentation on the proposed fatigue mechanism.
F2a	1/11	Presentation	Presentation on the data analysis performed to date.
F2a	1/11	Decision Point	The team will decide which fatigue mechanism is better supported by the experimental data.
F2a	3/11	Journal Paper	A journal paper will be submitted for publication describing the proposed fatigue mechanism and the experimental data supporting it.
F2e	05/10	Draft Report	Draft interim report summarizing progress and details of analysis of Linear Amplitude Sweep test.
F2e	07/10	Final Report	Final interim report on progress of the Linear Amplitude Sweep test.
F2e	07/10	Journal Paper	Summarizing fatigue characterization of binders following amplitude sweep and correlations to mixture fatigue and field performance.
F2e	10/10	Draft Report	Comparison of surrogate fatigue tests.
F2e	01/11	Final Report	Results of surrogate fatigue test verification.
F2e	01/11	Decision Point	Choose most promising fatigue test(s) to continue researching.
F2e	01/11	Presentation	Present binder fatigue progress at TRB, ETG or similar venue.
F2e	03/11	Model and Algorithm	Automated program for predicting field performance based on laboratory tests.
F3b-1	07/10	Journal Paper(s)	Paper(s) related to multiple scale material properties and updated computational modeling of asphalt concrete fracture and fatigue
F3b-1	01/11	Presentation(s)	Presentation(s) on multiple scale material properties and updated computational modeling of asphalt concrete fracture and fatigue
F3b-1	03/11	Model & Algorithm	Mathematical models developed and computational modules to simulate CZ fracture
F3b-1	06/11	Draft Report	Draft report that describes model development, testing protocols, test results and analyses, integration of test results into the micromechanics model, model simulations, and model calibration/validation
F3b-1	07/11	Journal Paper(s)	Papers presenting significant findings from the project
F3b-1	09/11	Decision Point	Time to make a decision on parallel paths as to which is more promising to follow
F3b-1	12/11	Final Report	Final report that comprehensively describes all activities performed for this project: model development, testing protocols, test results and analyses, integration of test results into the micromechanics model, model simulations, model calibration/validation, and model applications
F3b-1	01/12	Presentation(s)	Presentations of any significant findings resulting from the project

Table of Decision Points and Deliverables for the Fatigue Program Area (con't)

Work Element	Date	Deliverable	Description
F3c	02/31/10	Journal Paper	Submit a paper on thermodynamic consistency of the unified continuum damage model
F3c	03/31/10	Journal Paper	Submit a paper on evaluation of computational and modeling techniques for predicting rutting and performance of asphaltic layers
F3c	04/31/10	Decision Point	Finalize the integration of healing into the continuum damage model
F3c	05/31/10	Journal Paper	Submit a paper on integration of the healing model into the unified continuum damage model
F3c	6/31/10	Decision Point	Finalize the integration of aging into the unified continuum damage model
F3c	7/31/10	Journal Paper	Submit a paper on coupling aging model with the developed unified continuum damage model
F3c	10/31/10	Decision Point	Finish the majority of calibration and validation of the unified continuum damage model

	Fatigue Year 4	Year 4 (4/10-3/11)											
		4	5	6	7	8	9	10	11	12	1	2	3
Material Properties													
F1a	**Cohesive and Adhesive Properties**												
F1a-1	Critical review of literature												
F1a-2	Develop experiment design												
F1a-3	Thermodynamic work of adhesion and cohesion												
F1a-4	Mechanical work of adhesion and cohesion			D			F						
F1a-5	Evaluate acid-base scale for surface energy calculations												
F1b	**Viscoelastic Properties**												
F1b-1	Separation of nonlinear viscoelastic deformation from fracture energy under cyclic loading			M&A,F,JP			JP						
F1b-2	Separation of nonlinear viscoelastic deformation from fracture energy under monotonic loading												JP
F1c	**Aging**												
F1c-1	Critical review of binder oxidative aging and its impact on mixtures												
F1c-2	Develop experiment design												
F1c-3	Develop transport model for binder oxidation in pavements				P						P, JP		
F1c-4	Effect of binder aging on properties and performance										P, JP		
F1c-5	Polymer modified asphalt materials				P								
F1d	**Healing**												
F1d-1	Critical review of literature												
F1d-2	Select materials with targeted properties												
F1d-3	Develop experiment design												
F1d-4	Test methods to determine properties relevant to healing			D			F						
F1d-5	Testing of materials						JP						
F1d-6	Evaluate relationship between healing and endurance limit of asphalt binders						JP				P		
F1d-7	Coordinate with AFM analysis	JP											
F1d-8	Coordinate form of healing parameter with micromechanics and continuum damage models												
Test Methods													
F2a	**Binder tests and effect of composition**												
F2a-1	Analyze Existing Fatigue Data on PMA												
F2a-2	Select Virgin Binders and Modifiers and Prepare Modified Binder												
F2a-3	Laboratory Aging Procedures												
F2a-4	Collect Fatigue Test Data										DP, P		JP
F2a-5	Analyze data and propose mechanisms									P			
F2b	**Mastic testing protocol**												
F2b-1	Develop specimen preparation procedures				F								
F2b-2	Document test and analysis procedures in AASHTO format				F								
F2c	**Mixture testing protocol**												
F2d	**Tomography and microstructural characterization**												
F2d-1	Micro scale physicochemical and morphological changes in asphalt binders								JP				
F2e	**Verify relationship between DSR binder fatigue tests and mixture fatigue performance**												
F2e-1	Evaluate Binder Fatigue Correlation to Mixture Fatigue Data												
F2e-2	Selection of Testing Protocols		D		F								
F2e-3	Binder and Mixture Fatigue Testing												
F2e-4	Verification of Surrogate Fatigue Test							D			F, DP		
F2e-5	Interpretation and Modeling of Data				JP								M&A
F2e-6	Recommendations for Use in Unified Fatigue Damage Model										P		
Models													
F3a	**Asphalt microstructural model**												
F3b	**Micromechanics model**												
F3b-1	Model development				JP						P		
F3b-2	Account for material microstructure and fundamental material properties												
F3c	**Develop unified continuum model**												
F3c-1	Analytical fatigue model for mixture design												
F3c-2	Unified continuum model									JP		M&A	
F3c-3	Multi-scale modeling								JP				M&A
	Lattice Model		DP		DP,JP								
	Continuum Damage to Fracture			DP				JP					

LEGEND

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

Work planned

Work completed

Parallel topic

Fatigue Year 2 - 5

		Year 2 (4/08-3/09)				Year 3 (4/09-3/10)				Year 4 (04/10-03/11)				Year 5 (04/11-03/12)			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Material Properties																	
F1a	**Cohesive and Adhesive Properties**																
F1a-1	Critical review of literature			JP													
F1a-2	Develop experiment design																
F1a-3	Thermodynamic work of adhesion and cohesion																
F1a-4	Mechanical work of adhesion and cohesion						JP			D	F						
F1a-5	Evaluate acid-base scale for surface energy calculations														JP		
F1b	**Viscoelastic Properties**																
F1b-1	Separation of nonlinear viscoelastic deformation from fracture energy under cyclic loading			D,JP	M&A				JP	&A,F,J	JP		P		JP,M&A,D		F
F1b-2	Separation of nonlinear viscoelastic deformation from fracture energy under monotonic loading			JP	M&A				JP				JP		JP,M&A,D		F
F1c	**Aging**																
F1c-1	Critical review of binder oxidative aging and its impact on mixtures																
F1c-2	Develop experiment design			D		F											
F1c-3	Develop transport model for binder oxidation in pavements		P		P, JP		P		P, JP		P		P, JP			D, M&A	F
F1c-4	Effect of binder aging on properties and performance				JP, P		JP	D	F				P, JP		JP	D	F
F1c-5	Polymer modified asphalt materials						P				P					D	F
F1d	**Healing**																
F1d-1	Critical review of literature																
F1d-2	Select materials with targeted properties																
F1d-3	Develop experiment design																
F1d-4	Test methods to determine properties relevant to healing			JP					JP	D	F						
F1d-5	Testing of materials						JP				JP			M&A,D	JP, F		
F1d-6	Evaluate relationship between healing and endurance limit of asphalt binders	DP				DP	JP	DP			JP		P		JP	D	F
F1d-7	Coordinate with AFM analysis									JP							
F1d-8	Coordinate form of healing parameter with micromechanics and continuum damage models															JP,D	F
Test Methods																	
F2a	**Binder tests and effect of composition**																
F2a-1	Analyze Existing Fatigue Data on PMA		DP														
F2a-2	Select Virgin Binders and Modifiers and Prepare Modified Binder		DP														
F2a-3	Laboratory Aging Procedures																
F2a-4	Collect Fatigue Test Data		P		JP		P		P				P, DP, JP				
F2a-5	Analyze data and propose mechanisms				P			P				P			P	D	F
F2b	**Mastic testing protocol**																
F2b-1	Develop specimen preparation procedures		D								F						
F2b-2	Document test and analysis procedures in AASHTO format		D								F						
F2c	**Mixture testing protocol**		D, JP	F													
F2d	**Tomography and microstructural characterization**																
F2d-1	Micro scale physicochemical and morphological changes in asphalt binders						JP					JP					
F2e	**Verify relationship between DSR binder fatigue tests and mixture fatigue performance**																
F2e-1	Evaluate Binder Fatigue Correlation to Mixture Fatigue Data																
F2e-2	Selection of Testing Protocols					DP, D	F										
F2e-3	Binder and Mixture Fatigue Testing									D	F						
F2e-4	Verification of Surrogate Fatigue Test											D	F, DP				
F2e-5	Interpretation and Modeling of Data		JP		P		JP		P		JP		M&A				
F2e-6	Recommendations for Use in Unified Fatigue Damage Model												P			D	F
Models																	
F3a	**Asphalt microstructural model**							JP								M&A	F
F3b	**Micromechanics model**																
F3b-1	Model development				JP				JP		JP		P	D	DP	F, SW	
F3b-2	Account for material microstructure and fundamental material properties													D		F	
F3c	**Develop unified continuum model**																
F3c-1	Analytical fatigue model for mixture design														M&A,D		F
F3c-2	Unified continuum model			JP				JP				JP	M&A	D	DP	F, SW	
F3c-3	Multi-scale modeling											JP	M&A	D		F	
	Lattice Model									DP	DP, JP						
	Continuum Damage to Fracture									DP		JP					

LEGEND

Deliverable codes	Deliverable Description
D: Draft Report	Report delivered to FHWA for 3 week review period.
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[x]	Indicates completion of deliverable x

Work planned

Work completed

Parallel topic

PROGRAM AREA: ENGINEERED MATERIALS

CATEGORY E1: MODELING

Work Element E1a: Analytical and Micro-mechanics Models for Mechanical Behavior of Mixtures

<u>Major Findings and Status</u>

There are four sub-elements to this work element. The first three are focused on analytical micromechanical models of binder, modified mastic and asphalt mixtures. The fourth is an analytical model of asphalt mixture response and damage. Progress has been made on the micromechanical models of modified mastics and asphalt mixtures and the analytical model of asphalt mixture response and damage. Application of the latter two models to measured laboratory data has confirmed the accuracy, flexibility and robustness of these models to represent accurately the laboratory-measured properties. The work on the modified mastic models awaits confirmation in the next year's work plan.

The forward and inverse self-consistent micromechanics model of an asphalt mixture, when applied to test data on an asphalt mixture and its binder derived the stiffness of the aggregate. The analytically derived result showed that aggregates become stiffer with increasing frequency, meaning that they are viscoelastic. After recovering from that initial discovery and reviewing the literature of geophysicists, rock mechanics and petroleum engineers, we found that they have been modeling rocks as viscoelastic for over a quarter of a century and that we should not have been surprised at this result. We also found that with porous limestone aggregates in hot mix asphalt, ultraviolet light showed that the lighter and less polar components of the asphalt were selectively absorbed into the interior of the aggregates particles. This was confirmed by a series of tests run by the Chemistry Department at Texas A&M University using Laser Desorption Ionization-Ion Mobility-Mass Spectrometry (LDI-IM-MS) that there is a chromatographic effect within the aggregate with the lighter and less polar components in the center and the heavier and more polar components toward the surface or left on the surface outside the aggregate. This helped to explain the observed analytical result that as a mixture aged, the aggregates became stiffer and less dependent on frequency. It also suggests that the heavier and more polar asphalt molecules that are left behind on the aggregate surface may form a coating which assists in resisting moisture damage.

A further test on the aggregates was run by coring large aggregates into small (2-inch high X 1-inch diameter) columns and testing them for creep both before and after soaking them in hot asphalt. Another surprise was that the soaked limestone sample was less stiff and more viscoelastic than the original sample. All of these findings suggest that the micromechanics model of a mixture needs to consider the aggregate to be viscoelastic and instead of using binder properties, use the viscoelastic properties of the mastic or modified binder.

Using short term monotonically increasing tensile loading on an asphalt mixture at low levels of strain, we were able to use Laplace Transforms to convert the stress, axial strain, and radial strain measurements with time into frequency-dependent complex moduli and Poisson's Ratios. The test runs for no more than twenty seconds and the data are reliable between 5 and 20 seconds. Running this test at three different temperatures allows us to generate the complete master curves of both magnitude and phase angle of the complex modulus of the undamaged material and their time-temperature shift functions. These shift functions were different for the magnitude than for the phase angle. The Poisson's Ratio was found to be independent of frequency but dependent only upon the temperature. Each set of test data is digitized and gives us about forty or fifty data points with frequency at each temperature level. This very simple and accurate test procedure gives us a test protocol for determining the undamaged properties of an asphalt mixture, and is the basis from which all damage is inferred. When the sample is tested undamaged in both tension and compression, it is then ready to be subjected to a testing protocol that is intended to do damage.

We have also completed the formulation, testing, and analysis of the undamaged compressive viscoelastic and anisotropic properties of a mixture. Following the same procedure as described above, a single sample is tested in creep in compression, tension, and indirect tension at three different temperatures to produce the master curves (both magnitude and phase angle) of the vertical and horizontal compressive and tensile complex moduli and Poisson's Ratios. The vertical compressive modulus was found to be over twice as large as the horizontal at all frequencies of the master curves. The compressive phase angles peaked around 40 degrees and the tensile phase angle peaked around 75 degrees. The magnitude of the horizontal complex Poisson's Ratio rose to nearly 1.0 which is in accord with anisotropic elasticity theory. As with the tensile test, we use the Laplace Transform to determine the frequency dependent master curves. The complete characterization of the undamaged mixture in compression can be done in one day on a single sample.

In preparation for the tests on asphalt mixtures to determine the different kinds of damage and the effects of moisture and aging on the original properties and subsequent damage, we developed a complete analysis of a laboratory test of a mixture being tested with extended cycles of tension and compression, developing both fracture and plastic damage, and then resting for different periods between the extended loading cycles. The analysis was applied to a series of such tests and was shown to be able to detect and match analytically changes in the material properties due to both microcracking and plastic deformation and to establish the effects of different rest periods on the healing of both the fracture and plastic properties of the mixture. This formulation was shown to be able to determine the rate of change of dissipated pseudostrain energy that generates microcracking and to differentiate it from the dissipated pseudostrain energy that causes plastic deformation.

Subsequent tests were run on samples tested in repeated direct tension at a damaging level of strain and the two types of dissipated pseudo strain energy were measured. The change of phase angle and apparent modulus of the mixture on the first load cycle, together with the percent air voids was used to determine the initial mean radius of the air voids. The accumulated changes in dissipated pseudo-strain energy were used to determine the growth of the mean crack radius with repeated loads and to an estimate of the Paris' Law parameters, A and n, directly from the test data. The resulting values of A and n compared well with previously measured and published values and with values calculated from Schapery's theory of crack growth in viscoelastic materials. The new test protocol is run on a single sample from which is determined the undamaged master curves (magnitudes and phase angles) of both the Complex Modulus and Poisson's Ratio, the rate of change of both of the two dissipated pseudo-strain energies, the initial mean radius of the air voids and the number of air voids, the growth of those air voids with repeated loads, and finally the fracture parameters, A and n.

A further study of the initial mean air void radius was compared with the results of the X-Ray Computed tomography scan of the same sample. It was found that the mean air void radius as determined by the fracture energy approach was about the same size as the minimum size of air void that can be detected by the X-Ray CT apparatus and the number of such air voids was about twice the number that was determined by the X-Ray CT. Using the results of the two sets of measurements together, it is possible to determine the two Weibull parameters of the initial air void distribution and to determine the change of these two parameters as the mean crack size grows with repeated loads.

The modeling of modified mastics was done by computing the interactions of a mathematical particle model and the surface tension characteristics of different neat and aged binders. The particle model was varied through a wide range of shapes and sizes and a wide range of asphalt binders to find the compressive stress that is induced between particles by the surface tension of the asphalt that holds them together. Over 150,000 runs were made to generate the characteristic shapes of asphalt binder-particle interaction. One interesting finding of this is that particles smaller than 75μ are held together by most asphalts with a compressive stress greater than 1000kPa, the size of the tensile stress that is generated in pavement surfaces by truck tires. With this model, the effects of aging, chemical modification of the binder and particle shape and size can be studied and the relative effects can be evaluated.

Year Four Work Plan

Subtask E1a-1: Analytical Micromechanical Models of Binder Properties

We have received DSR data from Professor Hussain Bahia from the University of Wisconsin on both binders and mastics and expect to use these data to determine if the forward and inverse self-consistent micromechanics model can infer the mechanical effects of the filler on the properties of the mastic. It will also be able to infer the mechanical properties of the filler itself. If they are consistent they can be catalogued and used in the design of mastics. If successful, this approach can help to design the mastic to have the desired mechanical properties.

Subtask E1a-2: Analytical Micromechanical Models of Modified Mastic Systems

We have already received an extensive data base from Professor Hussain Bahia containing DSR test data for both neat binders and their companion mastics. In the next year, we will use the volumetric concentrations of the binder, filler and air in the mastic to determine the contributions of the filler on the properties of the mastic. If this is as successful as has been the forward and inverse self-consistent micromechanics model in inferring the properties of aggregates in an asphalt mixture, it may be possible to determine the mechanical contribution of the filler to the properties of the mastic. This has implications for the use of the self-consistent micromechanics model in mixtures. In order to determine the properties of aggregates from measurements of mixtures it may be necessary to use the properties of mastics, instead of binder to obtain accurate aggregate properties. Chemical modifiers will also have an effect on the mechanical properties of the mastic and we should be able to tell their effects by the use of this same model. We will also use the particle model and interact it with the properties of the binders to investigate to what extent this is capable of explaining the effect of fillers on the properties of the mastic.

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

We have formulated the protocol and are in the process of making of the laboratory measurements of the anisotropic viscoelastic undamaged properties of a mixture in compression. As with the tensile characterization of mixtures, this is expected to provide us with the complete master curves of the vertical and horizontal magnitude and phase angles of the complex moduli, complete with the time-temperature shift functions for each. We will also obtain the temperature dependence of the horizontal and vertical Poisson's Ratios and their frequency dependence, if they do have such a dependence. This protocol is intended to be used to measure the undamaged viscoelastic properties of an asphalt mixture in preparation for subsequent testing that will induce either aging or various kinds of damage and healing.

As an adjunct to these undamaged protocols, we expect in this next year to conduct a series of tests and analyses on Fine Aggregate Mixtures in the Dynamic Mechanical Analyzer to determine the effect of relative humidity on moisture damage. The reason for this is clear: relative humidity can be computed and predicted with existing models such as the Enhanced Integrated Climatic Model that is currently being used in the Mechanistic Empirical Design Guide. In being able to model moisture damage in the field, it is important to be able to relate the moisture damage to a condition that can be predicted reliably with existing (and future) models. In anticipation of these tests on the Fine Aggregate Mixtures (FAM), we have calculated the theoretical Adhesive and Cohesive Bond Energy as it varies with the level of Relative Humidity. It will be the objective of these tests to determine if the pattern predicted by the theoretical Bond Energies is matched by the measurements.

With the success that we have had with measuring the fracture properties of mixtures in tension making use of our ability to separate the dissipated pseudo-strain energies into the two parts, one which powers fracture and the other of which powers viscoplastic deformation, we are now prepared to make damaging compression tests to measure the incremental anisotropic viscoplastic strains with repeated loads. In this fourth year, we will conduct these compressive tests on a variety of asphalt mixtures to characterize the viscoplastic damage characteristics of these mixes. All estimates of damage must proceed as a departure from the properties of the mixtures in an undamaged state in both compression and tension. We have completed the mechanics formulation of the compression characterization of the anisotropic viscoplastic damage and are prepared to analyze the compressive tests in accordance with these formulations.

The test protocol that we have worked out to test field cores has proven capable of measuring the master curves of the complex moduli and Poisson's ratios at the top and bottom of an existing pavement layer and to determine the stiffness gradient of the mixture with depth into the pavement. This ability to measure the mixture stiffness with depth is expected to close the loop with DSR measurements that have been made on extracted binders taken from thin slices of field cores. As a preliminary observation of the results made to date, it appears that the higher the percent of air voids, the deeper the aged stiffness occurs beneath the pavement surface. We will continue to make these measurements on the field-aged cores that we receive from the ARC test pavements and provide this information to those who are researching the effects of aging. The measured effects of field aging of mixtures will provide target values for the pavement performance prediction model to match.

Depending upon the findings we make in the previous two tasks on binders and mastics, we will make a decision on whether it is necessary to extract the aggregate properties from tests on mixtures and binders or mixture and mastics. The extraction will be made with the forward and inverse self-consistent micromechanics model. We will seek out properties of asphalt mixtures with various aggregates in order to begin on a catalog of aggregate properties. It is becoming apparent from the studies we have made of the effects of absorbed asphalt on the mechanical properties of the aggregate itself and the possible surface coatings left behind on the surface of the aggregates by selective absorption that the absorption properties of the aggregates may be a subtle, unexpected, but important characteristic of aggregates.

The self-consistent micromechanics model may prove to be a better model for determining the aged properties of an asphalt mixture by combining the properties of the aggregate with the aged properties of the mastic. Its success so far suggests that this may prove to be a good use for this model in determining the aged properties of a mix from the aged properties of its components.

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

The model of the response, the growth of microcracks and plastic deformation and of healing that has been demonstrated in the series of tests noted above will be further enhanced to incorporate two and three-dimensional effects. Both cracking and plastic deformation are affected by an apparent change of modulus and phase angle of the asphalt mixture. Healing engenders an apparent change in both of these quantities and thus healing affects the growth rate of both cracking and plastic deformation. A formulation has been discovered that shows how the two parts of the dissipated pseudo-strain energy are related to the current levels of both the original and current apparent modulus and phase angle. This formulation includes the easier controlled stress formulation and the more difficult controlled strain formulation. More tests will be run on asphalt mixtures to verify these formulations. This will be possible now that we have in hand a way of determining the undamaged properties of a mixture both in tension and compression. These tests will support the efforts in other tasks related to aging, fatigue, and moisture damage. Continued analysis of test data with the newly formulated set of dissipated pseudo-strain energy, cracking, plastic deformation, and healing characteristics of a mixture will very likely point up needs for further developments that will produce a refined final product. An effort will be made to determine if an improvement can be made in the current formulations of the thermal coefficient of expansion and contraction of an asphalt mixture using the principles of self-consistent micromechanics.

In this fourth year, we will work together with the part of the team which is assembling the ABAQUS model of pavement performance to try out our measured material properties, both damaged and undamaged, to see if predictions of pavement performance made with these measured material properties will produce realistic predicted results. Because we have been able to separate the dissipated pseudo-strain energy into the two parts that cause cracking and viscoplastic deformation, our predictions will show the development of both cracking and rutting. The cracking output will be in the form of color contours of the size and density of cracks in each of the finite elements used in the computations. The viscoplasticity deformation output will be in the form of color contours of total accumulated movements after a given number of passes of traffic loads.

Table for Decision Points and Deliverables

Date	Deliverable	Description
07/31/10	Journal Paper	Viscoelastic characterization of field-aged asphalt mixtures
09/30/10	Journal Paper	Viscoelastic anisotropic compressive characterization of viscoplastic damage in asphalt mixtures
09/30/10	Journal Paper	Fatigue damage and plasticity evaluation of asphalt mixtures with dissipated pseudo-strain energy
11/30/10	Journal Paper	Bond energy and dissipated pseudo-strain energy in moisture damage
11/30/10	Journal Paper	Self-consistent micromechanics model of binder-mastic relations
07/15/10	Presentation	Presentation of results of E1a-3 at the Pavement Performance Prediction Symposium in Laramie, Wyoming
07/15/10	Presentation	Presentation of results of E1a-1 and E1a-2 at the Pavement Performance Prediction Symposium in Laramie, Wyoming
01/31/11	Presentation	Presentation of results of E1a-1 and E1a-2 at the Transportation Research Board Meeting
01/31/11	Presentation	Presentation of results of E1a-3 at the Transportation Research Board Meeting
01/31/11	Presentation	Presentation of results of E1a-4 at the Transportation Research Board Meeting
03/31/11	Model and Algorithm	Providing the model and algorithm for testing and analysis of undamaged asphalt mixtures in tension and compression

Work Element E1b: Binder Damage Resistance Characterization (DRC)

Subtask E1b-1: Rutting of Asphalt Binders

Major Findings and Status

Year 3 activities focused on finalizing selection of binder, mastic and mixture materials to allow for simultaneous testing of all three portions. Preliminary results were used to determine potential adjustments needed in material selection or testing parameters. The technical reports submitted as part of the Year 3 ARC quarterly reports include the Multiple Stress Creep and Recovery (MSCR) results collected for two modified binders and four mastics, along with flow number (FN) conducted on the corresponding mixtures.

Analysis of the data resulted in several major findings. MSCR testing allowed for calculation of nonrecoverable creep compliance (Jnr) and percent recovery (%R), each of which showed clear distinction between binders. Temperature was shown to have a significant effect on the ranking of binders on the basis of the nonrecoverable compliance. When comparing binder and mastic results to a previously defined model (Delgadillo 2008), which was derived from elastomeric modified binder results, the model provided a reasonable prediction for the strain of the elastomer-modified binder used in this study and for mastics that incorporate the same binder.

The prediction of the mastic behavior needed the addition of a constant correction factor, which was found to vary based on filler type. Comparing Jnr for each binder with the corresponding mastics indicated that the relationship was linearly positive at high PG grade (64 °C) but did not exhibit the same trend at lower temperature (46 °C). %R of binder and mastics showed that there is a positive linear trend at both testing temperatures (64 °C and 46 °C). Both binder and mastic results show strong sensitivity to stress when comparing Jnr and %R. Mixture test results exhibit a coefficient of variation (COV) ranging from 0% to over 40%, and this variability appeared to be directly related to variation in percent air voids within the compacted sample. This variability highlighted the importance of controlling air voids and interfered with the correlation between mastic and mixture data.

Although implications of some major finding are inconclusive at this time, the results to date show that both binder and mineral filler type clearly influence the performance of mastics and mixtures and that stress sensitivity is a major factor controlling behavior. Initial results clearly show the complex role of elasticity that interacts with other mixture or mastic variables. Additional testing is required for clarification of several of the findings.

Issues Identified During the Previous Year and Their Implications on Future Work

The findings listed in the previous section are based on a limited data set. In some cases a trend that was the reverse of that expected (i.e., reduction in mixture FN with increase in mastic %R) was determined. Such trends cannot be clearly understood at this point. Additional testing should either verify the accuracy of the identified trend or determine that a limited data set provides too narrow a window to accurately identify a specific trend or correlation. To see the effect of specific variables, testing will continue at a designated set of temperatures (70 °C, 58 °C and 46

°C) to match the temperature of mixture testing. A third neat (unmodified) binder of different PG grade will be added to the testing matrix in Year 4. This new binder and one of the originally selected binders will be more closely investigated by incorporating two levels of modification into the testing plan (2% and 4% elastomer or plastomer). To offset the additional time required for this addition of materials, intermediate stresses have been removed from the Repeated Creep and Recovery (RCR) portion of binder and mastic testing. This is expected to allow the original schedule of this task to remain unchanged by these adjustments.

Year 3 analysis has led to the inclusion of additional materials on the binder and mastic levels. These additional materials will be carried into the mixture testing in accordance with the previously developed work plan. The additional binder incorporated in the material selection (see Valero below) results in the combination of materials for Year 4 testing described here.

The neat asphalt binders are:

- PG 64 FH neat.
- PG 58 Valero neat.

The first of these neat binders is to be modified with 2% and 4% elastomer and plastomer, while the second will be modified at only one level (4%) initially, resulting in the following modified asphalt binders:

- FH+4% CBE (plastomer).
- FH+4% styrene-butadiene-styrene (SBS) (elastomer).
- FH+2% CBE.
- FH+2% SBS.
- Valero+4% SBS.
- Valero+2% SBS.

The fillers to be combined with the above binders to produce mastics have been narrowed from three to two since submission of the Year 3 work plan. The mineral fillers are:

- Hydrated lime (HL2).
- Pulverized granite (GH1).

<u>Year 4 Work Plan</u>

Subtask E1b-1-1: Literature review

This subtask was completed during Year 2.

Subtask E1b-1-2: Select materials and develop work plan

This subtask was completed during Year 2.

Subtask E1b-1-3: Conduct testing

MSCR and RCR testing of binders and mastics will be conducted at 70 °C, 58 °C and 46 °C, regardless of PG grade of neat binder. This will allow for direct comparison at a high and intermediate temperature as well as temperature equivalent to mixture testing. RCR testing will be conducted at stress levels of 100, 3200 and 10000 Pa. FN testing of mixtures will continue to take place at 46 °C and stress levels of 50, 100 and 150 psi, since Year 3 results showed promising distinction between stress levels. Mixture preparation will be controlled by volumetric calculations performed per sample as opposed to a constant compaction effort. This will allow for consistent percent air voids for all mixture specimens, expected to result in greater repeatability than seen in Year 3 results.

Subtask E1b-1-4: Analysis and interpretation

The mastics will be tested and results analyzed to determine possible relationships between mastics and mixtures of coarse-graded granite aggregate for FN testing. Of the mastics carried into mixture production, a select number will be chosen to be tested with fine-graded granite aggregate to determine the effects of aggregate gradation on mixture performance. Preliminary results of gradation will determine if any additional fine-gradation testing is required.

Subtask E1b-1-5: Standard testing procedure and recommendation for specifications

Standard testing procedures will be developed based on the parameters listed previously in this report. Preliminary results suggest that recommendations for testing variables to be included in the specifications will not vary greatly from the parameters to be used in Year 4 work.

Table for Decision Points and Deliverables

Date	**Deliverable**	**Description**
04/10	Decision Point	Binder and mastic testing conducted during Q4 of Year 3 is expected to determine initial mixture combinations with newly included binder.
08/10	Presentation	Presentation on data collected to date and potential correlation between three phases to provide feedback in preparation for journal paper.
11/10	Journal Paper	Journal paper to present possible model that accounts for multiple modifiers.
02/11	Decision Point	Determine any additional experimental testing needed to complete or justify model.

Cited References

Delgadillo, R., 2008, Nonlinearity of Asphalt Binders and the Relationship with Asphalt Mixture Permanent Deformation, Ph.D. thesis, University of Wisconsin–Madison.

Subtask E1b-2: Feasibility of Determining Rheological and Fracture Properties of Asphalt Binders and Mastics Using Simple Indentation Tests (Modified Title)

<u>Major Findings and Status</u>

In Year 3, the team completed an extensive literature review on the use of indentation tests to obtain fundamental properties of asphalt materials. Specifically, the team focused on reviewing solutions for rigid indenters on viscoelastic materials.

Preliminary testing of binders and mastics using a penetration test with a ball (ASTM Standard D5329) showed that the standard indenter is too heavy for binder and mastic testing. A lighter, hemispherical shape indenter which allows the collection of more displacement points during the indentation test was built. The new indentation test setup allows the addition of 5-gram load increments up to a maximum of 225 grams. Testing stiffer materials or at different temperatures can be performed by adjusting the indenter's weight.

The indentation test method developed by the research group is working properly for intermediate temperatures (i.e., room temperature). The method shows good repeatability and can differentiate between different materials (e.g., different binder modifications). The team investigated the effect of sample size and wall thickness on the rheological properties obtained from the indentation test. Both effects need to be addressed when estimating the mechanical properties of binders and mastics. Preliminary comparisons between the creep compliance (J(t)) obtained from the indentation and Dynamic Shear Rheometer (DSR) tests was performed. A method was proposed to correct the J(t) from indentation tests due to the specimen size. Results presented in previous quarterly reports indicate that this method has promising results.

Preliminary finite element simulations were performed to investigate the influence of specimen size on the experimentally obtained J(t) and to estimate the stress state of the material under the indenter tip. An example of the finite element simulations of the indentation test is shown in figure E1b-2.1.

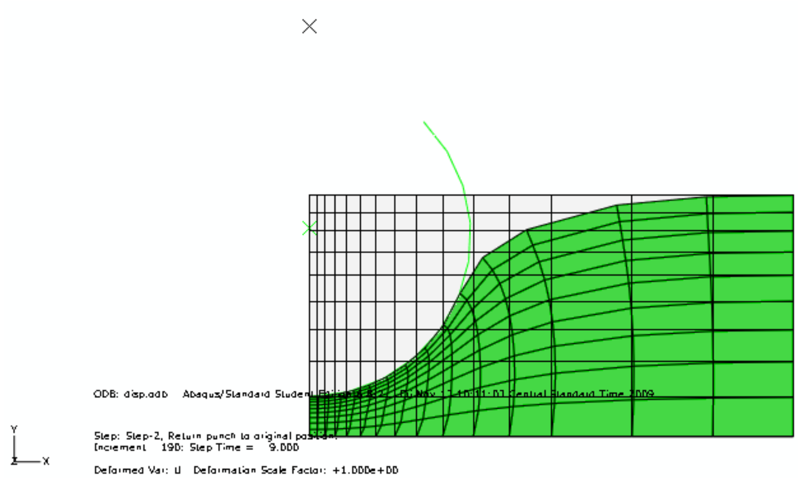

Figure E1b-2.1. Illustration. Finite element modeling of the indentation of a viscoelastic material.

Issues Identified During the Previous Year and Their Implications on Future Work

The primary difficulty in the indentation test is that it cannot be used at elevated temperatures (> 40 °C for soft binders) due to the high penetration rate of the indenter. The research team suggests testing at two intermediate temperatures. The testing results at these temperatures can be used to generate master curves. The rheological properties of the material at higher temperatures are then predicted from the master curves.

Year 4 Work Plan

Subtask E1b-2i: Literature review

The work for this subtask was completed during Year 3. The research group proposes the solution by Lee and Radok (1960) for the calculation of J(t). The boundary value problem solved by Lee and Radok is similar to the proposed indentation test; the only difference is in the specimen size. The indentation test is performed in a finite sample. However, the solution was derived for a semi-infinite space. The equation to be used for the calculation of the J(t) of asphalt binders and mastics in the indentation test is:

$$J(t) = \frac{8R^{1/2}\alpha(t)^{3/2}}{3P(1-\upsilon)} \qquad \text{(E1b-2.1)}$$

where
J(t) = creep compliance
δ(t) = displacement
R = radius of indenter (8 mm)
P = load
ν = Poisson's ratio; assume 0.5

Subtask E1b-2ii: Proposed Superpave testing modifications

The research team will work with the group at the University of Minnesota on modifications of the Bending Beam Rheometer (BBR) to run indentation tests for characterization of fracture properties at low temperature. After completing the extensive experimental plan and the numerical simulations with the finite element method, the research team will propose simple modifications of the current penetration test to run indentation tests at intermediate temperatures.

Subtask E1b-2iii: Preliminary testing and correlation of results

The research group plans to test binders and mastics of significantly different mechanical behavior (i.e., hard and soft). The experimental results obtained from the indentation test will be correlated to results obtained from the DSR. Finite element simulations will be used to determine the magnitude of shear stress under the tip of the indenter to define the stress level to be used in DSR testing. The experimental plan to be completed in Year 4 for binders and mastics is presented in tables E1b-2.1 and E1b-2.2, respectively. The experimental plan for the DSR includes the same binders, modifications and temperatures but only two replicates and one size, for a total of 24 tests.

Table E1b-2.1. Proposed indentation tests of asphalt binders.

Variables	**Factors**	**Remarks**
Temperature	2	20 °C and 30 °C
Binder	2	FH 64-22, Nustar 64-22
Size	3	Three sizes to model the size effects on J(t) (1.7, 3.4 and 5.1cm)
Modification	3	A neat binder, elastomer (styrene-butadiene-styrene (SBS)) and plastomer modification (CBE)
Replicates	3	To determine repeatability of testing and for statistical analysis
Total	**108**	

Table E1b-2.2. Proposed indentation tests of asphalt mastics.

Variables	**Factors**	**Remarks**
Temperature	2	20 °C and 30 °C
Binder	3	FH 64-22, FH 64-22 with SBS, FH 64-22 with CBE
Size	2	Two sizes to investigate size effects on J(t) (1.7 and 5.1cm)
Fillers	2	To determine if indentation test can differentiate performance of mastics with different fillers
Replicates	2	To determine repeatability of testing
Total	**48**	

Subtask E1b-2iv: Feasibility of using indentation tests for fracture and rheological properties

The research team will integrate results from the extensive test matrix of binders and mastics with the numerical simulations using finite elements in a report to be delivered at the end of Year

4. Findings from the low-temperature characterization using indentation from the University of Minnesota research group will be included. After completing the experimental plan, the statistical analysis of the results, and the numerical simulations, the research group will make a recommendation on the feasibility of using indentation tests for rheological characterization of asphalt binders and mastics.

<u>Table for Decision Points and Deliverables</u>

Date	Deliverable	Description
09/10	Journal Paper	Conference paper on the use of indentation test for characterization of asphalt binders.
01/11	Presentation	Presentation summarizing implementation of indentation tests for rheological characterization of asphalt binders.
03/11	Draft Report	Report on finite element simulations of the indentation test and correlations with DSR results.

<u>Cited References</u>

Lee, E. H., and J. R. M. Radok, 1960, The Contact Problem for Viscoelastic Bodies. *Journal of Applied Mechanics*, 27: 438-444.

Work Element E1c: Warm and Cold Mixes

Subtask E1c-1: Warm Mixes

<u>Major Findings and Status</u>

The main findings from analysis of results collected in Year 3 are summarized in the following:

- A testing procedure was developed to quantify the effects of warm mix asphalt (WMA) additives on asphalt binder workability. An extensive literature search on the fundamental concepts of tribology resulted in selecting the testing protocol presented in ASTM D5183-05, "Standard Test Method for Determination of the Coefficient of Friction of Lubricants Using the Four-Ball Wear Test Machine," to be used in the Dynamic Shear Rheometer (DSR) to evaluate the effects of WMA additives on binder lubricity.

- Evaluating the effects of select additives on asphalt binder performance grades continued in Year 3. Work focused on the high-temperature properties, including the Superpave G*/sin(δ) parameter and Multiple Stress Creep and Recovery (MSCR) test results, stiffness and "m" value, and fatigue performance.

- Asphalt mix workability was evaluated by conducting aggregate coating testing. Gyratory compaction was also conducted to determine the Construction Force Index (CFI) using the Gyratory Pressure Distribution Analyzer (GPDA), and to determine the number of gyrations to 92% G_{mm} (N92). Two binders—unmodified PG 64 and modified PG 76—and three warm mix additives—Revix, Rediset and Sasobit—were included in the study. In addition, foaming was included as one of the methods for warm mix production.

- Initial results of mixture testing indicate that aggregate coating is very sensitive to temperature and appears to be highly controlled by viscosity and lubricity of binders. Results also show that the effect of warm mix additives is highly dependent on gradation of aggregates. While certain additives had significant effects on fine-graded mixes, there were only marginal effects on coating of coarse-graded aggregates.

- Initial binder lubricity data collected with the use of the newly developed DSR test indicate that normal force and binder grade are very important factors to be considered in lubricity measurements.

- Significant effort was put toward coordinating field projects, field materials procurement, and sharing results and concepts with the University of Nevada, Reno. Efforts focused on evaluating mixture performance at the University of Nevada, Reno using the mix designs and materials produced at UW–Madison. The following field trial sections have been identified:

    - *City of Reno*: On June 11, 2009, WMA mixture was placed on a test strip along Chism Street in Reno, Nevada. The WMA mix was produced at the Granite Construction Inc. plant in Lockwood, Nevada, using the Ultrafoam technology. The asphalt mixture consisted of a Type 2, 50 blows, 4% air voids Marshall Mix design manufactured with a PG 64-22 asphalt binder. The mix included 15% recycled asphalt pavement (RAP) and 1.5% of hydrated lime by dry weight of aggregate. Approximately 900 tons of WMA was produced for this project and placed into a thickness of 6 inches.

      The Ultrafoam GXTM foaming system is a water-based technology that uses a foaming nozzle to inject steam into the asphalt binder flow line. The system can achieve consistent foaming at varying production rates, pressures and temperatures without the use of a powered mixing device. This project used a water addition rate of 1.25% by weight of binder. The evaluation included the effect of reheating on the volumetric and mechanical properties of the WMA mix. The reheating process consisted of first heating the plant-sampled WMA in the oven at 275 °F for 4 hours in a sealed container before splitting the material into individual sample sizes and conditioning them for 1.5 hours at 250 °F before compaction. The data collected show that reheating of the WMA mix significantly impacted its undamaged and moisture-damaged dynamic modulus while it did not impact its resistance to thermal cracking.

    - *Manitoba Infrastructure and Transportation*: Construction of two 500-foot sections using each of the following materials: HMA, HMA compacted at lower temperatures, Sasobit, Advera and Evotherm. Mixes workability for the binder course testing was completed, and a detailed testing plan for pre- and post-construction activities was submitted.

- *NCHRP 9-43*: Preliminary contact has been made to work with the NCHRP 9-43 research team in evaluating foamed mixes for some of their field projects.

<u>Year 4 Work Plan</u>

Subtask E1c-1i: Effects of warm mix additives on rheological properties of binders

Effect of warm mix additives on binder lubricity will be measured using the lubricity testing developed in Year 3. The testing procedure will be further evaluated to include higher temperatures and different speeds. Materials to be tested are shown in table E1c-1.1.

Table E1c-1.1. Materials for subtask E1c-1i.

Asphalt Binders	Warm Mix Technology
PG 64-22	Mineral
PG 76-22	Surfactant
	Foaming Wax

Subtask E1c-1ii: Effects of warm mix additives on mixture workability and stability

Year 4 will continue work begun during Years 2 and 3 on mixture workability and stability. A new gradation will be selected to cover a wider range of gradations. In Years 2 and 3, only one aggregate type was used (granite). A different type of aggregate will be selected, such as limestone or gravel, to cover a different mineralogy and aggregate shape properties (i.e., angularity).

Results obtained from subtask E1c-1i will be correlated with mixture workability and stability from this subtask to identify the effect of changes in binder coefficient of friction with mixture workability and stability.

The UNR research team will conduct an experiment to identify an effective method to produce foamed WMA in the laboratory. A joint research project of the UNR research team and Granite Construction Inc. will effectively simulate the foaming process in the laboratory. The Granite Construction asphalt mix plant, located five miles east of the UNR campus, has been retrofitted to produce WMA mixtures using a foaming technology (free water). UNR will purchase a laboratory foaming device to produce foamed WMA mixtures in the laboratory. The UNR-Granite project will use plant-produced foamed WMA mixtures with two binder grades (neat PG 64-22 and polymer-modified PG 64-28), two gradations (fine and coarse), and a single source of aggregate to establish an effective method for producing foamed WMA mixtures in the laboratory.

Subtask E1c-1iii: Mixture performance testing

The following tests are scheduled to be performed at the University of Nevada, Reno:

- Dynamic Modulus: E* (AASHTO TP62), 3 replicates.
- Resistance to Deformation: Repeated Load Triaxial (RLT), binder PG high temperature [°C], 3 replicates.
- Fatigue Life: Flexural Beam Fatigue, 20 °C, 3 strain levels, 3 replicates.
- Thermal Cracking: Thermal Stress Restrained Specimen Test (TSRST), 3 replicates.
- Moisture Damage: Tensile Strength Ratio (TSR) (AASHTO T283), 5 dry, 5 wet replicates:
    - Case I: Dry aggregates.
    - Case II: Wet aggregates.

Year 4 will include a major emphasis on the effect of temperatures on energy and emissions of HMA and WMA. Energy analysis will be conducted to estimate the effect of aggregate drying and binder temperature on moisture damage. Two cases will be considered as a starting point. In Case I, dry aggregates will be used in preparing the samples, as is conventional practice. In Case II, wet aggregate will be used. The moisture content will be monitored by weighting the aggregate dry, then weighting the aggregate again after adding a certain amount of water and heating it to the mixing temperature. The need for different levels of aggregate moisture content will be evaluated after analyzing preliminary results.

Such analyses can then be related to HMA plant operations. Current models for estimating energy consumption and emissions at HMA plants differ significantly and must be refined to accurately characterize plant operational performance and efficiency. Data related to energy consumption, resource consumption and plant efficiency are needed to accurately characterize system processes but are currently lacking. A better understanding of HMA production operations is needed. It is important to investigate which operational parameters affect plant energy consumption and emissions, and how these parameters may be modeled to reduce environmental impact. By identifying the critical operational parameters that significantly affect plant energy consumption and emissions, a business-as-usual scenario for HMA production can be developed to evaluate promising alternative asphalt technologies such as WMA.

Subtask E1c-1iv: Develop revised mix design procedures

This subtask will be coordinated pending the status of NCHRP 9-43.

Subtask E1c-1v: Field evaluation of mix design procedures and performance recommendations

This subtask will continue the work started in Year 3. Coordination with the Manitoba project will carry on once the 2010 construction season begins. The UNR team will evaluate the mechanical properties of the WMA sections in Manitoba. Work with the NCHRP researchers will be coordinated pending the status of NCHRP 9-43.

Table for Decision Points and Deliverables

Date	Deliverable	Description
05/10	Decision Point	Details of aggregate moisture experiment.
05/10	Presentation	Offer an update at the WMA ETG.
08/10	Journal Paper	Submit paper to TRB or AAPT on findings from compaction and mechanical testing of WMA.

Subtask E1c-2: Improvement of Emulsions' Characterization and Mixture Design for Cold Bitumen Applications

Major Findings and Status

Investigation of emulsified binder properties improved the understanding of emulsion construction properties. Significant effort was invested in determining a test method to quantify the effects of emulsion type, aggregate type and curing conditions on curing rates and the development of adhesion between binders and substrates. Two test methods were the primary focus: the Dynamic Shear Rheometer (DSR) and the Pneumatic Adhesion Tensile Testing Instrument (PATTI). Significant progress was made in terms of procedure development, factor screening and parameter control for both tests. Results suggest that the PATTI may be preferred over the DSR for measuring adhesion and quantifying curing rates. The investigation will be presented at the TRB 2010 Annual Meeting in a poster session. A draft AASHTO standard titled "Determining Asphalt Binder Bond Strength by Means of the Bitumen Bond Strength (BBS) Test" was submitted in December 2009 for review by the Emulsion Task Force, which is part of the Pavement Preservation Expert Task Group, in an effort to formalize experimental procedures and protocols.

Other efforts focused on investigating the efficacy of existing performance tests for surface seal techniques, namely the standard chip seal procedure defined in ASTM D7000. Preliminary investigations focused on characterizing the effect of binder and aggregate application rates on percent aggregate loss as measured by the sweep test. Results presented in the ARC July–September 2009 report illustrate the effect of varying binder and aggregate applications rates, with higher aggregate rates contributing to higher aggregate loss. Subsequent testing involved the investigation of chip embedment depth using the standard sand-patch procedure. Results suggest that the sand-patch method, which is typically used to measure mixture macrotexture, is inadequate for characterizing chip embedment in standard sweep test samples. A literature review confirmed that construction methods rely on the concept of Average Least Dimension (ALD) in determining application rates. It is the research team's opinion that the ALD concept is in need of revision and there is possibility of significant improvement. Other methods of characterizing aggregate orientation and chip embedment will be investigated in Year 4, including the Aggregate Imaging System (AIMS) and laser profilometer, to improve upon the concept of ALD.

Binder viscosity was investigated using a Brookfield rotational viscometer (RV) to evaluate the construction properties as defined by sprayability and drain-out performance. Current practice relies on measurement of Saybolt-Furol viscosity, a laborious procedure that has little relationship to the shear rates experienced by emulsions in the field. A procedure was developed to use the RV to investigate sprayability at high shear rates and drain-out at low shear rates. Preliminary results from the RV testing indicate that viscosity reduces with time and emulsions reach an equilibrium value of viscosity, which is typical of thixotropic behavior. Results also show that shear rate and temperature have significant effect on the viscosity of an emulsion and the time it reaches equilibrium viscosity. Higher shear rates and higher temperatures are observed to result in lower equilibrium viscosities, confirming that emulsions exhibit thixotropic behavior. Further repeated testing showed that the thixotropy exhibited by emulsions during initial RV testing appears to be nonrecoverable, thus the initial shearing of the material results in permanent changes to the emulsion's microstructure.

A complete review of the literature on the subjects of mix designs for cold in-place recycling (CIR) and cold mix asphalt (CMA) mixtures was conducted to cover all national and international activities in these two areas. The most promising design methods will be recommended for further evaluation in the laboratory experiment. A summary report will be prepared on the literature review effort and submitted by March 31, 2010.

Issues Identified During the Previous Year and Their Implications on Future Work

Preparation of material substrates for use with the PATTI is somewhat time-consuming, laborious and highly dependent on access to appropriate lapidary equipment. In seeking to standardize a testing procedure, the need for a standard substrate preparation process was identified. Two possible options were considered for the substrate preparation process. Gyratory-compacted HMA samples or standard portland cement concrete cylinders, each of which may be cut into slices using standard sawing equipment, are possible solutions to provide substrates for PATTI testing. Testing will be conducted on samples prepared by each of these options to determine their applicability to current testing procedures.

Complications of using the DSR to evaluate breaking and setting rates encouraged the team to pursue alternative testing methods, namely the Bitumen Bond Strength (BBS) test using the PATTI. The DSR results provided weaker correlations to sweep test results than did the results from the PATTI. Although the DSR is not found to be a good test for measuring breaking and setting rates, the strain sweep procedure used in the DSR testing for the emulsion residue has shown potential as a measure of strain tolerance to relate to early and late raveling experienced by chip seals. This activity will be further pursued under the emulsion residue testing subtask.

The research team also reviewed literature dedicated to the concept of ALD. Existing methods used in this concept to analyze aggregate orientation and chip embedment depth were identified as being inadequate to fully characterize chip seal performance. In addition, the sand-patch method was used in preliminary trials in an attempt to characterize chip embedment depth. This method also possessed certain limitations that diminished its appropriateness for replicating field performance. As a result, other test methods utilizing AIMS technology or a laser profilometer will be developed in a laboratory setting to better understand the fundamental behaviors of aggregates in the chip seal. With an improved theoretical understanding, field performance tests may be developed. Further testing will be required to determine if these methods are appropriate for characterizing chip seal performance. A final report on chip seal pavement preservation strategies by the NCHRP (NCHRP 2009) will also be reviewed to identify other potential test methods.

Year 4 Work Plan

Subtask E1c-2i: Review of literature and standards

Review of literature and standards will focus on the following activity:

- Applicability of AIMS, imaging techniques, and the laser profilometer test method being developed as part of work element VP2a for analyzing aggregate orientation and chip seal performance.

The findings from this literature review will be summarized and submitted by October 29, 2010.

Subtask E1c-2ii: Creation of advisory group

The advisory group remains actively engaged with the research team. Conference calls and face-to-face meetings will continue in Year 4 to discuss the focus of research progress. A tentative schedule for the meetings is as follows:

- Teleconference #1: Summer 2010.
- Teleconference #2: Fall 2010.
- Face-to-face meeting #1: January 2011 (TRB).

Subtask E1c-2iii: Identify tests and develop experimental plan

In addition to continuing refining test procedures for evaluating emulsion construction properties, performance properties of emulsion residues and field validation will be the focus of Year 4. Specifically, the following activities will be performed:

- Performance properties of emulsions.
    - Establish a range of residue tests related to performance using existing and new methods, as outlined in subtask E1c-2v.
    - Combine tests for performance properties of residue with construction properties of emulsions to provide a complete set for performance grading of emulsions.
- Improvements to the standard sweep test.
    - Examine modifications to the existing sweep test procedure to recommend application rates for binder and aggregates typically used in the field. This is necessary for aligning practical application rates with standard laboratory application rates, which may represent significant improvements to the existing procedure.
    - Utilize the sweep test as a design tool to determine the appropriate binder and aggregate application rates and reduce risk of aggregate loss.

    - Apply the sweep test to other chip seal distress modes. Fitting the testing apparatus with a roller assembly rather than a brush may allow for evaluation of bleeding distress that is very common for chip seals. Modification of the testing apparatus will also be used to investigate relationships with short- and long-term raveling.
- Field validation.
    - Evaluate construction and performance properties obtained in a laboratory setting to establish thresholds for acceptable field performance of chip seals.
    - Identify field tests to evaluate construction and performance properties. Existing field test methods are generally simplistic and may be improved to represent true construction and performance characteristics.
- Dense cold mixes.
    - Define emulsion selection framework for use in dense cold mix applications.
    - Develop mix design procedure and evaluation parameters that will enable dense cold mixes to be produced, tested and evaluated in the laboratory environment.

Experimental designs for each of these will be developed pending the results of relevant literature reviews.

Subtask E1c-2iv: Develop material library and collect materials

Materials obtained from a local production facility will continue to be collected and integrated into a materials library. As new emulsion types become available, they will be tested with the proposed battery of tests for both construction and performance properties. Materials used in local chip sealing projects will also be acquired and tested using applicable tests such as the sweep test.

Subtask E1c-2v: Conduct testing plan

Emulsion Residue Properties

Several emulsion residue properties will be evaluated using a variety of procedures in the DSR on recovered and pressure aging vessel (PAV)-aged residues. Emulsion residues will be recovered using ASTM D7497 Evaporation Recovery Method – Method A or B. Method B was recently adopted by the ASTM and involves residue recovery for 6 hours at 60 $^{\circ}$C using a thin film. The research team will collaborate with the Emulsion Task Force and may conduct limited laboratory experiments to decide which method is most appropriate for evaluation of residues. From a practical standpoint, Method B is preferred because it requires a much shorter recovery time and results in less aging of the residue. A preliminary matrix of candidate residue tests is provided in table E1c-2.1.

Table E1c-2.1. Proposed residue evaluation framework for emulsion construction properties.

Property	Aging Level	Testing Temperature (°C)	Proposed Procedure	Potential Evaluation Criteria
Resistance to Bleeding	Recovered Residue	High surface temperature	MSCR	J_{nr} Stress sensitivity
Resistance to Early and Late Raveling	Recovered Residue, PAV Residue	TBD	Strain Sweep	Strain at 50% Reduction in G*
Fatigue Cracking	PAV Residue	TBD	Frequency Sweep	TBD
Thermal Cracking Resistance	PAV Residue	10	Frequency Sweep	Estimates of BBR Properties S(60) and m(60)
Polymer Identifier	Recovered Residue	25	Elastic Recovery MSCR	% ER % Recovery

MSCR = Multiple Stress Creep and Recovery. Jnr = nonrecoverable creep compliance.
BBR = Bending Beam Rheometer.

An appropriate method for long-term aging of emulsion residues is needed to complete the testing plan. Resistance to late raveling, fatigue cracking and low-temperature properties all rely on residues being aged in the PAV. Existing PAV procedures are applicable only to hot binders because the temperature used in the procedure exceeds the softening point of emulsion residues, potentially damaging the effects of polymer or latex modification. Current hot-binder specifications call for aging materials at 90 °C to 110 °C at 300 psi for 20 hours. As a starting point, the existing procedure will be modified by using a combination of reduced temperature and film thickness to achieve long-term aging at a temperature that does not degrade the rheological properties of the emulsion residue.

Based on discussions related to Emulsion Task Force research efforts, testing protocols for the MSCR and strain sweep tests are in need of revision. Specifically, the stress levels will be modified and testing temperatures reduced for the MSCR test based on the recommendations of the recently completed Federal Lands Bureau study. The testing procedure and evaluation parameters for the strain sweep test will also be modified. Potential modifications to the evaluation criteria include specification of a maximum initial stiffness and evaluation of appropriate thresholds for reduction in stiffness. Other analysis methods will also be explored. It is anticipated that the DSR elastic recovery procedure recently established by UW–Madison will be implemented as published.

Procedure development is also needed for characterization of PAV-aged residues, including the strain sweep procedure. Furthermore, additional data is needed to confirm that use of the frequency sweep in the DSR is able to accurately predict BBR properties. Tests will be conducted on a wide range of neat and modified hot-applied binders to assess the accuracy of this prediction. Recommendations will be made regarding the feasibility of this test based on the results. An appropriate fatigue test will be selected based on the outcomes of other ARC work elements.

UW–Madison received emulsions for testing from a local emulsion supplier, from which the research team has selected six emulsions for initial evaluation of the proposed residue testing protocols. At this time, research efforts are focused on characterizing emulsions for chip seals. Preliminary emulsions selected are provided in table E1c-2.2. The research team plans to prepare results of this initial effort to characterize the performance properties of emulsions for publication at the 2011 annual meetings of the TRB or AAPT. A deadline of September 30, 2010, has been established for this subtask.

Table E1c-2.2. Emulsion selection for evaluation of performance properties.

<table>
<tr><th>Chemistry</th><th>Set</th><th>Modification</th></tr>
<tr><td rowspan="3">Cationic</td><td rowspan="3">Rapid</td><td>Neat</td></tr>
<tr><td>Polymer</td></tr>
<tr><td>Latex</td></tr>
<tr><td rowspan="3">Anionic</td><td rowspan="3">Rapid
(High Float)</td><td>Neat</td></tr>
<tr><td>Polymer</td></tr>
<tr><td>Latex</td></tr>
</table>

Dense-Graded Cold Mixes

A mix design method will be developed for dense CMA and CIR mixtures. The mix design method will be consistent with the Superpave volumetric mix design method for HMA. The Superpave Gyratory Compactor (SGC) will be modified as necessary to be applicable for the design of CIR and CMA mixtures. The developed mix design method will take into consideration the unique features of CMA mixtures in terms of workability, short- and long-term stability, and long-term performance. This effort will make use of the information developed by the UW–Madison team on the performance of asphalt emulsions in the various applications of cold mixes.

Subtask E1c-2vi: Develop performance selection guidelines

Performance selection guidelines will be developed using the laboratory testing specified in previous subtasks and will be selected for the following properties:

- Construction properties.
    - *Storage stability*. The existing test outlined in ASTM D6930 will be used as an initial specification.
    - *Sprayability and drain-out*. Viscosity measurements at different shear rates will simulate emulsion behavior during pumping and placement.
    - *Breaking and setting rate*. Changes in bond strength over time will indicate behaviors associated with breaking and setting.
    - *Early raveling*. Bond strengths measured at particular curing intervals will indicate an emulsion's ability to resist early raveling.

- Performance properties.
    - *Resistance to bleeding*. Recovered residues may be tested at the high surface temperature using the MSCR procedure to evaluate Jnr and stress sensitivity.
    - *Resistance to early and late raveling*. Recovered and PAV-aged residues may be evaluated using DSR strain sweep procedures to investigate reductions in G*.
    - *Fatigue cracking*. PAV-aged residues may be tested using DSR frequency sweep procedures to evaluate resistance to fatigue cracking.
    - *Thermal cracking resistance*. PAV-aged residues may be analyzed using DSR frequency sweep procedures to estimate low-temperature BBR properties.
    - *Polymer identification*. Recovered residues may be analyzed using MSCR and elastic recovery methods to identify the effects of polymer modification.

The research team will continue to use the sweep test while evaluating other methods to measure chip seal performance in order to establish these guidelines.

Subtask E1c-2vii: Validate performance guidelines

Guidelines established in subtask E1c-2vi will be validated through selected field sections. Field sites surveyed in June and July 2009 will serve as locations for follow-up assessments in Year 4. Three field-constructed chip seal sites will be evaluated to investigate salient construction and performance properties.

Subtask E1c-2viii: Develop CMA mix design guidelines

The UNR team will work on developing a mix design method for CIR and central plant dense CMA. A preliminary procedure for conducting a laboratory study of dense cold mixtures has been proposed (Jorda 2008). The procedure generally follows that of an HMA mixture with minor modifications. The process for developing a CMA mix design procedure includes:

- *Definition of the aggregate gradation curve and aggregate properties*. Properties of particular importance include measurements of fine particle surface area and aggregates' reactivity to an acidic medium.
- *Definition of minimum total water content*. Determination of design water content is important for ascertaining the degree to which aggregates can be coated by the emulsified binder.
- *Selection of emulsifier content*. Specifying the optimum emulsifier content depends on the particular type of emulsion used and typical contractor construction practices.
- *Adjustment of pH*. Due to the high sensitivity of emulsions properties to pH levels, adjusting the pH as a function of aggregate properties is essential.
- *Definition of minimum emulsion content*. Emulsion content may be calculated by comparing the surface area of asphalt droplets to the surface area of the aggregate.

- *Determination of the final mix design*. The final mix design may be optimized by considering particular mechanical properties of the mix such as initial workability, mechanical resistance and moisture susceptibility after aging.

Subtask E1c-2ix: Develop CMA performance guidelines

CMA may be evaluated by several performance criteria. Coating and workability must be evaluated to determine field constructability. An evaluation of coating may be undertaken following emulsion setting on two different mix formulations. SGC samples may also be evaluated for void content and drainage. Compressive strength may be evaluated as a function of curing time, and curing conditions may give insight into cohesion of the emulsified binder to aggregates and the resistance to moisture damage.

The UNR team will work on developing a manual for design, testing and construction of CIR and CMA mixtures. The manual will cover the various aspects of the cold mix technologies as they apply to CIR and CMA mixtures. The manual will be based on the information developed in item E1c-2viii.

Table for Decision Points and Deliverables

Date	**Deliverable**	**Description**
4/30/2010	Draft Report	Emulsion Evaluation: Literature review, testing protocols and preliminary experimental results for emulsion construction properties. Experimental plan and testing protocols for the evaluation of emulsion residues will also be submitted.
8/1/2010	Journal Paper (2)	Topics to be published include “Using the RV to Evaluate Emulsion Viscosity” and “Performance Properties of Emulsions.”
10/29/2010	Draft Report	Sweep Test Imaging: Literature review and preliminary experimental design.
01/10/2011	Presentation (2)	Presentations related to construction and performance properties.
03/31/2011	Final Report	Final report on the development of performance selection guidelines.

Cited References

Jorda, E., 2008, Dense Cold Mixes: Preservation of County Roads. Presented at the American Emulsion Manufacturers Association Conference, Arlington, VA.

NCHRP, 2009, “Manual for Emulsion-Based Chip Seals for Pavement Preservation,” Report NCHRP 14-17. National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C.

CATEGORY E2: DESIGN GUIDANCE

Work Element E2a: Comparison of Modification Techniques

Major Findings and Status

The research team finished collecting the materials needed for this task. The material library for this study includes 17 materials from six sources, including five base binder grades and 12 modified binder grades. The team also began testing the materials following the approved testing matrix. Tests performed to date are Dynamic Shear Rheometer (DSR) rheological measurements according to AASHTO TP5 and Multiple Stress Creep and Recovery (MSCR) tests according to ASTM D7405-08a. The collected materials were also subjected to laboratory aging techniques including rolling thin film oven (RTFO) (AASHTO T240) and pressure aging vessel (PAV) (AASHTO R28). The results of the tests are described in more detail in the project team's quarterly reports.

Styrene-butadiene-styrene (SBS) triblock copolymer, ethylene terpolymers, plastomers and polyphosphoric acid (PPA) are some of the modifiers used in this study. They cover a broad range of the modifier spectrum by including reactive and nonreactive elastomers, cross-linked and uncross-linked polymeric additives, and a low molecular weight acid modifier. Two levels of modification are selected for every polymer modifier used. From the preliminary results, very different responses can be observed based on composition, type and level of modification, and base binder source. By analyzing the data collected from testing these materials, the research team will be able to better understand how different modification techniques influence the behavior of asphalt binders, and how different modifiers improve different properties from the large spectrum of asphalt binder requirements.

Year 4 Work Plan

Subtask E2a-1: Identify modification targets and material suppliers

This subtask was completed during Year 3.

Subtask E2a-2: Test material properties

The team will continue work on this subtask following the schedule shown in the Gantt charts. The testing schedule remains the same as the one proposed and approved in the Year 3 work plan.

Subtask E2a-3: Develop model to estimate level of modification needed and cost index

Based on the testing results from subtask E2a-2, the team will develop a model to help estimate the level of binder modification needed and provide a costing index.

Subtask E2a-4: Write asphalt modification guideline/report on modifier impact over binder properties

This subtask will focus on developing a guideline for use of different modifiers to help improve the modifier selection process and to reduce the risk of negatively impacting construction and performance of asphalt pavements.

Table for Decision Points and Deliverables

Date	Deliverable	Description
07/10	Presentation	Presentation will be made on the testing progress to date.
08/10	Journal Paper	A journal paper will be prepared and submitted for publication on the data collected to date.

Work Element E2b: Design System for HMA Containing a High Percentage of RAP Materials

Major Findings and Status

University of Nevada–Reno's efforts on this work element in Year 3 focused on subtask E2b-1.a, "Develop a System to Evaluate the Properties of the Recycled Asphalt Pavement (RAP) Aggregates," subtask E2b-3, "Develop a Mix Design Procedure," and E2b-5, "Field Trials." University of Wisconsin–Madison's efforts on this work element in Year 3 focused on subtask E2b-1.b, "Develop a System to Evaluate the Properties of the Recycled Asphalt Pavement (RAP) Binder."

Under subtask E2b-1.a, the impact of the current extraction techniques (i.e. ignition, centrifuge, and reflux) on the properties of the extracted RAP aggregates experiment was completed and a final report summarizing the findings was prepared. Two papers have been submitted for publication to present the findings of this subtask.

The major finding for the subtask E2b-1.b was the establishment of a testing and analysis procedure to estimate the PG grade of aged binder in RAP. The procedure also allows for estimating the allowable percentage of RAP in new asphalt mixes based on the target PG grade required for a project. The testing protocols utilize the Bending Beam Rheometer (BBR) for the low-temperature grade and the Dynamic Shear Rheometer (DSR) for the intermediate- and high-temperature grading. A procedure for aging RAP mortars in the pressure aging vessel (PAV) was also established and evaluated. Two papers have been submitted for publication to explain the details of the BBR procedure for testing RAP mortars and estimating the aged binder properties.

The Excel spreadsheet developed in connection with the analysis procedure was finalized; the final spreadsheet includes the three testing temperature levels (low, intermediate and high). Figure E2b.1 shows an example of the spreadsheet summary chart, which indicates the allowable percent of RAP binder in the total binder for different target PG grades.

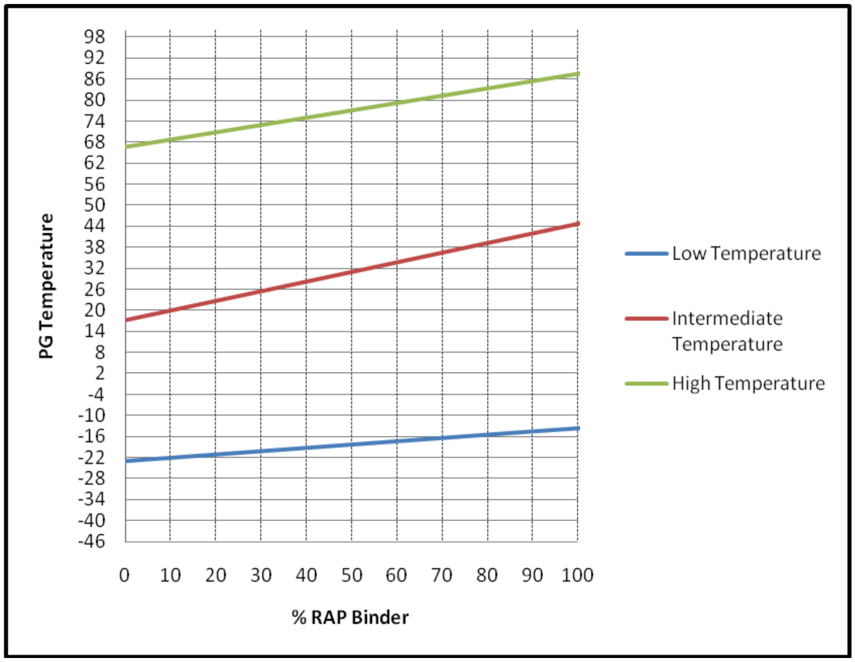

Figure E2b.1. Percent RAP binder as percent of total binder.

The research team started a verification experiment for the testing and analysis procedure. The verification is based on testing artificially produced RAP produced from double PAV-aged binder (40-hour PAV) blended with selected aggregate to produce artificial RAP. The artificial RAP is then tested for the low-, intermediate- and high-temperature grading using the developed testing and analysis procedure. The double PAV-aged binder is also tested to determine its PG grading properties. The direct testing results are compared to estimates from the developed testing and analysis procedure for verification.

Under subtask E2b-3, a meeting was held on June 15, 2009 in Sacramento to discuss the experimental plan for this subtask. The meeting was attended by Jon Epps and Adam hand from Granite Construction, Inc., Randy West from NCAT, Hussain Bahia from UWM, and Peter Sebaaly and Elie Hajj from UNR. The purpose of the meeting was to meet with the NCAT researchers who are working on NCHRP 09-46 to avoid any duplication of efforts. Based on the meeting an experimental plan was developed for this subtask with the objective of developing a laboratory mixing process that closely simulates the actual conditions in the field under which the RAP materials are incorporated into the mixing of HMA mixtures. Typically, field production of HMA mixtures containing RAP materials follows the process of superheating the virgin aggregates and introducing the RAP materials at ambient temperature. This process relies on the heat transfer between the superheated virgin aggregates and the RAP materials to achieve the required mixing temperature for the entire mix while in the meantime avoiding the heating/aging of the RAP binder.

The following experiment will be conducted to assess the most effective laboratory process to mix virgin aggregates and binder with RAP materials for the purpose of conducting mix design. The following three laboratory mixing methods will be evaluated:

A. Heat the virgin aggregates and RAP materials to the appropriate mixing temperature of the virgin binder grade.
B. Superheat the virgin aggregates to the appropriate temperature based on NAPA's recommendations and add the RAP materials at their dry condition.
C. Superheat the virgin aggregates to the appropriate temperature based on NAPA's recommendations and add the RAP materials at their wet condition.

The three mixing methods will be evaluated on the following materials:

- Select four field projects with the following characteristics:
    - Two projects from the east (NCAT) and two projects from the west (UNR)
    - Superpave mix designs
    - Un-modified asphalt binders
    - RAP percent greater or equal to 25%
- Obtain virgin aggregates, virgin binders, and RAP materials from the four projects: NCAT will sample the east projects and UNR will sample the west projects.
- Obtain loose HMA samples from the four projects at 5 days throughout the construction of each project: NCAT will sample the east projects and UNR will sample the west projects.
- Ship all the virgin, RAP, and loose HMA samples to the UNR laboratory. UNR will cover the cost of shipping the materials.
- The UNR researchers will conduct the following evaluations:
    - Mix laboratory samples for all four projects following the mixing procedures: A, B, and C.
    - Monitor the temperature of the total mix during the mixing process to assess the heat transfer between the virgin aggregates and RAP materials.
    - Short term oven age the laboratory produced mixtures.
    - Extract/recover and test the binder properties of the laboratory and field produced mixtures.
    - Measure the volumetric properties of the lab mixed lab compacted (LMLC) and field mixed lab compacted (FMLC) mixtures.
    - Measure the E* property of the LMLC and FMLC mixtures (subject the E* samples to 4 hours of short term aging).
- The measured properties of the LMLC mixtures prepared with mixing methods A, B, and C will be compared to the measured properties of the FMLC samples.

Under subtask E2b-5, a new comparative pavement performance site was constructed in Manitoba, Canada. The project is on provincial highway 8 between Gimli and Hnausa. The total project length is about 28 km (17 miles), with the ARC comparative pavement site accounting for 14 km (8.7 miles) of the project. The existing pavement is being recycled using a ratio of 50% RAP and 50% new material in the two bottom 50 mm lifts. The ARC sections were constructed over the 50% RAP material, using two 50 mm lifts with conventional hot-mix, 15% RAP, and 50% RAP, with no grade change for the new asphalt and 50% RAP with a grade change.

Western Research Institute is leading the field construction of the comparative sections, and the University of Nevada, Reno and University of Wisconsin, Madison are performing the laboratory testing. Materials have been collected from the project during production and testing is undergoing.

The physical properties of the sampled RAP materials as well as the mechanical properties of the virgin and RAP-containing HMA mixtures will be evaluated. The extracted/recovered RAP binder and the extracted/recovered blended asphalt binder from the RAP-containing HMA mixtures will also be evaluated for rheological properties. The testing matrix will include laboratory mixed laboratory compacted (LMLC) samples as well as field mixed laboratory compacted (FMLC) samples. Table E2b.1 summarizes the mixtures that will be evaluated in this project. The long-term performance of the field test sections will be monitored in cooperation with MIT and the data will be used to validate the design and evaluation systems developed under ARC. Preliminary data will be presented at the March meeting with the Manitoba Infrastructure & Transportation (MIT) in Manitoba, Canada.

Table E2b.5. Mixtures evaluated in the Manitoba Field Section.

Bottom Lift /North Bound Lane				**Bottom Lift /South Bound Lane**			
RAP	Oil used	St. Station	End Station	RAP	Oil used	St. Station	End Station
50%	200/300	113+80	89+50	50%	200/300	113+80	98+00
50%	150/200	89+50	62+60	50%	150/200	98+00	62+60
15%	150/200	62+60	36+80	15%	150/200	62+60	37+80
0%	150/200	36+80	13+60	0%	150/200	37+80	13+60
Top Lift /North Bound Lane				**Top Lift /South Bound Lane**			
RAP	Oil used	St. Station	End Station	RAP	Oil used	St. Station	End Station
50%	200/300	102+60	90+20	50%	200/300	101+60	88+40
50%	150/200	90+20	76+60	50%	150/200	88+40	76+60
10%	150/200	76+60	52+00	10%	150/200	76+60	52+00
15%	150/200	52+00	36+37	15%	150/200	52+00	35+70
0%	150/200	36+37	13+60	0%	150/200	35+70	13+60
3rd and 4th Lift/Northbound Lane				**3rd and 4th Lift/Southbound Lane**			
RAP	Oil used	St. Station	End Station	RAP	Oil used	St. Station	End Station
50%	200/300	102+60	90+20	50%	200/300	101+60	98+00
50%	150/200	89+50	76+60	50%	150/200	88+40	76+60
15%	150/200	52+00	36+80	15%	150/200	52+00	37+80
0%	150/200	36+37	13+60	0%	150/200	35+70	13+60

Issues Identified During the Previous Year and Their Implications on Future Work

None.

Year 4 Work Plan

Subtask E2b-1: Develop a System to Evaluate the Properties of RAP Materials

E2b-1.a: Develop a System to Evaluate the Properties of RAP Aggregates

Work for Year 4 will consist of evaluating the impact of solvent on key aggregate properties.

E2b-1.b: Develop a System to Evaluate the Properties of the RAP Binder

Work in Year 4 will focus on finalizing the verification and repeatability analysis of the RAP binder grading testing and analysis procedure developed in Year 3. Work will also focus on estimating the fracture properties of the RAP binder. The Single-Edge Notched Bending (SENB) testing protocol will be used to evaluate the fracture properties of the RAP binder. A specific testing and analysis procedure will be developed to estimate the RAP binder properties from binder and mortar testing as previously done for the PG grading.

Glass transition temperature (Tg) testing will also be carried out, and a procedure to obtain the Tg for the RAP binder will be developed. Details of SENB and Tg testing can be found in Year 3 quarterly reports for work element E2d. The materials that will be used in the experimental design are shown in table E2b.1. A complete set of testing will be conducted using these materials. The testing set consists of three replicates for each mortar and binder tested.

Table E2b.1. Materials for experimental design.

Virgin Binder Grades	**RAP Sources**
PG 58-28	University of Nevada, Reno
PG 64-22	University of Wisconsin–Madison
PG 76-22	Possible third source

Subtask E2b-2: Compatibility of RAP and Virgin Binders

Background

Determining the degree to which the RAP component of asphalt mixes with a virgin asphalt component in a RAP modified binder is a complex problem. No less daunting is determining the compatibility of the resultant asphalt/RAP blend. Fortunately, the degree of mixing and the compatibility of recycled and virgin materials should be directly related. In addition to determining compatibility, there is much to gain from determining some fundamental chemical properties of the virgin, recycled, and mixed materials. For instance, if only a fraction of the asphalt component of RAP actually mixes with the new binder, what fraction is it? Is the fraction that mixes representative of the entire RAP binder or does it contain a disproportionate amount of asphaltenes or waxes, for example? These questions can be answered using chromatographic separations developed at WRI and the results can be applied to determining RAP/Virgin asphalt compatibilities for the composition of material that is most likely to exist in a pavement.

Year 4 Work Plan

Part I: Compatibility of RAP and Virgin Binder

Research in Part I will include the extraction and characterization of RAP from three RAP sources: South Carolina, California, and Manitoba. Following RAP characterization, virgin binders from the SHRP library will be selected to blend with the RAP binders at concentrations of 0, 15, and 50%. The virgin binders selected will include one compatible asphalt and one asphalt that is less compatible based on known properties. Automated Flocculation Titrimetry (AFT) will be used to characterize the blends. This work is specifically designed to determine if incompatible RAP/Virgin blends are produced.

Part II: Determining the composition of RAP-Virgin binder mixes for compatibility analysis

Work in Part II will further characterize the three extracted RAP binders, the virgin binders and the blends from Part I.

A new method for the separation and chemical characterization of heavy oil and asphalt has recently been developed by Schabron and coworkers at WRI (Schabron 2008). This chromatographic method of separation, known as the asphaltene determinator (AD), is used to separate asphalt into four fractions based on solubility and builds off of historically significant techniques like the SARA /Corbett separations. Results obtained from the AD allow us to quickly and accurately determine the chemical composition of an asphalt in comparison to others using an automated high performance liquid chromatographic separation technique. In one hour an asphalt or an asphaltene fraction can be characterized by separation into four chemically distinct fractions defined here as heptane-soluble maltenes, cyclohexane-soluble asphaltenes, toluene-soluble asphaltenes, and dichloromethane-soluble asphaltenes. For the sake of this project the AD will be used to chemically characterize the materials being used both before and after mixing. Each asphalt (RAP and virgin) will have a different AD separation profile and the subsequent mixtures should be representative of what fraction of each asphalt is present in the extracted binder.

Part III: Characterization of the soluble/usable RAP binders

The three RAP materials used in *Part II* will be mixed with super heated aggregates to mimic what occurs at the mix plant as closely as is possible in the laboratory. The RAP materials and the new aggregate will be sized differently in order for them to be easily separated. Original RAP and virgin aggregate will be physically separated from each other and extracted. The extracted material from both will be subjected to the AD and the profiles compared to each other and with virgin samples. These comparisons will help to determine whether the initial mixing of RAP with virgin aggregate yields any appreciable loss of asphalt from the RAP and whether that loss is representative of the RAP in general or is comprised primarily of a particular fraction of the asphalt. To make this easier, the RAP will be sieved to include only 0.25” material for study and all virgin aggregate will be sieved to include only 0.5” material before mixing. By being able to evaluate the properties of the asphalt on the different aggregates we will be able to help determine if properties vary throughout the mix based on what or how much virgin aggregate is used versus RAP content. This procedure will include two different types of virgin aggregate, one limestone and one granite, to help determine whether the nature of the aggregate could affect the initial mixing process as well.

The next phase of this study will incorporate virgin binder into the mix after mixing RAP and virgin aggregate. After mixing, the virgin aggregate and RAP will be separated using the size differential and extracted using toluene-ethanol. Samples will, again, be subject to AD and their relative chemical compositions will be compared to one another as well as with the virgin material. Automated flocculation titrimetry (AFT) can be used to determine Heithaus compatibility parameters of RAP-virgin binder blends. Results from AFT will be compared with the AD results to determine corrleations. The results with and without virgin asphalt can be compared to determine if virgin asphalt increases the amount of RAP binder that is effectively combining with new binder relative to simply mixing with virgin aggregate . These results will provide a good indication of whether the materials, after mixing, are essentially uniform throughout a mix or if original RAP and virgin aggregates are significantly different such that compatibilities and long term performance might need to be evaluated independently.

In conjunction with the mixing performed above, identical RAP materials (as used above) will be extracted using cyclohexane. Cyclohexane is the solvent of choice because it has similar solvent characteristics (similar solubility parameters) to asphalt. The hypothesis is that extracting RAP with cyclohexane should give an indication of how much of the RAP asphalt actually mixes with a virgin binder and what is retained on the original RAP aggregate. AD separation profiles of cyclohexane-soluble RAP material will be compared to what is found to mix with the virgin asphalt of the RAP-Virgin binder analogue. If the AD profiles indicate that cyclohexane-soluble RAP material is similar to what is mixed with a virgin binder a new method of predicting the degree of mixing is the result. This method could be used to characterize a RAP pile of unknown origin to help determine what asphalt would be most compatible as a blend and what additives might be most advantageous.

The inclusion of rheological analyses will be ubiquitous throughout this study. Of particular interest will be to what extent the rheological properties, composition, and compatibility of these materials relate to each other. As such, DSR will be utilized on both old, new, and blended materials in order to determine the effects of mixing.

At this point of the study, there is a good indication of what comprises the RAP-virgin binder blend such that informed decisions can be made regarding material selection. Currently the accepted practice is that about 15% RAP has little or no affect on binder properties and thus, pavement performance, regardless of the source materials; between 15 and 25% RAP may require a binder grade change; and above 25% RAP, the binder grade is changed. Results from this study will indicate whether or not 15% RAP in a virgin binder will have little effect on binder compatibility, and thus performance, even for a virgin binder that is expected to be incompatible with the RAP. Similarly, the results should lend insight into whether high RAP concentrations (40%) are favorable when using an appropriate virgin asphalt for good blend compatibility. Additionally, results may indicate whether high RAP concentration with an incompatible virgin asphalt binder represents a risk for the use of high RAP content without improved characterization of the RAP-virgin asphalt mix.

Cited Reference

Schabron, J. F., and Joseph F. Rovani, Jr., 2008, On column precipitation and re-dissolution of asphaltenes in petroleum residua. *Fuel*, 87: 165-176.

Subtask E2b-3: Develop a Mix Design Procedure

Complete the experimental plan for this subtask. A follow-up plan will be developed based on the findings of this experiment and work will begin shortly after.

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

Work for year 4 will consist of collecting the fundamental properties for the field RAP mixes.

Subtask E2b-5: Field Trials

Continue to work with state agencies to construct field test sections to evaluate the performance of HMA containing high RAP contents. Continue to work on Manitoba mixes.

Table for Decision Points and Deliverables

Date	**Deliverable**	**Description**
5/15/2010	Presentation	Presentation at the RAP ETG to explain procedure and collect feedback.
5/31/2010	Journal Paper	Summarizing all testing and analysis procedure to obtain the complete PG grade of RAP binder; the paper will also include the verification and repeatability study.
8/1/2010	Journal Paper	Summarizing the developed procedures for measuring the fracture properties of the RAP binder.
8/1/2010	Journal Paper	Summarizing the test results from the Manitoba site
10/1/2010	Draft Report	Summarizing the findings of the RAP mixing experiment
12/15/2010	Presentation	Follow-up at the RAP ETG and sharing of progress.

Work Element E2c: Critically Designed HMA Mixtures

Major Findings and Status

During Year 3, the focus of the work at UNR was on subtasks E2c-1, "Identify the Critical Conditions" and E2c-2, "Conduct Mixtures Evaluations."

The 3D-Move analyses for uniform loading under braking and non-braking conditions were completed as described in the experimental plan of subtask E2c-1. The main objective of this subtask is to develop simplified recommendations to undertake the flow number test under repeated triaxial loading conditions. The protocols relative to the loading pulse duration and magnitude of the deviator (σ_d) and confining stresses (σ_c) are important testing specifications and they can significantly affect the results of the FN test. An extensive database of computed stress histories of three different asphalt pavement structures subjected to moving traffic loads at various speeds and under braking and non-braking conditions using the 3D-Move was completed.

The characteristics of the pulse were determined by best-fitting a haversine wave shape for the equivalent triaxial deviator stress pulse that was calculated from the octahedral shear stress (τ_{oct}) at 2-inch below pavement surface under a moving 18-wheel truck at different speeds and temperatures. It was found that the haversine pulse duration is a function of the vehicle speed and pavement temperature. In all evaluated cases, neither pavement thickness nor mixture properties significantly impacted the pulse duration at 2 inches below the pavement surface. Prediction equations for estimating the anticipated deviator pulse duration as a function of pavement temperature, and vehicle speed have been developed with fitting parameters (R^2) of 0.983 and 0.999 for the non-braking and braking conditions, respectively. Figure E2c.1 shows the predicted versus the calculated pulse duration for non-braking condition.

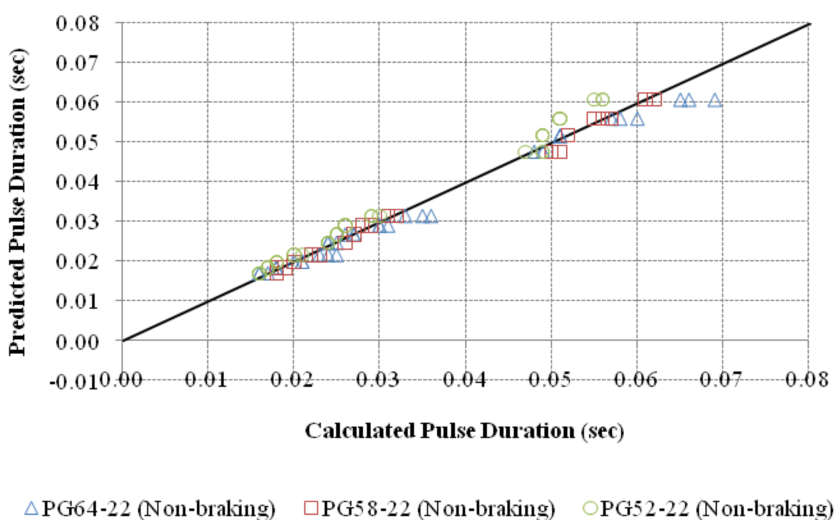

Figure E2c.1. Predicted versus calculated pulse duration – without braking condition

The magnitude of σ_d and σ_c were determined by converting the stress tensor computed in the HMA layer at 2 inch below pavement surface under a moving 18-wheel truck using the octahedral normal and shear stresses. The amplitude of the equivalent triaxial deviator and confining stresses were found to be highly affected by the mixture's dynamic modulus, |E*|, and vehicle speed and independent of the pavement structure. Under no braking conditions, the magnitude of the deviator and confining stresses ranged from 69-102 psi and 27-47 psi, respectively. In the case of braking, the magnitude of the deviator and confining stresses ranged from 108-132 psi and 30-47 psi, respectively. On average, the imposed additional shear stresses generated by the braking of the vehicle at stopping areas resulted in a 40% increase in the deviator stress (from 85 to 119 psi) and a slight increase (5%) in the confining stress. Additionally, higher deviator stresses coupled with similar or lower confining stresses were observed in the 4" HMA layer when compared to the 8" HMA layer.

Generalized equations for estimating the triaxial deviator and confining stresses for a given pavement structure and temperature and under a given vehicle speed have been provided. Overall, good correlations between the calculated and predicted stresses were found. Figure E2c.2 shows the predicted versus the computed maximum deviator and confining stresses for the three evaluated HMA mixes. Two papers have been submitted for publication to present the findings of subtask E2c.1.

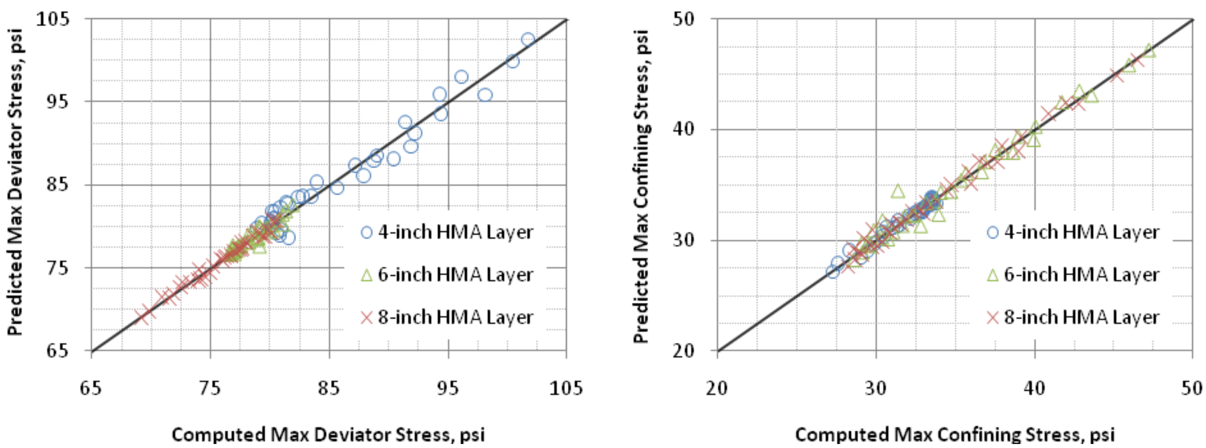

Figure E2c.2. Predicted versus computed maximum deviator and confining stress

An excel spreadsheet that incorporates the findings of subtasks E2c.1 was developed. The spreadsheet (figure E2c.3) helps identify the repeated load triaxial / flow number test conditions at a specified temperature. The following inputs are needed in order to determine the testing conditions:

- Selection of ***Braking*** (e.g. at intersection ...) or ***Non-Braking*** condition.
- ***Effective pavement temperature*** in °C at 2 inch below pavement surface.
- ***Vehicle operating speed*** in mph.

- ***Asphalt mixture stiffness*** in ksi at the effective pavement temperature and loading frequency at 2 inch below the pavement surface. A given/selected stiffness can be provided or it can be calculated using the dynamic modulus parameters (including shift factors) for the determined loading time and temperature.
- ***Asphalt layer thickness*** in inches.

The example in figure E2c.3 is for a PG64-22 dense graded asphalt mixture where the effective pavement temperature at 2 inch below pavement surface is 60°C and the vehicle operational speed is 20 mph. The dynamic modulus data was used to determine the stiffness of the mix. Figure E2c.3 shows that to simulate a truck travelling at 20 mph the following testing conditions needs to be implemented in the laboratory for an effective pavement temperature of 60°C:

- Loading Pulse Time: 0.05 seconds
- Deviator Stress: 78 psi
- Confining Stress: 32 psi

Repeated Load Triaxial Loading Conditions — Date: 04/30/09

Project:	ARC - Critical Mix	**Binder Source:**	Paramount Asphalt	**Aggregate Source:**	Granite - Lockwood
Mix Design:	Lockwood-64-22	**Binder Grade:**	PG64-22	**Other:**	

Step 1: Loading Pulse Time at 2-inch Below Pavement Surface

Select Braking Condition: No Braking
Select Effective Pavement Temperature (°C): 60
Select Operating Speed (mph): 20

$\log(pulse\ time) = -0.6654 - 0.00353(T) - 0.0236(S) + 0.00015414(S^2)$

Loading Pulse Time at 2-inch Below Pavement Surface (seconds)	0.052

Step 2: Asphalt Mixture Stiffness

Select Method for Asphalt Mixture Stiffness: Dynamic Modulus Data

Dynamic Modulus Data (Ksi): 52.2

$\log(|E^*|) = \delta + \alpha/[1+\exp(\beta+\gamma\times\log t_r)]$ $\quad \text{Log}(a_T) = a\times T^2 + b\times T + c$ Note: |E*| in ksi and Temperature in °F

δ	α	β	γ	a	b	c
0.2697	3.0491	-1.5350	0.5640	0.0003	-0.1225	7.1458

Step 3: Deviator and Confining Stresses at 2 inches Below Pavement Surface

Select Asphalt Layer Thickness (inches): 6.0

Deviator Stress at 2-inch Below Pavement Surface (psi)	78
Confining Stress at 2-inch Below Pavement Surface (psi)	32

Step 4: Recommended Testing Conditions

Loading Pulse Time at 2-inch Below Pavement Surface:	**0.052 seconds**
Deviator Stress at 2-inch Below Pavement Surface:	**78 psi**
Confining Stress at 2-inch Below Pavement Surface:	**32 psi**

Figure E2c.3. Snapshot for triaxial testing loading conditions spreadsheet

Under subtask E2c.2, an investigation was carried out in an attempt to evaluate the applicability of the recommended pulse time and deviator and confining stresses. Repeated load flow number testing was performed for the WesTrack Cell 55 plant mixture. The laboratory determined critical temperature showed consistency with the rutting field performance of the mix where an increase in rutting was observed at a given ESALs range along with an increase in the maximum pavement temperature during seven consecutive days from 40°C to 46°C.

Additionally, the permanent deformation characteristics of three laboratory-produced mixtures (i.e. PG64-22, PG58-22, and PG52-22 mix) were evaluated under subtask E2c-2. The flow number was evaluated at different temperatures and three air voids levels: 7, 4, and 2%.

<u>Issues Identified During the Previous Year and Their Implications on Future Work</u>

None

Year 4 Work Plan

Subtask E2c-1: Identify the Critical Conditions

Work for Year 4 will consist of completing the 3D-Move analysis for non-uniform loading conditions that are described in the experimental plan for this subtask.

Subtask E2c-2: Conduct Mixtures Evaluations

Work for Year 4 will consist of evaluating the permanent deformation characteristics of laboratory-produced and field-produced mixtures under the testing conditions identified in Subtask E2c-1. The impact of air-voids, gradation, and binder type on the asphalt mixture critical temperature will be evaluated.

Subtask E2c-3: Develop a Simple Test

Work for Year 4 will consist of developing an experimental plan for this subtask to investigate the possibility of developing a simpler version of the RLT test.

Subtask E2c-4: Develop Standard Test Procedure

No work on this subtask is planned for Year 4.

Subtask E2c-5: Evaluate the Impact of Mix Characteristics

No work on this subtask is planned for Year 4.

Table for Decision Points and Deliverables

Date	Deliverable	Description
8/31/10	Journal Paper	Regarding the testing of the laboratory produced and field produced mixes.

Work Element E2d: Thermal Cracking Resistant Mixes for Intermountain States

Major Findings and Status

In Year 3, under subtask E2d-1, the air and pavement temperature profiles analyses for the NATC WesTrack project in Nevada and the identified LTPP Seasonal Monitoring Pavement (SMP) sections were completed and a draft report that summarizes the findings was prepared.

Under subtask E2d-3, significant improvements to the dilatometric testing system of binders were implemented. New dilatometric cells were designed, as shown in figure E2d.1, and o-rings with military specifications were selected to minimize the effect of rubber contraction on the test results. Figure E2d.2 shows an example of the dilatometric tests for two binders with different glass transition temperatures (Tg). The Tg and the coefficient of thermal contraction below and above the Tg obtained for these binders are consistent with measurements reported in the literature (Bahia 1991).

Figure E2d.1. New dilatometric testing system.

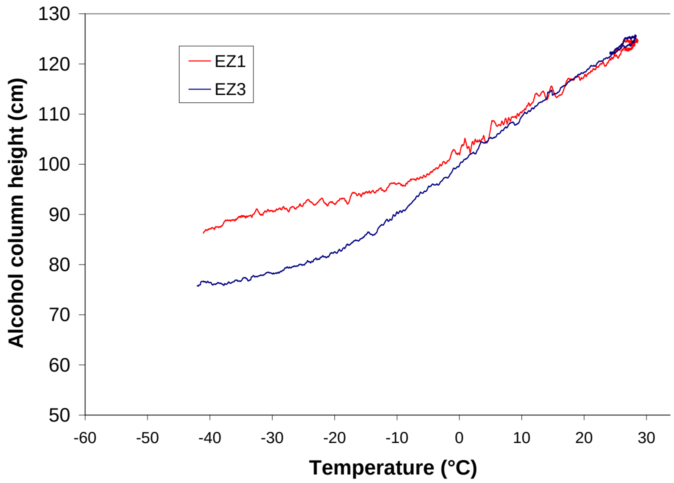

Figure E2d.2. Tg measurements for two binders.

A procedure for testing the Tg and the coefficient of thermal expansion/contraction for mixtures was implemented. Specimens for Tg testing are obtained by gluing cores extracted from gyratory-compacted cylinders. The research group found that the effect on the experimental results of the epoxy used in gluing is minimal.

A Single-Edge Notched Bending (SENB) testing system was successfully implemented for testing fracture properties of asphalt binders. The ductile-to-brittle transition of binders at low temperatures is detected with the SENB system. The research team encountered difficulties controlling the displacement rate for mastics testing (i.e., stiffer material). The step motor used in the SENB device does not provide sufficient torque to maintain a constant displacement rate. Preliminary results in Year 3 indicated that the SENB device can be used to perform fracture tests of asphalt mixtures at low temperatures. Asphalt mixtures prepared with granite and limestone were successfully tested with the system.

Fourier transform infrared (FTIR) spectroscopy tests for measuring the carbonyl peak growth were performed on a group of binders provided by the University of Nevada, Reno.

Under Subtask E2d-3.a, the UNR team continued the long-term oven aging experiment and measured the mass loss and gain of the various asphalt binders. Additionally, the aged asphalt binders were tested for rheological properties.

Under Subtask E2d-3.b and c, significant progress has been made in sample production. All of the mix designs for both tasks are complete, and nearly half of the samples have completed the laboratory aging. The remaining half is at various points throughout the aging process. Approximately third of the samples have been tested for E* in compression. Further implementation is required for the E* in tension testing.

Following the mix testing, the binder is extracted and recovered for DSR and FTIR testing. This testing has begun, with a few results being available. A brief outline of the work plan was presented at TRB 2010 in January.

<u>Issues Identified During the Previous Year and Their Implications on Future Work</u>

The experimental plan for Tg of binders and mixtures is delayed due to difficulties during the design and implementation of the testing device. The research team expects to finish the experimental matrix for both binders and mixtures by the end of Year 4.

The SENB device cannot provide enough torque to maintain a constant displacement rate during mastics testing. The research team will focus on defining a mastic specimen geometry that will eliminate this issue. To reflect the actual progress of this work element, the 5-year and Year 4 Gantt charts have been updated.

<u>Year 4 Work Plan</u>

Subtask E2d-1: Identify Field Sections

No work on this subtask is planned for Year 4.

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

Work for Year 4 will consist of identifying the LTPP sections that are located in proximity to the LTPP SMP sections and have materials available in the MRL. Once the sections are identified materials will be sampled from the various pavement sites to conduct the experimental plan of subtask E2d-2. Sections from the WesTrack project will also be identified. Additionally, the

MnROAD test track will be checked for pavement sections that are experiencing thermal cracking.

Subtask E2d-3: Identify an Evaluation and Testing System

The research team plans to complete the testing matrix for Tg and thermal expansion/contraction of both binders and mixtures. Adjustments to the SENB procedure will be made to run tests on mastic specimens. The team also plans to implement the Thermal Stress Restrained Specimen Test (TSRST) into a unified system that characterizes both binders and mixtures for thermal cracking. The final device will test binders and mixtures for Tg, coefficients of thermal expansion/contraction, and TSRST. The proposed test matrices for Tg testing of binders and mixtures are presented in tables E2d.1 and E2d.2, respectively. Tables E2d.3 and E2d.4 show the proposed testing program for binders and mastics using the SENB, respectively.

Table E2d.1. Proposed Tg tests of asphalt binders.

Variables	**Factors**	**Description**
Binder	1	FH 64-22
Cooling Rate	2	1°C and 10 °C/min
Modification	4	Styrene-butadiene-styrene (SBS), Elvaloy, polyphosphoric acid (PPA), warm mix additives
Replicates	3	To determine repeatability of testing and for statistical analysis
Total	**24**	

Table E2d.2. Proposed Tg tests of asphalt mixtures.

Variables	**Factors**	**Description**
Cooling Rate	2	1 °C and 10 °C/min
Binder	3	FH 64-22, FH 64-22 with SBS, FH 64-22 with warm mix additives
Aggregates	2	Limestone and granite
Replicates	2	To determine repeatability of testing
Total	**24**	

Table E2d.3. Proposed SENB tests of asphalt binders.

Variables	**Factors**	**Description**
Binder	1	FH 64-22
Temperature	3	-6 °C, -12 °C and -18 °C
Modification	4	SBS, Elvaloy, PPA, warm mix additives
Replicates	3	To determine repeatability of testing and for statistical analysis
Total	**36**	

Table E2d.4. Proposed SENB tests of mastics.

Variables	**Factors**	**Description**
Temperature	2	-6 °C and -12 °C
Binder	3	FH 64-22, FH 64-22 with SBS, FH 64-22 with warm mix additives
Fillers	2	To be defined
Replicates	3	To determine repeatability of testing
Total	**36**	

E2d-3.a: Evaluate Long-Term Aging of Asphalt Binders Subjected to Free Atmospheric Oxygen

Continue the experiment to evaluate the aging characteristics (oxidation and hardening kinetics) of asphalt binders when aged in forced convection (horizontal airflow) ovens. The materials used in the experimental design are shown in Table E2d.5

Table E2d.5. Materials for long-term aging experiment (E2d-3.a)

Asphalt binder	Additives
PG64-22	none
	10% hydrated lime by weight
	20% hydrated lime by weight
	3% SBS polymer
PG64-28	Polymer modified

E2d.3.b: Evaluate the Impact of Aggregate Absorption on the Aging of the Asphalt Binder

Continue the work on this subtask according to the following experimental plan.

Table E2d.6. Experimental plan for aggregate absorption experiment (E2d-3.b)

<table>
<tr><th>Source (Mineralogy)</th><th>Gradation</th><th>Aggregate Absorption</th><th>Binder</th><th>Film Thickness</th><th>Air Void</th><th>Binder Content</th><th>Opt Binder</th></tr>
<tr><td rowspan="4">Lockwood, NV (Rhyolite)</td><td rowspan="2">Int.</td><td rowspan="4">2.71</td><td rowspan="2">64-22</td><td>Var.</td><td>7</td><td>4.5</td><td rowspan="2">5.18</td></tr>
<tr><td>9</td><td>7</td><td>5.38</td></tr>
<tr><td rowspan="2">Int.</td><td rowspan="2">64-28</td><td>Var.</td><td>7</td><td>4.5</td><td rowspan="2">5.11</td></tr>
<tr><td>9</td><td>7</td><td>5.22</td></tr>
<tr><td rowspan="4">Colorado (Granite/ Gneiss)</td><td rowspan="2">Int.</td><td rowspan="4">0.87</td><td rowspan="2">64-22</td><td>Var.</td><td>7</td><td>4.5</td><td rowspan="2">4.36</td></tr>
<tr><td>9</td><td>7</td><td>3.61</td></tr>
<tr><td rowspan="2">Int.</td><td rowspan="2">64-28</td><td>Var.</td><td>7</td><td>4.5</td><td rowspan="2">4.4</td></tr>
<tr><td>9</td><td>7</td><td>3.65</td></tr>
<tr><td rowspan="4">California (Var./Gravel)</td><td rowspan="2">Int.</td><td rowspan="4">4.48</td><td rowspan="2">64-22</td><td></td><td></td><td></td><td rowspan="2">6.65</td></tr>
<tr><td>9</td><td>7</td><td>7.05</td></tr>
<tr><td rowspan="2">Int.</td><td rowspan="2">64-28</td><td></td><td></td><td></td><td rowspan="2">TBD</td></tr>
<tr><td>9</td><td>7</td><td>TBD</td></tr>
</table>

Activities on the mixtures will include continuation of sample aging in ovens, E* testing in compression, and implementation of E* tension testing. Following the mixture tests, the samples will then be extracted and recovered for DSR and FTIR testing.

The E* testing in tension requires modification to the current software package being used, validation of new procedure, and will include initial testing for E* in tension during year 4.

E2d-3.c: Evaluate the Impact of HMA Mix Characteristics on the Aging of the Asphalt Binder

With the mix designs completed, the mixture and asphalt binder activities will closely resemble the aggregate absorption task (E2d-3.b). The current experimental plan including the selected aggregate sources for this subtask is in accordance with the following Table E2d.X2.

Table E2d.7. Experimental plan for mix characteristics experiment (E2d-3.c)

Source	Gradation	Binder	Film Thickness	Air Voids
Lockwood, NV (Rhyolite)	Int.	64-28	9	4
				7
				11
	Fine	64-28	9	7
Utah (Var./Gravel)	Int.	64-28	9	4
				7
				11
	Fine	64-28	9	7
California (Var./Gravel)	Int.	64-22	9	4
				7
				11
	Fine	64-22	~9	7
WesTrack	Coarse (Andesite)	64-22	9.21	4
				7
				11
	Fine (Gravel/Weath. And.)	64-22	9	7

Subtask E2d-4: Modeling and validation of the Developed System

This task focuses on development of a program for the prediction of critical cracking temperatures using the input variables measured from the proposed tests procedures (e.g., TSRST, Tg, SENB). The UNR research team leads the efforts associated with this subtask. The University of Wisconsin–Madison research team will provide feedback and input during software development.

The UW–Madison research team will validate the developed system based on two approaches. First, thermal cracking performance of national pavement sites identified in the LTTP database will be collected and available materials will be tested using the proposed procedures. Comparisons between the field and laboratory performance will be obtained based on statistical analysis. Second, finite element modeling of thermal loading of different asphalt mixtures will be performed to determine the effects of several factors on the development of thermal stresses and strains in asphalt mixtures. Among the factors to be investigated include cooling rate, aggregate distribution, and the Tg of the components.

Subtask E2d-5: Develop a Standard

A preliminary standard prepared in AASHTO format will be developed for Tg measurements of asphalt binder and mixtures.

Table for Decision Points and Deliverables

Date	**Deliverable**	**Description**
08/31/10	Journal Paper	Thermal cracking characterization of binders and mixtures by means of Tg measurements and the TSRST.
08/31/10	Journal Paper	Field validation of testing procedure and model using LTPP sections' performance.
08/31/10	Journal Paper	Environmental Conditions in the Intermountain Region of the United States
01/11	Presentation	Update on the development of the standard for thermal cracking at TRB, ETG or similar venue.
02/11	Presentation	Update on field validation to ETG (Binder or Mixture).

Cited References

Bahia, H. U., 1991, Low Temperature Isothermal Physical Hardening of Asphalt Cements, Ph.D. thesis, The Pennsylvania State University, College Station, PA.

Work Element E2e: Design Guidance for Fatigue and Rut Resistant Mixtures

Major Findings & Status

In National Cooperative Highway Research Program (NCHRP) Projects 9-25 and 9-31, models relating mixture composition to engineering and performance properties were developed. Specific models were developed for:

- Dynamic modulus
- Rutting resistance
- Fatigue cracking resistance
- Permeability

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.

In Year 1, the NCHRP Project 9-25 and 9-31 composition to engineering property models and the data included in their development were reviewed and specific improvements were identified as summarized in Table E2e.1. Preliminary experimental designs for each of the recommend improvements were developed and presented in the Year 2 work plan. Preliminary experimental designs were developed for the Hirsch Model, the Resistivity Model, and the Continuum Damage Fatigue Model. Further development of the Permeability Model involves supplementing the current permeability database with published results from other researchers. It was planned that the experiments would be initiated in Year 2 of the project, however, testing was delayed to allow the experiment designs to be modified to incorporate the core asphalts, aggregates, and modifiers in the testing. In Year 3, the preliminary experimental designs were modified to incorporate the core materials.

Table E2e.1. Summary of recommended improvements to the NCHRP Project 9-25 and 9-31 composition to engineering property models.

Model	Recommended Improvement	Approach
Hirsch Model for Dynamic Modulus	Curing time	Laboratory Experiment
	Low stiffness stress dependency	
	Limiting maximum modulus	
Resistivity Model for Rutting Resistance	Incorporate MSCR binder characterization	Laboratory Experiment
Continuum Damage Fatigue Model	Healing	Laboratory Experiment
	Damage tolerance	
Permeability	Expand data set	Data from Literature
	Aggregate size effect	

<u>Year Four Work Plan</u>

Subtask E2e-2: Design and Execute Laboratory Testing Program

Laboratory testing will be initiated in Year 4 and will continue into Year 5.

Subtask E2e-3: Perform Engineering and Statistical Analysis to Refine Models

Work on this task will be initiated in Year 4 as data from Subtask E2e-2 become available.

Subtask E2e-4: Validate Refined Models

None. Work on this subtask has been delayed to Year 5.

Subtask E2e-5: Prepare Design Guidance

None. Work on this subtask was planned for Year 5.

Table for Decision Points & Deliverables

Date	**Deliverable**	**Description**
9/1/2010	Journal Paper	Summarizing selected improved models
9/1/2011	Draft Report	Draft report on findings from subtasks E2e-2 and E2e-3
9/1/2011	Final Report	Final report on findings from subtasks E2e-2 and E2e-3
9/1/2011	Presentation	At TRB or AAPT of 9/1/2010 journal paper.
9/1/2011	Journal Paper	Summarizing results of model validation efforts
12/31/2011	Models	Improved composition to engineering property models • Hirsch Model for Dynamic Modulus • Resistivity Model for Rutting Resistance • Continuum Damage Fatigue Model • Permeability
Q1 2012	Draft Report	Draft report on entire Task E2e
Q1 2012	Final Report	Final report on entire Task E2e
Q1 2012	Presentation	At TRB or AAPT of 9/1/2011 journal paper

Table of Decision Points and Deliverables for the Engineered Materials Program Area

Work Element	Date	Deliverable	Description
E1a	07/31/10	Journal Paper	Viscoelastic characterization of field-aged asphalt mixtures
E1a	09/30/10	Journal Paper	Viscoelastic anisotropic compressive characterization of viscoplastic damage in asphalt mixtures
E1a	09/30/10	Journal Paper	Fatigue damage and plasticity evaluation of asphalt mixtures with dissipated pseudo-strain energy
E1a	11/30/10	Journal Paper	Bond energy and dissipated pseudo-strain energy in moisture damage
E1a	11/30/10	Journal Paper	Self-consistent micromechanics model of binder-mastic relations
E1a	07/15/10	Presentation	Presentation of results of E1a-3 at the Pavement Performance Prediction Symposium in Laramie, Wyoming
E1a	07/15/10	Presentation	Presentation of results of E1a-1 and E1a-2 at the Pavement Performance Prediction Symposium in Laramie, Wyoming
E1a	01/31/11	Presentation	Presentation of results of E1a-1 and E1a-2 at the Transportation Research Board Meeting
E1a	01/31/11	Presentation	Presentation of results of E1a-3 at the Transportation Research Board Meeting
E1a	01/31/11	Presentation	Presentation of results of E1a-4 at the Transportation Research Board Meeting
E1a	03/31/11	Model and Algorithm	Providing the model and algorithm for testing and analysis of undamaged asphalt mixtures in tension and compression
E1b-1	04/10	Decision Point	Binder and mastic testing conducted during Q4 of Year 3 is expected to determine initial mixture combinations with newly included binder.
E1b-1	08/10	Presentation	Presentation on data collected to date and potential correlation between three phases to provide feedback in preparation for journal paper.
E1b-1	11/10	Journal Paper	Journal paper to present possible model that accounts for multiple modifiers.
E1b-1	02/11	Decision Point	Determine any additional experimental testing needed to complete or justify model.
E1b-2	09/10	Journal Paper	Conference paper on the use of indentation test for characterization of asphalt binders.
E1b-2	01/11	Presentation	Presentation summarizing implementation of indentation tests for rheological characterization of asphalt binders.
E1b-2	03/11	Draft Report	Report on finite element simulations of the indentation test and correlations with DSR results.
E1c-1	05/10	Decision Point	Details of aggregate moisture experiment.
E1c-1	05/10	Presentation	Offer an update at the WMA ETG.
E1c-1	08/10	Journal Paper	Submit paper to TRB or AAPT on findings from compaction and mechanical testing of WMA.

Table of Decision Points and Deliverables for the Engineered Materials Program Area (con't)

Work Element	Date	Deliverable	Description
E1c-2	4/30/2010	Draft Report	Emulsion Evaluation: Literature review, testing protocols and preliminary experimental results for emulsion construction properties. Experimental plan and testing protocols for the evaluation of emulsion residues will also be submitted.
E1c-2	8/1/2010	Journal Paper (2)	Topics to be published include "Using the RV to Evaluate Emulsion Viscosity" and "Performance Properties of Emulsions."
E1c-2	10/29/2010	Draft Report	Sweep Test Imaging: Literature review and preliminary experimental design.
E1c-2	01/10/2011	Presentation (2)	Presentations related to construction and performance properties.
E1c-2	03/31/2011	Final Report	Final report on the development of performance selection guidelines.
E2a	07/10	Presentation	Presentation will be made on the testing progress to date.
E2a	08/10	Journal Paper	A journal paper will be prepared and submitted for publication on the data collected to date.
E2b	5/15/2010	Presentation	Presentation at the RAP ETG to explain procedure and collect feedback.
E2b	5/31/2010	Journal Paper	Summarizing all testing and analysis procedure to obtain the complete PG grade of RAP binder; the paper will also include the verification and repeatability study.
E2b	8/1/2010	Journal Paper	Summarizing the developed procedures for measuring the fracture properties of the RAP binder.
E2b	8/1/2010	Journal Paper	Summarizing the test results from the Manitoba site
E2b	10/1/2010	Draft Report	Summarizing the findings of the RAP mixing experiment
E2b	12/15/2010	Presentation	Follow-up at the RAP ETG and sharing of progress.
E2c	8/31/10	Journal Paper	Regarding the testing of the laboratory produced and field produced mixes.
E2d	08/31/10	Journal Paper	Thermal cracking characterization of binders and mixtures by means of Tg measurements and the TSRST.
E2d	08/31/10	Journal Paper	Field validation of testing procedure and model using LTPP sections' performance.
E2d	08/31/10	Journal Paper	Environmental Conditions in the Intermountain Region of the United States
E2d	01/11	Presentation	Update on the development of the standard for thermal cracking at TRB, ETG or similar venue.
E2d	02/11	Presentation	Update on field validation to ETG (Binder or Mixture).

Table of Decision Points and Deliverables for the Engineered Materials Program Area (con't)

Work Element	Date	Deliverable	Description
E2e	9/1/2010	Journal Paper	Summarizing selected improved models
E2e	9/1/2011	Draft Report	Draft report on findings from subtasks E2e-2 and E2e-3
E2e	9/1/2011	Final Report	Final report on findings from subtasks E2e-2 and E2e-3
E2e	9/1/2011	Presentation	At TRB or AAPT of 9/1/2010 journal paper.
E2e	9/1/2011	Journal Paper	Summarizing results of model validation efforts
E2e	12/31/2011	Models	Improved composition to engineering property models • Hirsch Model for Dynamic Modulus • Resistivity Model for Rutting Resistance • Continuum Damage Fatigue Model • Permeability
E2e	Q1 2012	Draft Report	Draft report on entire Task E2e
E2e	Q1 2012	Final Report	Final report on entire Task E2e
E2e	Q1 2012	Presentation	At TRB or AAPT of 9/1/2011 journal paper

Engineered Materials Year 4	Year 4 (4/2010-3/2011)												Team
	4	5	6	7	8	9	10	11	12	1	2	3	
(1) High Performance Asphalt Materials													
E1a: Analytical and Micro-mechanics Models for Mechanical behavior of mixtures													TAMU
E1a-1: Analytical Micromechanical Models of Binder Properties				P						P			
E1a-2: Analytical Micromechanical Models of Modified Mastic Systems				P						P			
E1a-3: Analytical Models of Mechanical Properties of Asphalt Mixtures				P, JP		JP (2)		JP (2)		P		M&A	
E1a-4: Analytical Model of Asphalt Mixture Response and Damage										P			
E1b: Binder Damage Resistance Characterization													UWM
E1b-1: Rutting of Asphalt Binders													
E1b-1-1: Literature review													
E1b1-2: Select Materials & Develop Work Plan													
E1b1-3: Conduct Testing	DP												
E1b1-4: Analysis & Interpretation								JP					
E1b1-5: Standard Testing Procedure and Recommendation for Specifications					P						DP		
E1b-2: Feasibility of determining rheological and fracture properties of asphalt binders and mastics using simple indentation tests (modified title)													UWM
E1b-2i. Literature Review													
E1b-2ii. Proposed SuperPave testing modifications													
E1b-2iii. Preliminary testing and correlation of results						JP							
E1b-2iv. Feasibility of using indentation tests for fracture and rheological properties										P		D	
E2a: Comparison of Modification Techniques													UWM
E2a-1: Identify modification targets and material suppliers													
E2a-2: Test material properties				P									
E2a-3: Develop model to estimate level of modification needed and cost index													
E2a-4: Write asphalt modification guideline/report on modifier impact over binder properties					JP								
E2c: Critically Designed HMA Mixtures													UNR
E2c-1: Identify the Critical Conditions													
E2c-2: Conduct Mixtures Evaluations					JP								
E2c-3: Develop a Simple Test													
E2c-4: Develop Standard Test Procedure													
E2c-5: Evaluate the Impact of Mix Characteristics													
E2d: Thermal Cracking Resistant Mixes for Intermountain States													UWM/UNR
E2d-1: Identify Field Sections													
E2d-2: Identify the Causes of the Thermal Cracking													
E2d-3: Identify an Evaluation and Testing System					JP					P			
E2d-4: Modeling and Validation of the Developed System					JP						P		
E2d-5: Develop a Standard													
E2e: Design Guidance for Fatigue and Rut Resistance Mixtures													AAT
E2e-1: Identify Model Improvements													
E2e-2: Design and Execute Laboratory Testing Program													
E2e-3: Perform Engineering and Statistical Analysis to Refine Models						JP							
E2e-4: Validate Refined Models													
E2e-5: Prepare Design Guidance													
(2) Green Asphalt Materials													
E2b: Design System for HMA Containing a High Percentage of RAP Material		P, JP			JP				P				UNR
E2b-1: Develop a System to Evaluate the Properties of RAP Materials													
E2b-2: Compatibility of RAP and Virgin Binders													
E2b-3: Develop a Mix Design Procedure							D						
E2b-4: Impact of RAP Materials on Performance of Mixtures													
E2b-5: Field Trials					JP								
E1c: Warm and Cold Mixes													UWM
E1c-1: Warm Mixes													
E1c-1i: Effects of Warm Mix Additives on Rheological Properties of Binders													
E1c-1ii. Effects of Warm Mix Additives on Mixture Workability and Stability					JP								
E1c-1iii. Mixture Performance Testing		DP, P											
E1c-1iv. Develop Revised Mix Design Procedures													
E1c-1v. Field Evaluation of Mix Design Procedures and Performance Recommendations													
E1c-2: Improvement of Emulsions' Characterization and Mixture Design for Cold Bitumen Applications													UWM/UNR
E1c-2i: Review of Literature and Standards							D						
E1c-2ii: Creation of Advisory Group													
E1c-2iii: Identify Tests and Develop Experimental Plan	D												
E1c-2iv. Develop Material Library and Collect Materials.													
E1c-2-v. Conduct Testing Plan					JP					P			
E1c-2-vi. Develop Performance Selection Guidelines					JP					P		F	
E1c-2-vii. Validate Performance Guidelines													
E1c-2-viii. Develop CMA Mix Design Guidelines													
E1c-2ix. Develop CMA Performance Guidelines													

Deliverable codes
D: Draft Report
F: Final Report
M&A: Model and algorithm
SW: Software
JP: Journal paper
P: Presentation
DP: Decision Point

Deliverable Description
Report delivered to FHWA for 3 week review period.
Final report delivered in compliance with FHWA publication standards
Mathematical model and sample code
Executable software, code and user manual
Paper submitted to conference or journal
Presentation for symposium, conference or other
Time to make a decision on two parallel paths as to which is most promising to follow througjh

Work planned
Work completed
Parallel topic

Engineered Materials Year 2 - 5	Year 2 (4/08-3/09)				Year 3 (4/09-3/10)				Year 4 (04/10-03/11)				Year 5 (04/11-03/12)				Team
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	
(1) High Performance Asphalt Materials																	
E1a: Analytical and Micro-mechanics Models for Mechanical behavior of mixtures																	TAMU
E1a-1: Analytical Micromechanical Models of Binder Properties				P, JP	JP	P	P	JP		P		P	P	JP	D, JP	F	
E1a-2: Analytical Micromechanical Models of Modified Mastic Systems				P, JP	JP	P	P			P		P	P	JP	D	F, SW, M&A	
E1a-3: Analytical Models of Mechanical Properties of Asphalt Mixtures	P	P,JP		P, JP	JP	P	P	M&A		P, JP(3)	JP (2)	P, M&A	P	JP(2)	D, JP	F, SW, M&A	
E1a-4: Analytical Model of Asphalt Mixture Response and Damage				P, JP	JP	P	P					P	P		D	F, SW, M&A	
E1b: Binder Damage Resistance Characterization																	UWM
E1b-1: Rutting of Asphalt Binders																	
E1b-1-1: Literature review																	
E1b1-2: Select Materials & Develop Work Plan	DP, P		P														
E1b1-3: Conduct Testing			P			JP		P	DP								
E1b1-4: Analysis & Interpretation		JP	P	JP		JP		P			JP						
E1b1-5: Standard Testing Procedure and Recommendation for Specifications										P		DP	P	D	JP	F	
E1b-2: Feasibility of Determining rheological and fracture properties of asphalt binders and mastics using simple indentation tests (modified title)																	
E1b-2i. Literature Review						D											
E1b-2ii. Proposed SuperPave testing modifications or new testing devices						P											
E1b-2iii. Preliminary testing and correlation of results								D		JP							
E1b-2iv. Feasibility of using indentation tests for fracture and rheological properties						JP		P				P, D	F				
E2a: Comparison of Modification Techniques																	UWM
E2a-1: Identify modification targets and material suppliers				DP		DP											
E2a-2: Test material properties								P		P							
E2a-3: Develop model to estimate level of modification needed and cost index																	
E2a-4: Write asphalt modification guideline/report on modifier impact over binder properties										JP							
E2c: Critically Designed HMA Mixtures																	UNR
E2c-1: Identify the Critical Conditions		JP		D, F		JP	D	F									
E2c-2: Conduct Mixtures Evaluations								D		JP							
E2c-3: Develop a Simple Test													D, F	JP			
E2c-4: Develop Standard Test Procedure													D, F				
E2c-5: Evaluate the Impact of Mix Characteristics																D, F	
E2d: Thermal Cracking Resistant Mixes for Intermountain States																	UWM/UNR
E2d-1: Identify Field Sections			D, F	D, F	D	F											
E2d-2: Identify the Causes of the Thermal Cracking																	
E2d-3: Identify an Evaluation and Testing System					DP	JP	DP, D			JP		P	JP				
E2d-4: Modeling and Validation of the Developed System										JP		P				D, F	
E2d-5: Develop a Standard																D, F	
E2e: Design Guidance for Fatigue and Rut Resistance Mixtures																	AAT
E2e-1: Identify Model Improvements																	
E2e-2: Design and Execute Laboratory Testing Program																	
E2e-3: Perform Engineering and Statistical Analysis to Refine Models										JP				P, D, F			
E2e-4: Validate Refined Models														JP			
E2e-5: Prepare Design Guidance															M&A	P,D,F	
(2) Green Asphalt Materials																	
E2b: Design System for HMA Containing a High Percentage of RAP Material																	UNR
E2b-1: Develop a System to Evaluate the Properties of RAP Materials		JP		P	D	D, F	D		P, JP	JP	P						
E2b-2: Compatibility of RAP and Virgin Binders														D, F	JP		
E2b-3: Develop a Mix Design Procedure								D			D			D, F	JP		
E2b-4: Impact of RAP Materials on Performance of Mixtures																D, F	
E2b-5: Field Trials										JP						D, F	
E1c: Warm and Cold Mixes																	
E1c-1: Warm Mixes																	
E1c-1i: Effects of Warm Mix Additives on Rheological Properties of Binders.																	UWM
E1c-1ii. Effects of Warm Mix Additives on Mixture Workability and Stability		P	D	F,DP						JP							UWM
E1c-1iii. Mixture Performance Testing						JP		P, DP	DP, P								UW/UNR
E1c-1iv. Develop Revised Mix Design Procedures																	UW/UNR
E1c-1v. Field Evaluation of Mix Design Procedures and Performance Recommendations														JP	D	P,F	UW/UNR
E1c-2: Improvement of Emulsions' Characterization and Mixture Design for Cold Bitumen Applications																	UWM
E1c-2i: Review of Literature and Standards		JP, P, D	F		D1	D3		D6			D						
E1c-2ii: Creation of Advisory Group																	
E1c-2ii: Identify Tests and Develop Experimental Plan				P, DP	D1		D4		D								
E1c-2iv. Develop Material Library and Collect Materials.																	
E1c-2v. Conduct Testing Plan						JP	D5	P		JP		P					
E1c-2vi. Develop Performance Selection Guidelines										JP		P, F					
E1c-2vii. Validate Guidelines						D2								JP		P, F	
E1c-2viii. Develop CMA Mix Design Procedure																	
E1c-2ix. Develop CMA Performance Guidelines														JP	D	P, F	

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

Work planned
Work completed
Parallel topic
Delayed

PROGRAM AREA: VEHICLE-PAVEMENT INTERACTION

CATEGORY VP1: WORKSHOP

Work Element VP1a: Workshop on Super-Single Tires

Major Findings and Status

No activity in year 3.

Year 4 Work Plan

There is no activity planned for year 4.

CATEGORY VP2: DESIGN GUIDANCE

Work Element VP2a: Mixture Design to Enhance Safety and Reduce Noise of HMA

Major Findings and Status

In Year 3 the research team focused on measuring the surface macrotexture and microtexture (friction properties) of laboratory-prepared gyratory specimens using the sand-patch method and the British Pendulum Skid Resistance Tester, respectively. Measurements were conducted for approximately 140 samples. The samples covered a wide range of mix variables, such as aggregate gradation, aggregate type, design equivalent single axle loads (ESALs), compaction pressure and compaction temperature. A parametric/statistical analysis to identify the relationship between asphalt surface properties and the different mix variables was completed for laboratory samples.

A preliminary procedure for the abrasion/polishing of asphalt mix specimens using a circular rotating abrasion device was developed. Significant effort was put toward selecting an appropriate laser profilometer and noise absorption measuring device. Several samples were shipped to the University of Pisa, Italy, for surface profile measurements and absorption coefficient as part of the collaboration between the University of Wisconsin–Madison and the asphalt research group at the University of Pisa. This collaboration has resulted in significant development of new protocols for analysis of texture spectrum of lab-produced samples using a simple laser measuring device. Split samples have been shared at the two labs and comparative testing is being used to verify acceptable accuracy and repeatability of results.

Issues Identified During the Previous Year and Their Implications on Future Work

The work progress for Year 3 is somewhat behind the work plan proposed for Year 3 due to unforeseen problems that arose with developing and calibrating the in-house-made impedance tube. After extensive trials and consulting with experts, the research team decided to purchase a commercially available noise absorption measuring device. With the noise absorption device ready to be used, and the laser profilometer device purchased and also ready to be used, it is expected that the progress of this task will accelerate to catch up with the 5-year plan.

Year Four Work Plan

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

A literature review of the salient physical and mechanical characteristics of the pavement mixtures with improved skid characteristics will be conducted to document the overall properties of asphalt pavement designs. Emphasis will be placed on aggregate properties and binder requirements for mixture types that improve not only frictional skid properties, but also reduce cost and improve durability and comfort. Examples are open-graded, porous asphalts and pavement friction courses. NCHRP’s most recent reports and worldwide literature will be covered.

Subtask VP2a-2: Evaluate pavement macro- and microtextures and their relation to tire and pavement noise-generation mechanisms

Based on the literature review conducted in Year 3, macrotexture expressed in texture spectrum plays a very significant role in noise generation. In Year 4, the macro- and microtexture for different asphalt mixes (different gradations) will be evaluated in an effort to define a mix design procedure that will minimize noise generation.

Subtask VP2a-3: Develop a laboratory testing protocol for the rapid evaluation of the macro- and microtexture of pavements

The protocol developed in Year 3 will be further evaluated. Laser profilometer measurements will be conducted, and the possibility of replacing/complementing the sand-patch method will be assessed. The testing protocol will be used on core samples from field projects. Statistical analysis will be conducted to explore the relationship between surface properties of the laboratory-prepared samples and field-compacted samples. Table VP2a.1 shows a sample list of field projects and their corresponding laboratory specimens.

Table VP2a.1. Sample of field projects and corresponding laboratory specimens.

NMAS	Coarse Agg.	Design ESALs	Binder, PG	Project Name	Project I.D.	County	P6 T12	P6 T9	P6 T6	P3 T12	P3 T9	P3 T6	Notes
25 mm	Gravel	E-10	58-28*	USH 53	1191-09-74	Chippewa	4.55%	6.40%	6.47%	6.09%	5.05%	10.44%	
19 mm	Limestone	E-1	58-28	STH 33	5121-09-71	LaCrosse	4.31%	4.79%	5.79%	5.59%	5.83%	8.07%	
				STH 67	3100-08-70	Waukesha							
			64-22*	STH 60	5190-06-71	Richland							
		E-3	64-22	USH 18	2200-10-70	Milwaukee	3.22%	4.75%	6.30%	5.83%	8.80%	11.19%	
				USH 18	1660-04-73	Iowa							
				STH 32	3240-05-71	Racine	3.58%	4.14%	5.77%	5.58%	5.97%	8.28%	
				STH 59	2230-01-70	Waukesha	4.72%	2.99%	6.21%	4.68%	4.95%	7.50%	
		E-10	64-22	STH 181	2140-08-71	Milwaukee	1.45%	1.68%	3.25%	4.78%	4.78%	5.37%	
	Gravel	E-3	58-28	STH 153	6370-01-60	Marathon							Will be used once data becomes available
		E-10	64-28	STH 60	2310-02-60	Washington							STH 60 to be compacted to see if better AV range is found
			58-28*	USH 53	1191-09-74	Chippewa	2.26%	2.49%	5.10%	3.62%	3.89%	7.51%	
12.5 mm	Limestone	E-1	58-28*	STH 44	6090-00-70	Fond du Lac	3.11%	3.81%	5.22%	5.10%	5.45%	8.33%	
			64-22*	STH 60	5190-06-71	Richland	5.04%	5.79%	6.70%	6.15%	6.15%	8.05%	
		E-3	58-28	STH 96	1510-01-73	Waupaca	3.01%	3.72%	4.31%	3.96%	4.79%	6.37%	
				STH 32/57	4085-22-71	Brown							Another layer needs to be evaluated to see if wider range of air voids can be made available
			64-22	USH 18	1660-04-73	Iowa							
				USH 18	2200-10-70	Milwaukee							
			64-22*	USH 53	1633-07-71	Trempealeau							
		E-10	64-22	STH 181	2140-08-71	Milwaukee							One of these layers will be used for testing
		E-30	64-22 ??	USH 41	2120-06-71	Fond du Lac							
	Gravel	E-1	58-28	STH 70	9090-03-60	Vilas							
			58-28*	STH 77	9260-03-71	Ashland	3.86%	4.48%	6.29%	4.72%	5.18%	7.15%	
		E-3	58-28	USH 8	1590-12-60	Oneida	2.93%	3.01%	3.61%	3.81%	4.05%	8.42%	
				STH 153	6370-01-60	Marathon							
				USH 45	9847-03-60	Langlade							
		E-10	58-28	IH 39	1166-04-76	Portage	5.37%	5.84%	6.54%	7.05%	8.41%	7.63%	
				IH 39	1166-04-80	Marquette	2.24%	2.64%	2.71%	3.97%	4.52%	5.78%	
			58-28*	USH 53	1191-09-74	Chippewa	3.36%	4.26%	7.15%	4.61%	5.35%	8.48%	
			64-28	STH 60	2310-02-60	Washington							

*Warranty - check JMF

= to be tested

NMAS = nominal maximum aggregate size. JMF = job mix formula.

Subtask VP2a-4: Run parametric studies on tire-pavement noise and skid response

Using the data collected in subtasks VP2a-1 and VP2a-2 and the laboratory testing protocol developed in subtask VP2a-3, a set of parametric studies for different pavement mixtures will be performed to evaluate the correlation between measured macro- and microtexture 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. Noise absorption of the different mixes will also be evaluated using the impedance tube.

Subtask VP2a-5: Establish collaboration with established national and international laboratories specialized in transportation noise measurements. Gather expertise on measurements and analysis

UW–Madison researchers are in a constant contact with the asphalt research group in University of Pisa, Italy. Professor Losa's research in noise generation and absorption is well advanced and recognized in Europe and internationally. UW–Madison researchers will continue this collaboration.

Subtask VP2a-6: Model and correlate acoustic response of tested tire-pavement systems

Results obtained in subtasks VP2a-4 and VP2a-5 will be correlated to pavement mixture design parameters such as gradation, maximum aggregate size, angularity and binder type. The obtained physical/engineering correlations will be used to construct numerical models for the evaluation and estimation of frictional skid, and for pavement-tire noise-reduction designs. These results will be incorporated into new design guidelines for 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 elements 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 or increasing comfort and reducing construction costs. State departments of transportation and nationally recognized laboratories and centers will be contacted to collect feedback about the practicality and merits of the holistic pavement mixture designs.

Table for Decision Points and Deliverables

Date	Deliverable	Description
5/31/2010	Journal Paper	Journal paper describing the relationship between surface macrotexture and noise generation and defining specific parameters to optimize it.
8/1/2010	Journal Paper	A paper introducing the modeling of noise absorption as function of gradation and compaction effort.
9/15/2010	Presentation	A progress update presentation will be offered at the Modeling or Mixture ETGs.
1/1/2011	Presentation	If paper accepted at the TRB annual meeting, a presentation will be offered.

CATEGORY VP3: MODELING

Work Element VP3a: Pavement Response Model to Dynamic Loads

Major Findings and Status

During year 3, the beta version of 3D-Move model is released. The alpha version of 3D-Move model was tested under a variety of loading conditions and material properties. The 3D-Move model will provide the following analysis options:

- Option A: Pre-Defined Load Cases.
- Option B: User-Selected Pre-Defined Axle/Tire Configuration (uniform Pressure).
- Option C: User-Selected Tire Configuration and Contact Pressure Distribution from Database.
- Option D: Semi-Trailor Truck Including Vehicle Dynamics.
- Option E: Special Non-Highway Vehicles.

- Option F: User-Input Tire Configuration and Contact Pressure Distribution.

A database of non-uniform stress distributions was developed and is incorporated into the 3D-Move Model.

<u>Year 3 Work Plan</u>

Subtask VP3a-1: Dynamic Loads

Work for Year 4 will consist of continuing the review of the factors that affect the dynamic loads at the tire-pavement interface and continue to include the information into the 3D-Move model.

Subtask VP3a- 2: Stress Distribution at the Tire-Pavement Interface

No work planned for year 4. All the available data on non-uniform stress distributions were incorporated in the database for the 3D-Move beta-version.

Subtask VP3a-3: Pavement Response Model

Work for Year 4 will consist of continuing the work on the 3D-Move model beta-version to improve it and eliminate the bugs.

Subtask VP3a-4: Overall Model

Work for Year 4 will consist of continuing the work on the overall model that combines the dynamic loads, stress distributions at the tire-pavement interface, and the pavement response model.

<u>Table for Decision Points and Deliverables</u>

Date	**Deliverable**	**Description**
12/31/10	Software	Release of a newer version of the 3D-Move pavement response model

Table of Decision Points and Deliverables for the Vehicle-Pavement Interaction Program Area

Work Element	Date	Deliverable	Description
VP2a	5/31/2010	Journal Paper	Journal paper describing the relationship between surface macrotexture and noise generation and defining specific parameters to optimize it.
VP2a	8/1/2010	Journal Paper	A paper introducing the modeling of noise absorption as function of gradation and compaction effort.
VP2a	9/15/2010	Presentation	A progress update presentation will be offered at the Modeling or Mixture ETGs.
VP2a	1/1/2011	Presentation	If paper accepted at the TRB annual meeting, a presentation will be offered.
VP3a	12/31/10	Software	Release of a newer version of the 3D-Move pavement response model

Vehicle-Pavement Interaction Year 4

	Year 4 (4/2010-3/2011)												Team
	4	5	6	7	8	9	10	11	12	1	2	3	
(1) Workshop													
VP1a: Workshop on Super-Single Tires													UNR
(2) Design Guidance													
VP2a: Mixture Design to Enhance Safety and Reduce Noise of HMA													UWM
VP2a-1: Evaluate common physical and mechanical properties of asphalt mixtures with enhanced frictional skid characteristics													
VP2a-2: Evaluate pavement macro- and micro-textures and their relation to tire and pavement noise-generation mechanisms													
VP2a-3: Develop a laboratory testing protocol for the rapid evaluation of the macroand micro-texture of pavements													
VP2a-4: Run parametric studies on tire-pavement noise and skid response		JP											
VP2a-5: Establish collaboration with established national laboratories specialized in transportation noise measurements. Gather expertise on measurements and analysis													
VP2a-6: Model and correlate acoustic response of tested tire-pavement systems					JP	P							
VP2a-7: Proposed optimal guideline for design to include noise reduction, durability, safety and costs												P	
(3) Pavement Response Model Based on Dynamic Analyses													
VP3a: Pavement Response Model to Dynamic Loads													UNR
VP3a-1: Dynamic Loads													
VP3a-2: Stress Distribution at the Tire-Pavement Interface													
VP3a-3: Pavement Response Model									JP				
VP3a-4: Overall Model									SW				

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

Work planned

Work completed

Parallel topic

Vehicle-Pavement Interaction Years 2 - 5	Year 2 (4/08-3/09)				Year 3 (4/09-3/10)				Year 4 (04/10-03/11)				Year 5 (04/11-03/12)				Team
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	
(1) Workshop																	
VP1a: Workshop on Super-Single Tires																	UNR
(2) Design Guidance																	
VP2a: Mixture Design to Enhance Safety and Reduce Noise of HMA																	UWM
VP2a-1: Evaluate common physical and mechanical properties of asphalt mixtures with enhanced frictional skid characteristics				DP													
VP2a-2: Evaluate pavement macro- and micro-textures and their relation to tire and pavement noise-generation mechanisms				DP													
VP2a-3: Develop a laboratory testing protocol for the rapid evaluation of the macroand micro-texture of pavements		M&A															
VP2a-4: Run parametric studies on tire-pavement noise and skid response						JP		D	JP								
VP2a-5: Establish collaboration with established national laboratories specialized in transportation noise measurements. Gather expertise on measurements and analysis																	
VP2a-6: Model and correlate acoustic response of tested tire-pavement systems										JP, P							
VP2a-7: Proposed optimal guideline for design to include noise reduction, durability, safety and costs												P					
(3) Pavement Response Model Based on Dynamic Analyses																	
VP3a: Pavement Response Model to Dynamic Loads																	UNR
VP3a-1: Dynamic Loads			JP														
VP3a- 2: Stress Distribution at the Tire-Pavement Interface																	
VP3a-3: Pavement Response Model						SW, v. β					JP		SW, JP				
VP3a-4: Overall Model											SW		D	F			

Deliverable codes / **Deliverable Description**

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

Work planned
Work completed
Parallel topic

PROGRAM AREA: VALIDATION

CATEGORY V1: FIELD VALIDATION

Work Element V1a: Use and Monitoring of Warm Mix Asphalt Sections

Major Findings and Status

Construction of two warm-mix asphalt sections and a control hot-mix asphalt section were completed in early September 2007 near the East Entrance to Yellowstone National Park (YNP) on U. S. Highway 14-16-20. Samples of all construction materials were obtained during construction. After construction was completed, three 500-foot monitoring sections were established in each of the three different materials and initial monitoring data was obtained on each section. The construction material samples are being used to determine the effects of the warm mix additives on asphalt and mix properties. The performance of the sections will be used to determine the important properties of the materials that relate to performance.

The annual monitoring of the YNP sections occurred in September 2008 and again in September 2009. The YNP personnel did not want conventional core samples removed from the pavement because of the effect the samples would make on the aesthetics of the road, however, a small sampling technique was approved. The small sampling technique used a masonry drill and one-inch lapidary core bit. The samples are being analyzed to determine the aging of the pavement and the change in rheological properties.

Year 4 Work Plan

It is planned to continue to analyze the small samples taken from the sections and compare the results with conventional core samples taken from other sites. The third annual monitoring of the sections will occur around September 2010.

Work Element V1b: Construction and Monitoring of Additional Comparative Pavement Performance Sites

Major Findings and Status

Additional comparative pavement performance sites are being sought, mainly with states where existing LTPP SPS-5 and SPS-9 sections are going out of service.

The ARC and Manitoba Infrastructure &Transportation collaborated to plan and construct two new comparative pavement performance sites in the province of Manitoba, Canada. One site was planned to use two different amounts of RAP and the second site was planned to use warm-mix additives. Construction on the RAP comparative pavement performance site began in late September 2009 and finished in early October 2009. The RAP site is on provincial highway 8 about 10 km north of Gimli. The total project length is about 28 km (17 miles) but the ARC sections were placed in about 5 km (3.1 miles) of the project. The existing pavement was milled in the Fall of 2008 and stored for use this year.

The ARC sections at the RAP project were constructed using two 50 mm lifts with conventional hot-mix, 15% RAP, 50% RAP with no grade change for the new asphalt (150/200 pen), and 50% RAP with a grade change (200/300 pen). Over 400 5-gallon buckets, representing about 34,000 pounds, of construction material samples were obtained during construction. The samples were obtained for ARC research at the University of Nevada Reno, Western Research Institute, North Carolina State University, and for storage at the FHWA MRL in Sparks, Nevada. North Carolina State University will also use the samples for a separate contract between NCSU and FHWA.

After completion of construction, WRI personnel planned and established two 500 foot performance monitoring sections in each of the four different pavement sections. The eight monitoring sections will be used to acquire detailed performance monitoring data annually using LTPP protocols. Areas outside of the monitoring sections can be used to obtain core samples as the pavement ages in service.

The second comparative performance project site using warm-mix additives was begun in early October 2009. The bottom 50 mm lift (of two total lifts) of one hot-mix control section and a section using Advera were constructed before adverse weather forced the project to be stopped for the winter. ARC representatives and Manitoba officials will have future discussions on the possible effects of the partial construction and on possible alternatives.

Construction of comparative performance sections including RAP have been discussed with the DOT personnel in Texas and personnel with FHWA Western Federal Lands.

Year 4 Work Plan

It is planned to continue to pursue construction of comparative pavement performance sections that include material variation with state DOT’s, agencies having LTPP sections going out of service, and local agencies.

It is also planned to continue to work with Manitoba Infrastructure and Transportation on the completion of construction and sampling of the warm mix asphalt sections that were not completed in the fall of 2009.

Performance monitoring and sampling of the RAP sections in Manitoba will be planned for the late summer of 2010.

CATEGORY V2: ACCELERATED PAVEMENT TESTING

Work Element V2a: Accelerated Pavement Testing including Scale Model Load Simulation on a Small Test Track

Major Findings and Status

The Asphalt Research Consortium (ARC) acknowledges that accelerated performance testing is a viable method that can be used to validate the new test methods and predictive models that will be developed during the ARC agreement term. The most important aspect of accelerated pavement testing is the cost of construction of sections. Generally, the party that is interested in the testing is responsible for the cost of construction, which can run into the hundreds of thousands of dollars. Other factors that are important in the acquisition of accelerated testing are: the availability of a facility, cost of data acquisition, cost-share possibilities, and others. The cost-benefit analysis and the availability of adequate resources will need to be carefully weighed. One disadvantage of accelerated testing is little or no influence of environmental factors which are known to influence pavement performance.

There are several accelerated testing facilities that may be of use. The ARC researchers are committed to pursue accelerated testing during the agreement at locations such as the FHWA ALF at Turner-Fairbank Highway Research Center, the NCAT Test Track at Auburn University, the Minnesota Road Research Facility (MnRoad), the Accelerated Testing facility at Florida DOT, etc. The one-third scale model load simulator at Texas A&M may also be a possibility for accelerated testing.

Year 4 Work Plan

The ARC will continue to look for partners to pursue accelerated performance testing to compare materials for validation of test methods and performance prediction models.

Work Element V2b: Construction of Validation Sections at the Pecos Research & Testing Center

The Pecos Research & Testing Center (RTC) is a collaboration between Texas A&M / Texas Transportation Institute and industry. Accelerated performance testing at the Pecos site will most likely need an industry sponsor or industry support to make the cost reasonable.

CATEGORY V3: R&D VALIDATION

Work Element V3a: Continual Assessment of Specification

Major Findings and Status

Year 3 work included the development of protocols for new binder tests and the establishment of a database for properties measured by the Western Cooperative Testing Group (WCTG).

A new elastic recovery test using the Dynamic Shear Rheometer (DSR) was developed with the goal of replacing the current AASHTO T301 ductility bath procedure. The T301 procedure is very prone to operator variability and inconsistent sample geometry, so an analogous test on the DSR was desired to eliminate these problems. The DSR test uses a similar strain rate of 2.38% per second and a similar maximum strain of 238%, which is equivalent to a 10-cm elongation. The tests are run on pressure aging vessel (PAV)-aged binders at equal stiffness temperatures, where G* is equal to 18 MPa. The main difference between the two procedures is that the DSR test is run in shear, and the T301 is run in uniaxial tension. Also unlike T301, there is no pause between loading and relaxation. Test results so far show good distinction between binders with different modifications and very strong correlation with T301 results.

Both the Single-Edge Notched Bending (SENB) test and the Asphalt Binder Cracking Device (ABCD) show good potential. Tests conducted in the ABCD clearly show that the cracking temperature has a linear relationship with binder stiffness measured in the Bending Beam Rheometer (BBR). The SENB requires further development.

Results from the new Binder Yield Energy Test (BYET) have been compared to fatigue data obtained from the FHWA Accelerated Loading Facility (ALF). The test’s ability to rank binders according to their performance in full-scale pavement testing is verified. By measuring the area underneath the stress-strain curve and the strain at maximum stress, good correlations are shown with the pavement fatigue performance of the FHWA ALF modified binder test lanes. High values of both parameters indicate better fatigue resistance. The BYET has the potential to be used as a specification-type test for binder fatigue. By testing at temperatures that yield similar values of undamaged modulus, measured values of yield energy (YE) gave significantly differing results for 13 different binders, which may indicate differences in resistance to fatigue damage.

Progress was made in evaluating the high-temperature Multiple Stress Creep and Recovery (MSCR) procedure. Testing of binders and mastics showed that the nonrecoverable creep compliance (Jnr) and percent recovery (%R) have strong stress sensitivity. Binders and mastics exhibited a linear relationship in both the Jnr and %R parameters. The correlation between MSCR results and mixture performance remains undetermined. Binder type and mineral fillers clearly influence mastic and mixture performance.

A database for measured binder properties was established. Round-robin binder testing began in cooperation with the WCTG. All the results from the WCTG Test Report, which appears in the ARC Q3 2009 report, will be included in the database. The database will also be expanded to include mixture testing and pavement performance properties. The coefficient of variation from all WCTG member laboratories will be reported next to each measured property.

Year Four Work Plan

Subtask V3a-1: Evaluation of the PG-Plus practices and the motivations for selecting the "plus" tests

This subtask was completed in Year 3.

Subtask V3a-2: Detailed analysis of all PG-Plus tests being proposed or in use today, documentation of benefits and costs of these tests, and comparison with new tests

Evaluation of alternative elastic recovery tests using the DSR will continue.

Subtask V3a-3: Development of protocols for new binder tests and database for properties measured

Procedures for the new MSCR and DSR elastic recovery tests will be further developed. The usefulness of the stress levels tested in MSCR needs to be validated. The DSR elastic recovery test needs to be correlated with a specific binder performance property and validated with mixture performance data. The collection of data for the WCTG database established in Year 3 will continue into Year 4 and may be expanded to include more test results.

Subtask V3a-4: Development of specification criteria for new tests based on field evaluation of construction and performance

More tests will be conducted on binders collected from the material library associated with LTPP sections to refine the specifications for the new tests under development.

Subtask V3a-5: Interviews and surveys for soliciting feedback on binder tests and specifications

Cooperation with the WCTG could be expanded to include feedback from their member laboratories and information about mixtures test results. Specifications for the new binder tests will be submitted to department of transportation (DOT) personnel around the U.S. Interviews with DOT personnel and the WCTG board regarding the proposed specifications will be conducted.

Table for Decision Points and Deliverables

Date	Deliverable	Description
05/10	Presentation	At the Rocky Mountain Asphalt User/Producer Group to collect feedback on binder tests and specifications.
06/10	Presentation	In a conference call with the board of the WCTG about relationship between new binder tests and pavement performance.
07/10	Presentation	At the Petersen Conference to explain the new binder test protocols.
11/10	Journal Paper	Focused on assessment of binder tests and specifications.
02/11	Journal Paper	Focused on comparison of new test results to LTTP field performance.

Work Element V3b: Validation of the MEPDG Asphalt Materials Models and Early Verification of Technologies Developed by ARC using new MEPDG Sites and Selected LTPP Sites.

Major Findings and Status

In Year 3, the research team focused on the validation of protocols developed for characterization of fatigue cracking. Specifically, a set of LTPP binders was selected and tested using the Binder Yield Energy Test (BYET) and amplitude sweep procedures. Table V3b-3.1 shows the LTPP binders, performance grade (PG), climatic conditions of the sections from which binders were recovered, field performance, testing temperature and number of replicates.

Table V3b-3.1. LTPP binders selected and tested for fatigue cracking investigation.

SHRP ID	PG HT [°C]	PG LT [-°C]	Climate*	Fatigue Cracking (m^2)	Test Temp [°C]	BYET	Amplitude Sweep
04-B901	76	10	DN	328	37	XX	XX
09-0902	64	28	WF	0	22	XX	XX
09-0961	58	34	WF	2.1	16	XX	XX
34-0901	64	22	WF	49.5	25	XX	XX
34-0961	78	28	WF	178.8	28	XX	XX
35-0902	64	22	DN	32	25	XX	XX
37-0962	76	22	WN	0	31	XX	XX
89-A902	52	40	WN	6.7	10	XX	XX

DN = dry-nonfreeze. WF = wet-freeze. WN = wet-nonfreeze.

Preliminary results presented in the ARC Q3 2009 quarterly report indicate a fairly good correlation between the yield energy (YE) obtained from the BYET test and fatigue cracking measured in the field. Testing results indicate that with increasing YE, fatigue cracking is reduced.

Experimental results were collected for the linear amplitude sweep procedure; analysis of the data using viscoelastic continuum damage (VECD) theory is expected to be completed by the end of Year 3. Number of cycles to failure calculated using VECD will be compared to the field performance to assess the validity of the proposed procedure.

Selected binders from the LTPP Materials Reference Library were sent to Turner-Fairbank Highway Research Center (TFHRC) for characterization using the Double-Edge Notched Tension (DENT) test. The experimental matrix and analysis of the results from the DENT tests are expected to be completed by the end of Year 3.

<u>Issues Identified During the Previous Year and Their Implications on Future Work</u>

The ARC researchers faced hesitation from the DOTs to built MEPDG test sections. Therefore, no new MEPDG test sections were constructed in Year 3. The UNR team shifted the year 4 and 5 budgets allocated for the appropriate subtasks into the subtasks for warm mixes (E1c-1) and cold mixes (E1c-2).

<u>Year Four Work Plan</u>

Subtask V3b-1: Design and Build Sections

No work on this subtask is planned for Year 4.

Subtask V3b-2: Additional Testing

No work on this subtask is planned for Year 4.

Subtask V3b-3: Select LTPP sites to validate new binder testing procedures

The research team will select LTPP sections for which low-temperature cracking and moisture damage (i.e., stripping) performance is available. Based on the materials selected (i.e., asphalt binders and mixtures), a new testing matrix will be developed and completed to validate the testing procedures proposed in the thermal cracking and affinity of aggregate-binder subtasks.

Subtask V3b-4: Testing of Extracted Binders from LTPP Sections

No work planned.

Subtask V3b-5: Review and Revisions of Materials Models

No work on this subtask is planned for Year 4.

Subtask V3b-6: Evaluate the Impact of Moisture and Aging on Material Properties in MEPDG

No work planned.

<u>Table for Decision Points and Deliverables</u>

Date	**Deliverable**	**Description**
7/10	Decision Point	Decide on a testing plan for validation of the protocols and devices developed in the thermal cracking and moisture damage subtasks.
08/10	Journal Paper	Summary of field validation.
01/11	Presentation	Present results on the validation of the testing protocols for fatigue cracking, moisture damage and thermal cracking at ETG, TRB or similar venue.

Table of Decision Points and Deliverables for the Validation Program Area

Work Element	Date	Deliverable	Description
V3a	05/10	Presentation	At the Rocky Mountain Asphalt User/Producer Group to collect feedback on binder tests and specifications.
V3a	06/10	Presentation	In a conference call with the board of the WCTG about relationship between new binder tests and pavement performance.
V3a	07/10	Presentation	At the Petersen Conference to explain the new binder test protocols.
V3a	11/10	Journal Paper	Focused on assessment of binder tests and specifications.
V3a	02/11	Journal Paper	Focused on comparison of new test results to LTTP field performance.
V3b	7/10	Decision Point	Decide on a testing plan for validation of the protocols and devices developed in the thermal cracking and moisture damage subtasks.
V3b	08/10	Journal Paper	Summary of field validation.
V3b	01/11	Presentation	Present results on the validation of the testing protocols for fatigue cracking, moisture damage and thermal cracking at ETG, TRB or similar venue.

Validation Year 4

	Year 4 (4/2010-3/2011)												Team
	4	5	6	7	8	9	10	11	12	1	2	3	
(1) Field Validation													
V1a: Use and Monitoring of Warm Mix Asphalt Sections													WRI
V1b: Construction and Monitoring of additional Comparative Pavement Validation sites													WRI
(2) Accelerated Pavement Testing													
V2a: Accelerated Pavement Testing including Scale Model Load Simulation on small test track (This work element will include all accelerated pavement testing)													WRI
V2b: Construction of validation sections at the Pecos Research & Testing Center													WRI
(3) R&D Validation													
V3a: Continual Assessment of Specification													UWM
V3a-1: Evaluation of the PG-Plus practices and the motivations for selecting the "plus" tests.													
V3a-2: Detailed analysis of all PG-Plus tests being proposed or in use today, documentation of benefits and costs of these tests, and comparison with new tests													
V3a-3: Development of protocols for new binder tests and database for properties measured				P									
V3a-4: Development of specification criteria for new tests based on field evaluation of construction and performance			P								JP		
V3a-5: Interviews and surveys for soliciting feedback on binder tests and specifications		P						JP					
V3b: Validation of the MEPDG Asphalt Materials Models and Early Verification of Technologies Developed by ARC using new MEPDG Sites and Selected LTPP sites													UNR/UWM/ WRI
V3b-1: Design and Build Sections													UNR
V3b-2: Additional Testing (if needed)													
V3b-3: Select LTPP Sites to Validate New Binder Testing Procedures				DP	JP					P			UWM
V3b-4: Testing of Extracted Binders from LTPP Sections													
V3b-5: Review and Revisions of Materials Models													
V3b-6: Evaluate the Impact of Moisture and Aging													

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Work planned
Work completed
Parallel topic

Validation Years 2 - 5	Year 2 (4/08-3/09)				Year 3 (4/09-3/10)				Year 4 (04/10-03/11)				Year 5 (04/11-03/12)				Team
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	
(1) Field Validation																	
V1a: Use and Monitoring of Warm Mix Asphalt Sections																	WRI
V1b: Construction and Monitoring of additional Comparative Pavement Validation sites																	WRI
(2) Accelerated Pavement Testing																	
V2a: Accelerated Pavement Testing including Scale Model Load Simulation on small test track																	WRI
V2b: Construction of validation sections at the Pecos Research & Testing Center																	WRI
(3) R&D Validation																	
V3a: Continual Assessment of Specification																	UWM
V3a-1: Evaluation of the PG-Plus practices and the motivations for selecting the "plus" tests.		P	D,F														
V3a-2: Detailed analysis of all PG-Plus tests being proposed or in use today, documentation of benefits and costs of these tests, and comparison with new tests				P	D												
V3a-3: Development of protocols for new binder tests and database for properties measured						JP				P							
V3a-4: Development of specification criteria for new tests based on field evaluation of construction and performance						D		P	P			JP	P		JP		
V3a-5: Interviews and surveys for soliciting feedback on binder tests and specifications									P		JP		P		D	F	
V3b: Validation of the MEPDG Asphalt Materials Models and Early Verification of Technologies Developed by ARC using new MEPDG Sites and Selected LTPP sites																	UNR/UWM
V3b-1: Design and Build Sections																	
V3b-2: Additional Testing (if needed)																	
V3b-3: Select LTPP Sites to Validate New Binder Testing Procedures					DP			P		JP, DP		P			D	F	
V3b-4: Testing of Extracted Binders from LTPP Sections																	
V3b-5: Review and Revisions of Materials Models																	
V3b-6: Evaluate the Impact of Moisture and Aging																	

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Work planned
Work completed
Parallel topic

PROGRAM AREA: TECHNOLOGY DEVELOPMENT

Work Element TD1: Prioritize and Select Products for Early Development

This work element is complete.

Work Element TD2: Develop Early Products

Major Findings and Status

An improved method was developed for simplified analysis of continuum damage fatigue data. The method is called reduced cycles analysis. Two new and very useful concepts were included in the reduced cycles analysis. The first is the concept of reduced loading cycles. Reduced loading cycles is a much simpler alternative to the continuum damage parameter, S, in developing damage functions for asphalt concrete mixtures. The second concept introduced in the improved analysis approach is that of effective strain, which is the applied strain minus the endurance limit. This innovation in continuum damage analysis allows for the calculation of endurance limits from relatively limited fatigue data, and is a much quicker and more elegant approach to this problem than performing flexural fatigue tests over a range of strains for weeks or even months.

An Excel spreadsheet for performing the reduced cycles analysis has been developed and a draft standard test method for the testing and analysis has been prepared. The Interlaken Asphalt Mixture Performance Tester (AMPT) that is owned by the National Cooperative Highway Research Program (NCHRP) was modified to perform the basic testing required by the draft standard method; strain controlled cyclic tension-compression testing with minimal permanent deformation. Modifications to the draft standard test method were made based on preliminary testing with the modified AMPT.

Year Four Work Plan

A ruggedness test plan will be developed based on ASTM E1169, *Standard Practice for Conducting Ruggedness Tests*. The ruggedness test plan will be executed in Advanced Asphalt Technologies, LLC laboratory using the Interlaken AMPT. The data from the ruggedness testing will be analyzed and appropriate control limits for the testing will be developed. The draft standard test method will be modified based on the results of the ruggedness testing. Additionally, the equipment specifications for the AMPT that were developed in NCHRP Project 9-29 will be modified to include the continuum damage fatigue test with appropriate control limits as determined from the ruggedness testing.

Work Element TD3: Identify Products for Mid-Term and Long-Term Development

Major Findings and Status

The research team continued to review interim research products to identify potential mid-term and long-term development projects.

Year Four Work Plan

It is planned to continually review research progress to identify potential products.

Work Element TD4: Develop Mid-Term and Long-Term Products

Year Four Work Plan

Work on mid-term and long-term products will be initiated.

Budget

The budget for Technology Development is estimated at $1,200,000 over the five year period.

PROGRAM AREA: TECHNOLOGY TRANSFER

CATEGORY TT1: OUTREACH AND DATABASES

Work Element TT1a: Development and Maintenance of Consortium Website

Major Findings & Status

The Consortium Website has been developed since 2007. The website was maintained throughout year 3 of the Consortium. The final copies of the year 3 work plan, all the quarterly progress reports, the ARC newsletters, and any other technical reports have been uploaded to the website.

Year Four Work Plan

The Consortium Website will continue to be maintained and appropriate documents will be uploaded.

Table for Decision Points and Deliverables

Date	**Deliverable**	**Description**
05/31/10	Final Report	Upload newsletter
07/31/10	Final Report	Upload quarterly progress report
09/30/10	Final Report	Upload newsletter
10/31/10	Final Report	Upload quarterly progress report
01/31/11	Final Report	Upload quarterly progress report and newsletter
04/30/11	Final Report	Upload quarterly progress report

Work Element TT1b: Communications

Major Findings & Status

Three newsletters were published in year 3 of the Consortium. The newsletters were electronically distributed to the industry and were published on the Consortium Website.

Year Four Work Plan

Three ARC newsletters will be published.

Table for Decision Points and Deliverables

Date	Deliverable	Description
05/31/10	Final Report	Newsletter will be published
09/30/10	Final Report	Newsletter will be published
01/31/11	Final Report	Newsletter will be published

Work Element TT1c: Prepare Presentations and Publications

Major Findings & Status

Several presentations were made to the Expert Task Groups and in professional meetings. Several publications were developed and submitted to TRB, AAPT, and technical reports were uploaded onto the ARC Website.

Year Four Work Plan

The ARC team will continue to make presentations to ETGs and submit papers to various journals and conferences.

Work Element TT1d: Development of Materials Database

Major Findings and Status

During year 3, all the major forms for the database has been created, implemented, and tested. The following summarizes the function of each form in the database:

- ***Property Group***: this form provides the means to organize qualitative and quantitative properties. The grid on this form allows the user to create, edit, and delete property groups.
- ***Materials Browser***: the Materials page is used to create and edit new core and composite materials. The page is made up of the following sections:
  - The Material Editor allows users to select materials from the material tree and restrict the displayed materials based on the material type, material category, organization, and material source. Materials can also be restricted by work tasks.
  - The Material Details section allows users to edit the material selected from the Material Editor, create new materials, and delete materials. In this section, materials can also be associated with work items.
  - Materials are categorized into simple materials and complex materials. Simple materials have a material source, which can be edited on this form. Complex materials are made up of other materials.

- ***Properties***: this form allows the user to create, edit, and delete properties within each property group.
- ***Material Measures***: this form allows the user to create, edit, and delete measures for the created properties.
- ***Material Types***: this form provides the means to organize material types. The grid on this form allows the user to create, edit, and delete material types.
- ***Manage Tasks***: the grid on this form allows the user to create, edit, and delete ARC Program Areas, Categories, Work Elements, and Subtasks.
- ***Transfer Files***: this form is used to upload files to the ARC database so that they can be indexed from other parts of the application. Users must have access to upload files for approval and to approve files that have been uploaded.
- ***My Account***: this form allows authenticated users to update their own personal information.
- ***Manage Roles***: this form provides the means to manage the roles of the various users. All users granted access to the ARC system belongs to one or more different roles. Roles are used to tell the system which tasks the user can perform and which tasks the user cannot perform. Users must belong to the *administrative* role to use the page.
- ***Manage Users***: this form provides the means to add, change and delete users.
- ***Manage Organizations***: this form provides the means to create, edit, and delete organizations.
- ***Manage Suppliers***: this form provides the means to create, edit, and delete suppliers.

A Database training workshop for ARC members will be held on March 11, 2010 at UNR campus.

<u>Year 4 Work Plan</u>

Work for Year 4 will consist of testing the beta-version of the database.

<u>Table for Decision Points and Deliverables</u>

Date	Deliverable	Description
03/11/10	Workshop	Training for ARC members on how to use the materials database.

Work Element TT1e: Development of Research Database

<u>Major Findings & Status</u>

The final version of the year 3 work plan and the quarterly progress reports were uploaded onto the appropriate sections of the ARC Website.

The original ARC work plan and the year 2 work plan identify the information to be included in the Research Database as follows: problem statement, budget, timeline of activities, results update in forms of reports, white papers or any other type of documents, contact information, and relationship to other studies.

All of the information identified above has been incorporated in the various sections of the ARC Website. Specifically; problem statements, timeline of activities, and external coordination are incorporated in the yearly work plans that are published under the Publications section of the ARC Website. The results updates are incorporated in the quarterly progress reports that are published under the Publications section of the ARC Website. The contacts information for the ARC members are listed in the Home and Contact sections of the ARC Website.

In the future, all technical reports will be published in the Publications section of the ARC Website and the Materials Database (i.e. TT1d) will include a link to the specific reports that contain the information on the various materials that are being evaluated in the ARC.

Year Four Work Plan

Publish the annual work plan, quarterly progress reports, and any research reports on the ARC Website.

Work Element TT1f: Workshops and Training

Major Findings & Status

An intensive course on Advanced Constitutive Modeling and Characterization of Asphaltic Materials was held on 21-25 September 2009 at Texas A&M in collaboration with the Group of Mechanics of Infrastructure Materials of TU Delft. The course was under the auspices of the ISAP TC Constitutive Modeling of Asphaltic Materials and aimed at engineers, scientists and researchers who wanted to familiarize themselves with the mathematics, computational methods and characterization techniques associated with constitutive modeling of asphaltic materials.

A Database training workshop for ARC members will be held on March 11, 2010 at UNR campus.

Year Four Work Plan

The ARC researchers will assess the availability and need for workshops and training activities of the various areas of the ARC. If it were found necessary to conduct workshops and training activities, a request will be made to FHWA for the approval of such activities.

Technology Transfer Year 4

Technology Transfer Year 4	Year 4 (4/2010-3/2011)												Team
	4	5	6	7	8	9	10	11	12	1	2	3	
(1) Outreach and Databases													
TT1a: Development and Maintenance of Consortium Website													UNR
TT1b: Communications													UNR
TT1c: Prepare presentations and publications													UNR
TT1d: Development of Materials Database													UNR
TT1d-1: Identify the overall Features of the Web Application													
TT1d-2: Identify Materials Properties to Include in the Materials													
TT1d-3: Define the Structure of the Database													
TT1d-4: Create and Populate the Database													
TT1e: Development of Research Database													UNR
TT1e-1: Identify the Information to Include in the Research Database													
TT1e-2: Define the Structure of the Database													
TT1e-3: Create and Populate the Database													
TT1f: Workshops and Training													UNR

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Work planned
Work completed
Parallel topic

Technology Transfer	Year 2 (4/08-3/09)				Year 3 (4/09-3/10)				Year 4 (04/10-03/11)				Year 5 (04/11-03/12)				Team
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	
(1) Outreach and Databases																	
TT1a: Development and Maintenance of Consortium Website																	UNR
TT1b: Communications																	UNR
TT1c: Prepare presentations and publications																	ALL
TT1d: Development of Materials Database																	UNR
TT1d-1: Identify the overall Features of the Web Application																	
TT1d-2: Identify Materials Properties to Include in the Materials Database																	
TT1d-3: Define the Structure of the Database																	
TT1d-4: Create and Populate the Database							SW, v. β	SW									
TT1e: Development of Research Database																	UNR
TT1e-1: Identify the Information to Include in the Research Database																	
TT1e-2: Define the Structure of the Database																	
TT1e-3: Create and Populate the Database																	
TT1f: Workshops and Training																	UNR

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Work planned

Work completed

Parallel topic