Asphalt Research Consortium

Annual Work Plan for Year 3
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RESEARCH PLAN FOR YEAR 3 OF FEDERAL HIGHWAY ADMINISTRATION CONTRACT DTFH61-07-H-00009 "ASPHALT RESEARCH CONSORTIUM"

INTRODUCTION

This document is the proposed Research Plan for Year 3 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 3 Work Plans continue the research that was extensively detailed in the Year 2 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. The background information for the Year 3 Work Plan is contained in the Revised Year 2 Work Plan 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

The testing plans using ARC Core materials are listed in tables F3c.1 and F3c.2 under the Fatigue program area. This plan is for evaluation of test methods and analysis procedures. The testing for purpose of verification and validation will start in year 4.

Work Element M1a: Affinity of Asphalt to Aggregate

Major Findings and Status

In Year 2, the research team found that it could obtain more consistent testing results by employing a testing geometry with one rock disk and one steel plate rather than a system with two rock disks. The single rock disk also allowed for the use of cone-and-plate geometries (using the rock as the parallel disk together with a steel cone). The use of cone-and-plate geometry addresses the comments from reviewers received during Year 2.

By adjusting the testing gap, the research team matched measurement results from a parallel-plate geometry to those obtained with a cone-and-plate geometry.

It was also found that for amplitude sweep measurements, increasing the stress applied linearly rather than logarithmically allowed better discernment of the failure point of the binder.

Year 3 Work Plan

Subtask M1a-1: Select materials

Work was completed for this subtask during Year 2. Binders and mineral aggregates were selected during Year 2, and a detailed list has been reported in the quarterly technical progress reports.

Subtask M1a-2: Conduct modified DSR tests

Due to the multitude of tests required and unforeseen instrument difficulties, this subtask will continue into Year 3. The proposed tests for this subtask are detailed in table M1a.1.

Table M1a.1. Proposed tests on asphalt binders and mixes.

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

In this task, the modified Dynamic Shear Rheometer (DSR) will be used. The testing system consists of composite samples of one cored rock disk (25 mm diameter and 5 mm thickness) and one steel plate (25 mm diameter) sandwiched with asphalt binder (1 mm film thickness). The rock disk is glued on the DSR base metal plate. In the DSR setup, the parallelism is obtained by aligning the disk using the metal DSR top spindle while the epoxy binder dries. A water cup circumscribing the composite sample is used to allow the sample to be submerged. Shear stress or strain sweeps are then used to measure the change of rheological properties before and after conditioning with water. Results for selected combinations will be compared to the modified Pneumatic Adhesion Tensile Testing Instrument (PATTI) test results. It is expected that texture may influence the results. For this reason, the research team will try to test different mineral specimens with the same texture as obtained from the sawing and lapping during specimen preparation. By maintaining the texture consistency and changing the aggregate type, it should be possible to isolate testing parameters and evaluate the effect of mineralogy in the moisture damage of aggregate-binder systems.

This test setup will be used to collect data for shear stress or strain sweeps at different conditioning times, temperatures and loading rates. A range of combinations of materials will be included following the results from subtask M1a-1 as reported in the quarterly technical progress reports. The results will be analyzed in coordination with Texas A&M University’s research activities to verify that what is being measured is in fact explainable by fundamental surface energy measurements and that the conditions selected for measurements are effective in determining adhesive bond strength as well as cohesive strength.

<u>Subtask M1a-3: Evaluate the moisture damage of asphalt mixtures</u>

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

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

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

Subtask M1a-5: Propose a novel testing protocol

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

Table for Decision Points and Deliverables

Date	Deliverable	Description
9/09	Presentation	Presentation on progress of binder testing.
3/10	Presentation	Presentation on progress of correlation between mixture and binder moisture-damage test results.

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. Parts of this test protocol were also developed in another FHWA project on warm asphalt mixtures that are not reported here. The micro calorimeter can be used as a surrogate to other surface energy measurement methods in order to obtain rapid estimates for the energy of adhesion between the aggregate and the asphalt binder. Also, this methodology can be applied to determine the effect of active fillers on the interfacial bond strength at the binder-aggregate interface. The key steps involved in the test method are illustrated in figure M1b.1.

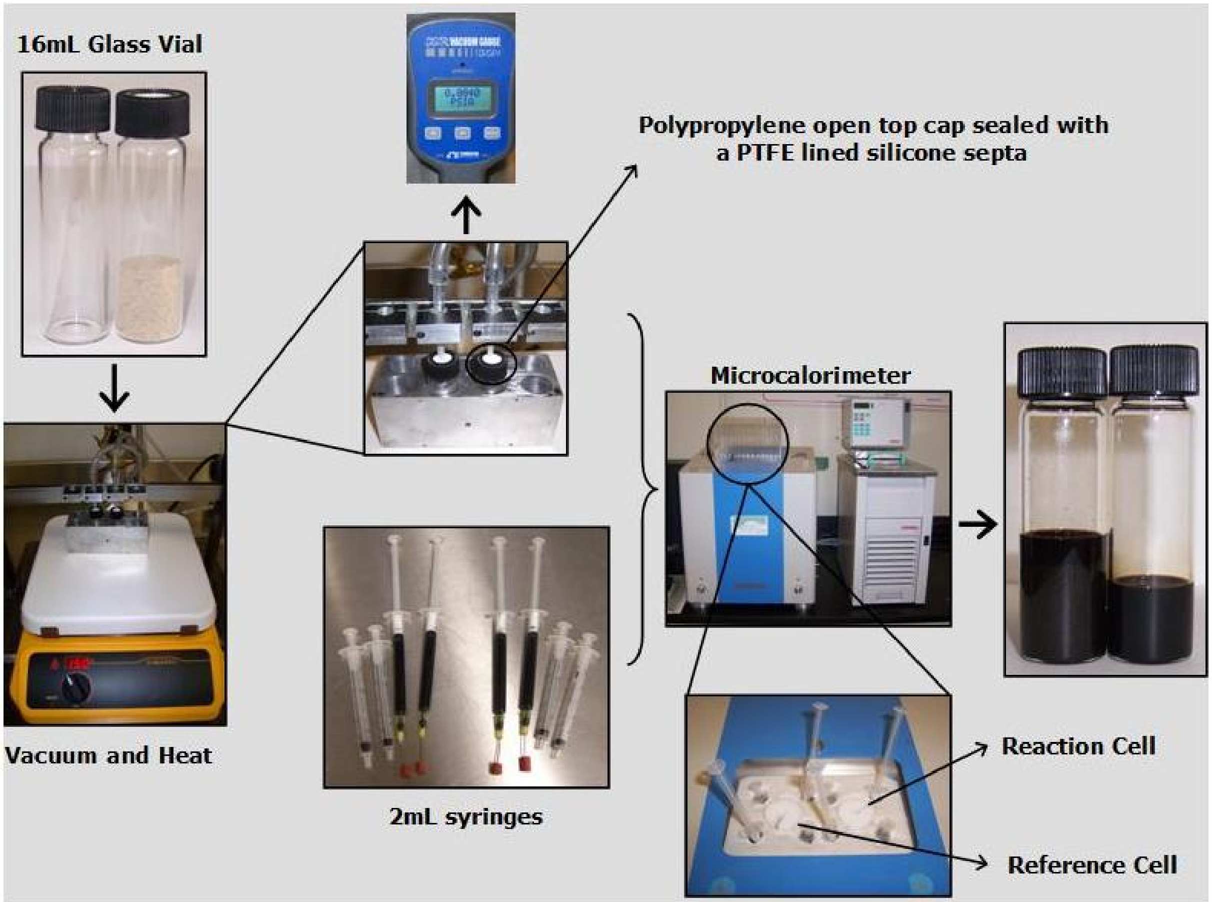

Figure M1b.1. Schematic showing the various steps to measure energy of adhesion between the asphalt binder and aggregate

Figure M1b.2 illustrates the typical heat flow from the reaction to the reference cell just before, during, and immediately after the completion of an immersion test. The figure shows the initial and final datum for the steady state heat flow and the point at which heat flow increases due to the surface interactions between the solid (aggregate) and the probe liquid (asphalt binder in solution). The area under the heat flow curve between the two equilibrium points is integrated to obtain the enthalpy of immersion or total energy of adhesion (TEA) between the aggregate and the asphalt binder solution.

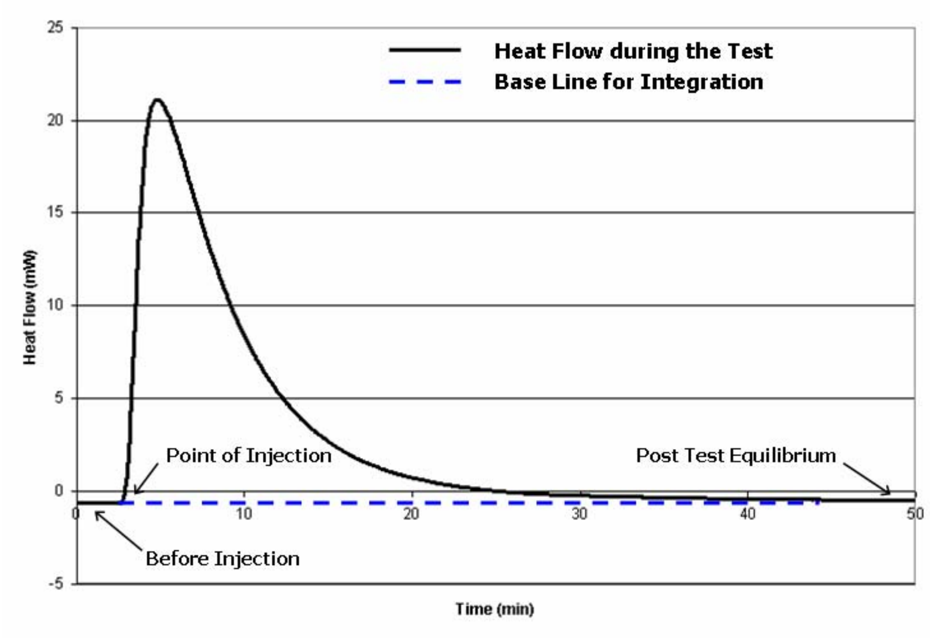

Figure M1b.2. Typical heat flow curve recorded with the micro calorimeter.

The net differential heat measured by the micro calorimeter during the process of immersion, ΔH_{meas}, is due to,

(i) enthalpy of immersion in the reaction cell, ΔH_{imm}, and
(ii) difference in heat of vaporization of the solvent (toluene) due to the difference in free volumes inside the vacuum sealed reaction and reference cells, $\Delta H_{\delta v}$.

Therefore, the corrected enthalpy of immersion is determined from the heat of immersion as follows:

$$\Delta H_{imm} = \Delta H_{meas} - \Delta H_{\delta v} = \Delta H_{vap} \frac{v_s p_0}{RT} \qquad \text{(M1b.1)}$$

where, v_s is the volume occupied by aggregates in the vacuum sealed reaction cell, p_0 is the saturation vapor pressure of the toluene at the test temperature, R is the universal gas constant, T is the test temperature, and ΔH_{vap} is the change in enthalpy due to vaporization or heat of vaporization per mole of the solvent (toluene).

Figure M1b.3 illustrates typical results for this test for two replicates of three different types of aggregates (RA, RK, and RL) immersed in one type of asphalt binder (AAD). The results indicate that this test method is repeatable with good precision and is sensitive to the type of aggregate.

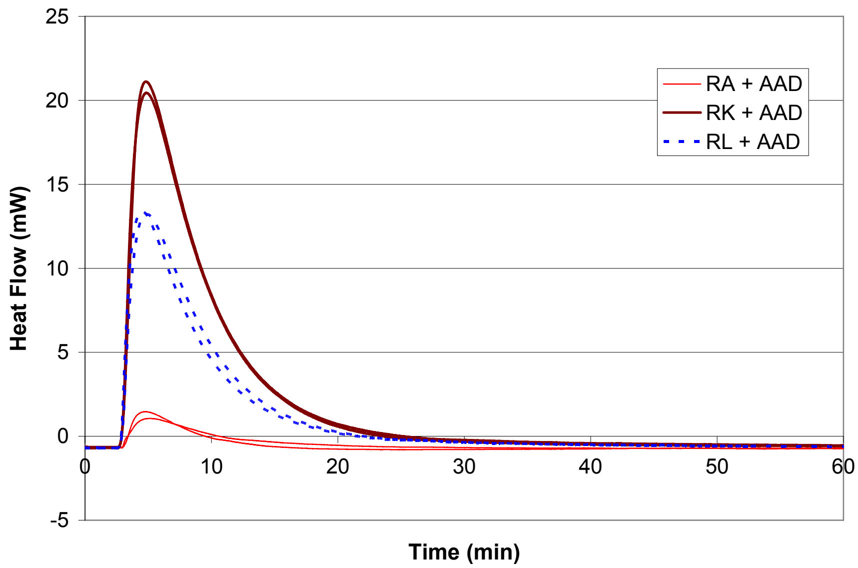

Figure M1b.3. Sensitivity and precision of measurements made using the micro calorimeter.

A more detailed description of the above methodology can be found in Vasconcelos et al. (2008, 2009a and b).

Year Three Work Plan

The main objective of this subtask is to develop and/or use methods to determine the thermodynamic work of adhesion between asphalt binders and aggregates. The use of the Wilhelmy plate device and the Universal sorption device to determine the surface free energy components of asphalt binders and aggregates, respectively, was developed in previous research. For this research only an implementation of these methods is envisioned. Also, it was originally planned to develop and use the micro-calorimeter to determine the total energy of adhesion between different asphalt binders and aggregates. The test method was developed jointly as part of another FHWA contract and it will be implemented in that project. Consequently, the deliverables for this subtask will be modified accordingly. The effort here will be redirected towards the development of models that utilize the results from these tests.

The plan for year three is simply to utilize these three tests (Micro-calorimeter, Universal Sorption device and Wilhelmy plate) to obtain adhesion characteristics for the various materials that have been included in the test plan. The information generated from this sub-task will serve as inputs 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
09/30/10	Journal Paper	[2] See note below
09/30/10	Final Report	[2] See note below

(1) Vasconcelos et al. (2009a and b)
(2) The journal papers and report were intended to document the development of the test method in this subtask. However, portions of the test method were developed in conjunction with another FHWA project. The effort here is redirected towards the development of models that utilize the results from these tests. Although we do not envision any further development of the test method, this task is crucial as it will provide data for the modeling efforts in other subtasks. Consequently, items marked as (2) will not appear as stand-alone deliverables. Instead, the data generated from this task will be incorporated into the reports and journal papers from other sub-tasks.

Cited 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." 88th Annual Meeting, Transportation Research Board, Washington, D.C., CD-ROM.

Vasconcelos, K.L., A. Bhasin, and D. N. Little, "Calorimetric Measurement of Adhesion between Bitumen and Aggregate Used in Asphalt Mixtures" Accepted for presentation at International Symposium on Asphalt Pavements and Environment, Zurich, Switzerland, 2008.

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

Major Findings & Status

The detailed work plan for this subtask was prepared during Year 2 and approved by FHWA in August 2008. Subsequent to that, the Year 2 work for was delayed significantly due to equipment problems that were not resolved until late in the last quarter (Oct. – Dec. 2008 Technical Progress Report). Sample preparation work associated with this work must be coordinated with reliable AFM metrology measurements. These measurements could not be made due to problems with our AFM metrology system. At the time of this writing, the AFM metrology system has been replaced, and year two work on has begun. There are no significant results to report at this time.

Work Plan Year Three

Because of delays related to equipment problems we have just begun to conduct year two experimental work. The year two test plan, as outlined below, will therefore be carried over to year three for the most part.

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

Work Element M1c: Quantifying Moisture Damage Using DMA

Major Findings & Status

The experimental and analytical procedure to evaluate the performance of moisture conditioned Fine Aggregate Matrix (FAM) specimens is very similar to the procedure used for unconditioned or dry specimens. Therefore, the work being developed and reported in work element F2b also applies to this work element.

As compared to the procedures developed in work element F2b, two additional components that are required to quantify moisture damage in FAM specimens are: i) an analytical method to combine results from tests on dry and moisture conditioned specimens, and ii) a methodology or protocol to moisture condition FAM specimens.

Item (i) from above was addressed in the research during previous years and is summarized below. Item (ii), a protocol to moisture condition FMA specimens will be developed as a part of the year 3 activities.

The use of a probabilistic model to compare the fatigue cracking life of dry specimens versus moisture conditioned specimens for a given type of material was developed. The probabilistic model accommodates the inherent variability associated with experimental data obtained from replicate tests. The effect of moisture induced damage on the fatigue cracking life of a FAM specimen can be quantified by comparing the crack growth index in dry and moisture conditioned states represented by ΔR_{dry} and ΔR_{wet}, respectively. The probabilistic approach involves comparing the ratio of these two parameters at different load cycles using a model that accommodates the variability in the measured data.

The probability of $\Delta R_{dry}(N)$ to be greater than $\Delta R_{wet}(N)$ at any load cycle, N, is:

$$p\left(\Delta R_{wet} > \Delta R_{wet} \middle| N\right) \qquad \text{(M1c.1)}$$

The probability, p, at any given load cycle, N, can be computed using a point-in-time approach, which implies that the probability at each load cycle is independent of the past damage and loading history. The following log normal fit was found to be the most appropriate based on a best-fit density distribution analysis. Therefore, the probability can be computed as:

$$p\left(\Delta R_{wet} > \Delta R_{wet} \middle| N\right) = \Phi\left(\frac{-\ln\left(\frac{\mu_{\Delta R(wet)}}{\mu_{\Delta R(dry)}} \left(\frac{1+V^2_{\Delta R(wet)}}{1+V^2_{\Delta R(dry)}} \right)^{\frac{1}{2}} \right)_N}{\left[\ln\left(\left(1+V^2_{\Delta R(wet)}\right)\left(1+V^2_{\Delta R(dry)}\right) \right) \right]^{1/2}_N} \right) \qquad \text{(M1c.2)}$$

where $\mu_{RN(dry)}$ and $\mu_{RN(wet)}$ are the mean values of $\Delta R(N)$ in dry and wet conditions; and $V_{RN(dry)}$ and $V_{RN(wet)}$ are the corresponding coefficients of variation obtained from replicate measurements. The sub-index N indicates that both, mean values and V, are computed for each load cycle separately. Figure M1c.1 shows the results obtained from this analysis for four different type of FAM, labeled NP2 through NP5. The four FAMs utilize the same asphalt binder but different fillers. Mixtures that incorporate these four materials were rigorously examined for their moisture sensitivity in another study conducted by the University of Nottingham, UK. Therefore, these materials are an ideal choice to for the preliminary evaluation of this probabilistic model. It is envisaged that this methodology can be adopted for the suite of materials that will be selected as a part of the experiment design in the moisture damage work area.

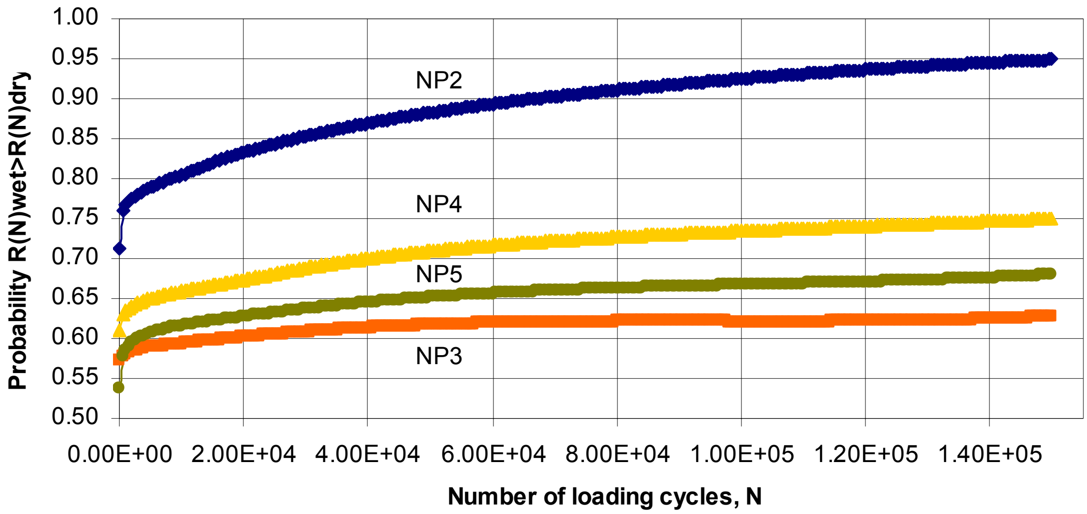

Figure M1c.1. Probability that ΔR(N)[wet]>ΔR(N)[dry] vs. number of load applications for all mixtures.

A more detailed description of the above methodology can be found in Caro et al. (2008a and b).

Year Three Work Plan

Work in year three will continue for this work element. The most important difference between this work element and Task F2b is the moisture conditioning procedure that is to be used for the DMA specimens. The moisture conditioning procedure will be developed in quarters three and four of year three in this work area.

Furthermore, there is ongoing work under work element M2b related to the measurement of diffusion rates of water through DMA specimens using gravimetric methods. Results from these measurements will establish a datum for water concentration versus time under natural conditions (without the aid of any accelerating technique). This information will serve as a useful reference to quantify the time scaling effect of accelerated moisture conditioning techniques such as vacuum saturation or submergence at elevated temperatures. For example, it will be possible to determine the amount of time a DMA specimen needs to be submerged in water at 50°C in order for the specimen to develop the same moisture concentration profile as a specimen submerged in water at room temperature for a specified duration. This relationship will establish the basis by which to determine the protocol for accelerated conditioning of DMA specimens to different levels of moisture prior to testing.

Table for Decision Points and Deliverables

Date	Deliverable	Description
09/30/09	Journal Paper	Moisture damage resistance of select FAM mixtures subjected to different moisture conditioning procedures
12/31/10	Draft Report	
03/31/10	Final Report	

Cited References

Caro, S., E. Masad, G. Airey, A. Bhasin, and D. N. Little, 2008a, Probabilistic Analysis of Fracture in Asphalt Mixtures Caused by Moisture Damage. *Transportation Research Record 2057*, p. 28-36.

Caro, S., G. D.Airey, E. Masad, A. Bhasin and D. N. Little, 2008b, "Moisture Susceptibility of Asphalt Mixtures Combined with Surface Free Energy and Fracture Property Characterization", Accepted for presentation at *International Symposium on Asphalt Pavements and Environment,* Zurich, Switzerland.

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

The objective of this subtask is to evaluate the change in surface properties of asphalt binders that are permeated with water or are saturated with water. The subtask is scheduled to start in year four of this project.

Year Three Work Plan

This subtask is scheduled to start in year four of this project.

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 was prepared during Year 2 and approved by FHWA in August 2008. Subsequent to that, the Year 2 work was delayed significantly due to equipment problems that were not resolved until late in the last quarter (Oct. – Dec. 2008 Technical Progress Report). The laboratory work associated with this subtask depends heavily on reliable AFM metrology measurements. These measurements could not be made due to problems with our AFM metrology system. At the time of this writing, the AFM metrology system has been replaced, and year two work on this subtask has just commenced. There are no significant results to report at this time.

Work Plan Year Three

Because of delays related to equipment problems we have just begun to conduct year two experimental work. The year two test plan, as outlined below, will for the most part be carried over to year three.

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.

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

Major Findings & Status

Two methodologies were most commonly reported in the literature for use with polymeric films and materials similar to asphalt binder. The first methodology is based on the use of Fourier Transform Infrared Spectroscopy (FTIR) and the second is based on gravimetric measurements.

We began the development of a methodology to determine the rate of moisture diffusion through thin films of asphalt binders using FTIR spectroscopy. An attenuated total reflectance (ATR) cell was used to determine the diffusivity of water through thin films of asphalt binders. An enclosure for the ATR cell was specifically designed for this and for future tests involving moisture diffusion. This enclosure makes it possible to immerse the ATR window coated with the thin asphalt binder film under water. The air tight enclosure is also designed to conduct experiments by passing air at different relative humidity through the cell (dry to 95% saturated). This enclosure will allow the measurement of hysteresis in the rate of moisture diffusion through asphalt binders. The various steps followed to determine the rate of moisture diffusion through the asphalt binder are illustrated in figure M2b.1.

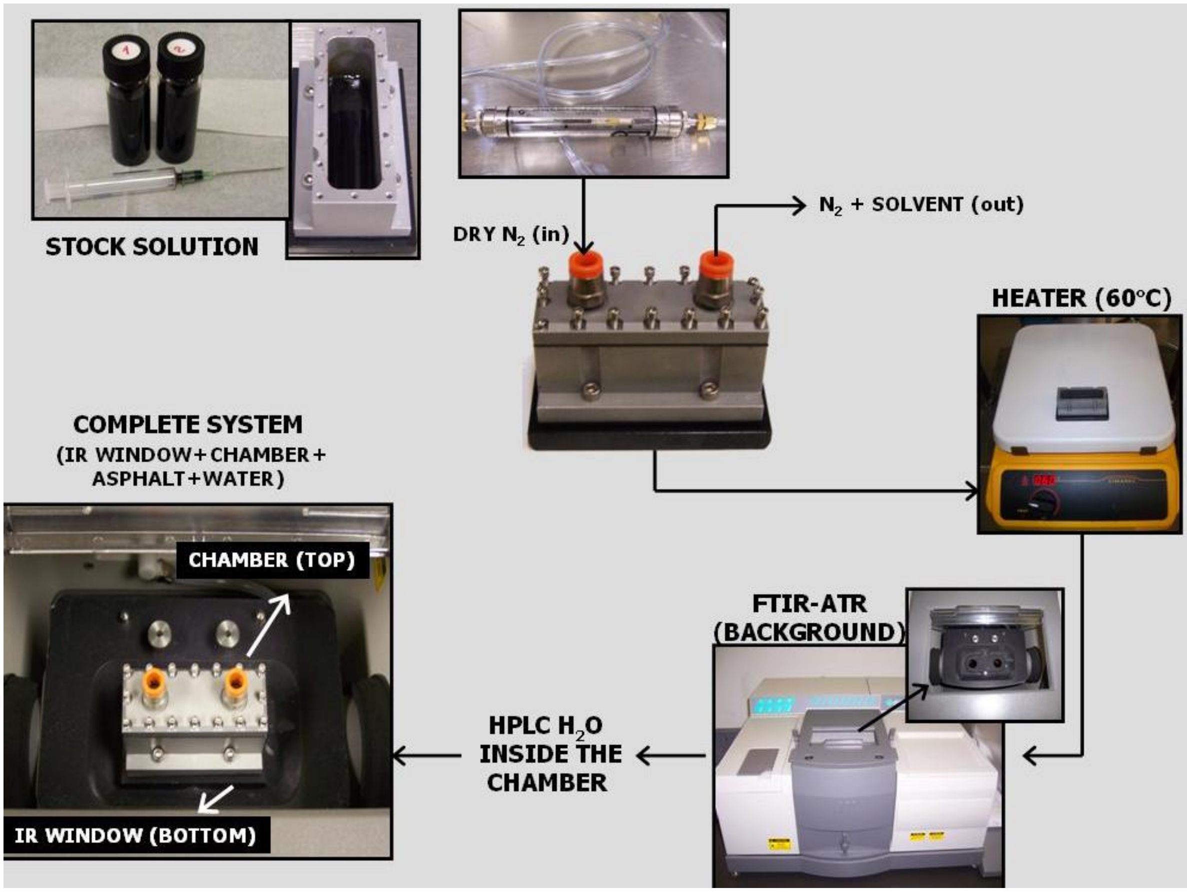

Figure M2b.1. Schematic showing the various steps followed to determine the rate of moisture diffusion through asphalt binder using ATR-FTIR spectroscopy.

The increase in the absorbance peak for the O-H bond in water (3400 cm^{-1}) was plotted over time to record the diffusion of water through the film. We are evaluating the use of Fick's second law to model the diffusion process through the thin film of the asphalt binder. The coefficient of diffusion of moisture through the thickness of a thin film following Fick's second law can be obtained from the following form (Crank 1975):

$$\frac{A_t}{A_\infty} = 1 - \frac{8\gamma}{\pi\left[1-\exp(-2\lambda L)\right]} \times \sum_{n=0}^{\infty} \left[\frac{\exp\frac{-D(2n+1)^2\pi^2 t}{4L^2}\left[\frac{(2n+1)\pi}{2L}\exp(-2\gamma L) + (-1)^n(2\gamma)\right]}{(2n+1)\left(4\gamma^2 + \frac{(2n+1)\pi}{2L}\right)} \right]$$

where,

$$d_p = \frac{\lambda}{2\pi n_1 (n_1^2 \sin^2 \phi - n_2^2)^{1/2}};$$

$$\gamma = \frac{1}{d_p};$$

A_t and A_∞ - spectral absorptions at a time t and equilibrium, respectively;
d_p – penetration depth;
L – film thickness;
D – diffusivity coefficient;
λ - wavelength of radiant energy;
n_1 and n_2 – index of refraction of the IRE and of the sample, respectively;
ϕ - angle of incidence radiation on the interface.

Problems were encountered in the first step during preparation of binder films (figure M2b.1). The thickness of the films was not uniform and could not be controlled to achieve consistency. If the film thickness was larger than the effective depth of penetration of the IR beam, it would take a long time for the water to diffuse through the bulk and fall in the detection range of the FTIR. In order to address this difficulty, a method was developed to fabricate thin films with optimal thickness using a spin coater (figure M2b.2). This resulted in a procedure to measure thicknesses of the bitumen film and its resulting refractive index (figure M2b.3). These films were then used to determine the diffusivity of water through thin films of asphalt binders (figure M2b.4).

Figure M2b.2. Spin coater being used to cast thin films of the binder on a Zn-Se FTIR window.

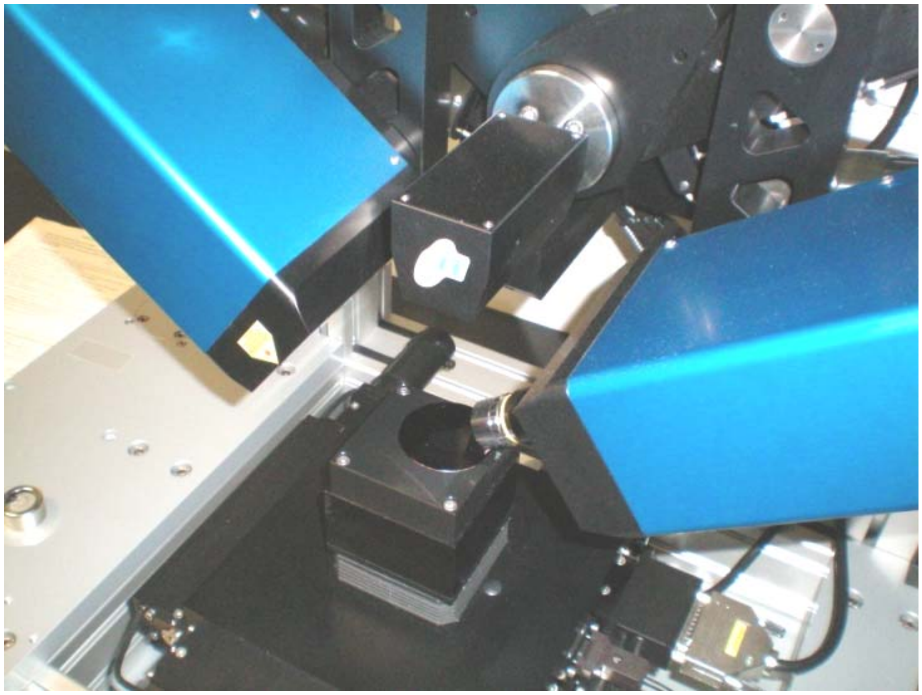

Figure M2b.3. Ellipsometer being used to measure the thickness of the thin film and its refractive index.

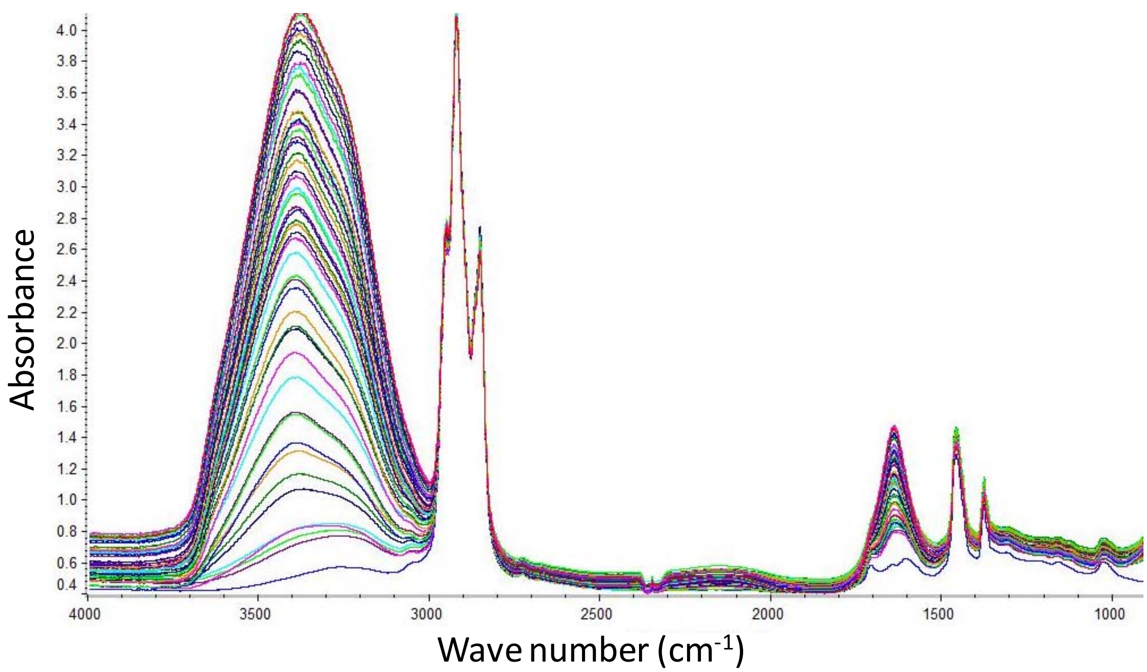

Figure M2b.4. Typical spectra indicating the increase in moisture concentration over time obtained for asphalt binder AAD (film thickness of about 1600 nm).

We have also started tests based on gravimetric measurements to determine the diffusivity of water in fine aggregate matrix (FAM) specimens. Although, the use of the gravimetric method requires significant amount of time, the measurements are relatively easy to obtain and can provide an initial estimate for the range of expected diffusivity in FAM specimens.

A more detailed description of the above methodology can be found in the previous quarterly reports.

Significant Problems, Issues and Potential Impact on Progress

Several experimental challenges were encountered during the development of this test procedure. While, we have now developed a working test procedure the schedule of deliverables will have to be modified to accommodate these changes.

Year Three Work Plan

Measurements using the FTIR to determine the diffusivity of water through asphalt binders will be continued through the first quarter of year three. Emphasis will be placed on establishing the repeatability of the test method; evaluating sensitivity of the test method to changes in film thickness and type of binder.

Four asphalts (AAB – PG 58-22; AAD – PG 58-28; AAF – PG 64-10; and ABD – PG 55-10) from the Strategic Highway Research Program (SHRP) Materials Reference Library (MRL) will be evaluated, since a significant research history has been established with these binders. At least three replicates of each asphalt binder will be tested. The tests will include measurement of diffusivity of water through these asphalt binders as well as measurement of hysteresis in the diffusivity of water through these binders.

Table for Decision Points and Deliverables

Date	**Deliverable**	**Description**
09/31/09(1)	Journal Paper	Measurement of diffusion of water through thin films of asphalt binders
12/31/09(1)	Draft Report	
01/31/10(1)	Final Report	
09/30/11(2)	Journal Paper	Kinetics of debonding at the binder-aggregate interface
12/31/11(2)	Draft Report	
03/31/12(2)	Final Report	
09/30/11	Journal Paper	Modeling moisture transport through a asphalt mixture composite
12/31/11	Draft Report	
03/31/12	Final Report	

(1) These deliverables have been delayed by approximately 6 months 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) These deliverables have been moved to coincide with the third area (modeling moisture transport). This is because in the first three deliverables an additional component on evaluating the hysteresis in moisture diffusivity was added.

Cited References

Crank, J., 1975, *The Mathematics of Diffusion*. 2nd ed., Oxford University Press, NY.

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

Major Findings and Status

The most notable finding for Year 2 was that the sample preparation procedure was completed to have a good control of the film thickness. Also, software was developed to record pressure and displacement as a function of time. The attempts to measure displacement in the modified Pneumatic Adhesion Tensile Testing Instrument (PATTI) device were unfortunately unsuccessful because the device does not allow good control of the pressure increase rate, and with the existing pressure control the rate of deformation is very fast and test takes less than a few seconds. The testing was too fast with a displacement too small for the linear variable differential transformer (LVDT) to provide accurate and repeatable sample strain measurements.

The modified PATTI device (with data acquisition) is now operational and is capable of delivering results with satisfactory repeatability on pressure measurements and ultimate stress determination. The new sample stub with film thickness control is finalized and all testing will be conducted at one film thickness.

The testing results indicated that there is an effect of application temperature on the ultimate stress. Therefore, more testing will be conducted to control temperature of aggregate surface and binder.

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

Due to the speed of the test and the LVDT's inherent faults in data acquisition speed for very small displacements, the attempts to measure strain in the modified PATTI device were unsuccessful. Instead, it was determined that by simply recording the stress applied to the sample versus time, it was possible to discern between binders with different modification levels or types of modification. To prevent further delays to this project, it was decided to base all measurements on stress versus time readings. By doing so, no significant changes or delays are expected to further affect the testing schedule.

Year 3 Work Plan

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

The research team plans on completing this subtask by the end of Year 2.

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

The research team anticipates completing this subtask by the end of the first quarter of Year 3. Only minor testing will be extended into the first quarter of Year 3, but it would not affect the progress of other subtasks in the work planned for Year 3 for this project.

Subtask M2c-3: Conduct testing

A summary of the tests to be performed in this subtask are highlighted in table M2c.1.

Table M2c.1. Proposed tests on asphalt binders and mixes.

Testing Techniques	Modified PATTI DSR
Mineral Surfaces	Three
Binders	Three
Conditioning Environments	Three
Binding Temperatures	Two (65 °C and 135 °C)
Conditioning Temperatures	One (65 °C)
Testing Temperatures	Two (10 °C and 25 °C)
Pullout Rates	Two (slow and fast)

Selected samples of the modified and unmodified binders tested in Subtask M2c-2 will be tested using the Dynamic Shear Rheometer (DSR). This testing will be used to validate the results from the modified PATTI test and to indicate which modifications are necessary or unnecessary to measure binder cohesion and aggregate-binder adhesion behavior. The tests will be structured to investigate the influence of the temperature of testing, the conditioning temperature and the pulling rate. Also, the comparison between the axial pull-off testing and shear stress sweep will be included in the testing.

Subtask M2c-4: Analysis and interpretation

The same testing protocol used for testing binders will also be used for testing selected mastics. The results will identify suitability of the test systems to binder-filler mastics.

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

The objective of this task is to analyze experimental data and evaluate the responses collected during the various tasks to make recommendations regarding the modified PATTI test and its applicability to moisture damage of asphalt mixtures. The results of binder and mastic testing will be used with research efforts in other ARC work elements to evaluate their relationship to surface energy testing and the results of the sorption device.

The research team believes that the modified PATTI device can be modified to provide more complete information about the binder during testing. In this task, manufacturers of the PATTI device will be contacted to explore the cost and commercialization possibilities of the modified PATTI test. State DOTs and consulting labs will be contacted to collect feedback about the practicality of the test system and the merits of standardizing the modified PATTI test for the evaluation of binder cohesion and aggregate-binder adhesion. Presentations at the binder and mixture ETGs will be prepared and delivered to collect feedback from experts. The feedback will be summarized and used to make modifications in the developed system.

Table for Decision Points and Deliverables

Date	Deliverable	Description
6/09	Standard Protocol for PATTI Testing	Deliver a report on the results and details of the standard testing procedure in ASTM/AASHTO format. The report will include information about contacts with manufacturers of PATTI.
9/09	Journal Paper	Submit to AAPT or TRB highlighting findings from this task.
1/10	Report on Comparison Between DSR Tackiness and PATTI Results	Deliver a project report on the possibility of using modified PATTI as a surrogate for measuring adhesion and cohesion with and without water conditioning .

CATEGORY M3: AGGREGATE SURFACE

Work Element M3a: Aggregate Surface

Major Findings & 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.

Current tasks are organized around the (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), and (2) the characterization of the surface energies of reference minerals and aggregates through the universal sorption device and microcalorimetry. The results from these tasks will support the development of a predictive model of aggregate surface energies based upon the surface energies of the minerals that compose the aggregate.

We propose to develop a predictive model of aggregate surface energy based upon a linear additive model of the surface energies of individual minerals that compose the aggregates.

While aggregate properties are very heterogeneous, most aggregates are composed of a relatively few minerals (Table 1).

Year Three Work Plan

Subtask M3a-1: Petrographic Analysis of Reference Aggregates and Minerals

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

Steps involved in the detailed characterization of the aggregates:

i) Examine a comprehensive range of representative aggregate materials to determine mineralogical content, grain size and texture. This will initially be done by optical petrography techniques (polished thin sections), followed by elemental distribution maps acquired on an electron microprobe using wavelength-dispersive (WDS) X-ray as well as backscattered electron (BSE) signals. The compositions of the individual aggregate minerals will then be determined by quantitative individual-point X-ray WDS analyses on the electron microprobe.

ii) Based on the mineralogy of the aggregates, acquire suitable individual mineral reference materials for further testing. These minerals will include both compositional end-members and intermediate members of the common rock forming minerals found in the aggregate materials. For example, in the plagioclase feldspar series, nearly pure Na plagioclase (albite), Ca plagioclase (anorthite) and intermediate Na-Ca plagioclase compositions (andesine, and/or labradorite, etc) will be acquired and analyzed so that these individual well-characterized mineral components can be used in some of the aggregate-asphalt experiments.

Table M3a.1 shows the current petrographic data set available for the reference aggregates while table M3a.2 shows the current petrographic data set available for the minerals.

Table M3a.1. Status of tasks associated with mineralogical and chemical characterization of aggregates.

SH RP	Name	08 Qtr	Thin Section Prep Status	Microprobe Analysis Status
RA	Lithonia Granite	1	1 aggr sample prepared, 2 more in progress	1 set of X-ray maps, 1 set of BSE images, 1 preliminary set of WDS quant analyses
		2	2 more aggregate samples prepared	2 sets of X-ray maps, BSE images are not needed because of grain size
RC	Limestone (higher absorption)	1	2 aggr samples prepared	1 set of X-ray maps, 1 set of BSE images, 1 preliminary set of WDS quant analyses
		2	-	No additional analyses
RD	Limestone (low absorp.)	1	4 aggr samples prepared,	4 sets of X-ray maps, 1 set of BSE images, 1 preliminary set of WDS quant analyses
		2	-	No additional analyses
RK	Basalt	1	2 aggr samples prepared, 1 more in progress	2 sets of X-ray maps, 1 set of BSE images, 1 preliminary set of WDS quant analyses
		2	1 sample in progress	3 additional sets of X-ray maps, 13 set of BSE images, 1 set of WDS quant analyses for pyroxene, olivine, amphibole
RL	Gulf Coast Gravel	1	5 aggr samples prepared, 9 more in progress	4 sets of X-ray maps, 1 set of BSE images, 1 preliminary set of WDS quant analyses
		2	9 more in progress	9 sets of X-ray maps

Table M3a.2. Status of tasks associated with mineralogical and chemical characterization of mineral components of aggregates.

Mineral	Group	08 Qtr	(1) Acquisition Status (2) Microprobe Mount Status	Microprobe Analysis Status
Quartz	Silica Mineral	1	(1) > 200 grams acquired (Arkansas, RNG specimen) (2) Polished microprobe mount in preparation	In progress
		2	In progress	In progress
Microcline	Alkali Feldspar	1	(1) > 160 grams acquired (G&G collection, B0434) (2) Preliminary polished mount prepared	Preliminary homogeneity and quantitative chemical analysis acquired.
		2	In progress	In progress
Albite	Plagioclase Feldspar	1	(1) > 100 grams acquired (G&G collection, B0469) (2) Polished mount to be prepared	In progress
		2	In progress	In progress
Oligoclase	Plagioclase Feldspar	3	> 100 grams acquired (G&G collection, 008)	In progress
Andesine	Plagioclase Feldspar	1	(1) > 65 grams acquired (G&G collection, B0513) (2) Preliminary polished mount prepared	Preliminary homogeneity and quantitative chemical analysis acquired.
		2	In progress	In progress
Labradorite	Plagioclase Feldspar	1	(1) > 160 grams acquired (Naim, Labrador; RNG specimen) (2) Preliminary polished mount prepared	Preliminary homogeneity and quantitative chemical analysis acquired.
		2	In progress	In progress
Anorthite	Plagioclase Feldspar	1	Samples to be acquired	NA
		2	NA	NA

Table M3a.2. Status of tasks associated with mineralogical and chemical characterization of mineral components of aggregates, cont.

Mineral	Group	08 Qtr	(1) Acquisition Status (2) Microprobe Mount Status	Microprobe Analysis Status
Hornblende	Amphibole	1	(1) > 350 grams acquired (G&G collection, B0545) (2) Preliminary polished mount prepared	Preliminary homogeneity and quantitative chemical analysis acquired.
		2	In progress	In progress
Hornblende	Amphibole	1	(1) > 70 grams acquired (G&G collection, Room 008) (2) Polished mount to be prepared	In progress
		2	In progress	In progress
Augite	Pyroxene	1	(1) > 0 (?) grams acquired (G&G collection, B1007) (2) Preliminary polished mount prepared	Preliminary homogeneity and quantitative chemical analysis acquired.
		2	In progress	In progress
Augite	Pyroxene	1	(1) > 80 grams acquired (G&G collection, Room 008) (2) Polished mount to be prepared	In progress
		2	In progress	In progress
Forsteritic Olivine	Olivine	1	(1) > 280 grams acquired (San Carlos, AZ) (2) Polished mount to be prepared	In progress
		2	In progress	In progress

Subtask M3a-1: Surface Energy Characterization of Reference Aggregates and Minerals

We seek to (1) characterize the relationship between chemical composition and surface morphology and the surface energies of aggregates, and (2) use these relationships to develop a predictive model of aggregate surface energies based upon aggregate mineralogy.

Methods –A Universal Sorption Device can be used to measure pure phase mineral surface energies. The equilibrium spreading pressure of each vapor is then used to calculate the three surface energy components using GvOC Equations. These values will then be used to establish an additive model of total surface energy for previously characterized rock samples based on percent of each constituent at the surface.

Experiments – Although rock mineralogy has the capacity to be very complex it is dominated by a relatively small group of minerals of predictable variability in North America. The mineralogy of common aggregates used in hot asphalt mixes across America is outlined in the aggregate analysis data from the Strategic Highway Research Program's (SHRP) materials reference library.

The surface energies of these pure phase minerals will be calculated using a Universal Sorption Device using three reference gases to determine spreading pressures. Each mineral will be crushed and passed through a number 10 sieve. Minerals will be washed with distilled water and heated for 24 hours at 80° Celsius in a Fisher Isotemp® Oven. Each reference gas will be used on a separate sample of each pure phase mineral. After the test is run each sample will be washed with distilled water and reheated at 80° C for future analysis.

Data - The specific surface area and adsorption isotherm of different gases used in the Universal Sorption Device are then used to calculate three surface energy components using the GvOC equation:

$$W = 2\sqrt{\gamma_S^{lw}\gamma_V^{lw}} + 2\sqrt{\gamma_S^{+}\gamma_V^{-}} + 2\sqrt{\gamma_S^{-}\gamma_V^{+}}$$

where g^{Total} = total surface energy of the material; g^{lw} = Lifhsitz–van der Waals or dispersive component; g^{AB} = acid-base component; g^{+} = Lewis acid component, and g^{-} = Lewis base component.

Model - We expect the bulk/total surface energy of an aggregate to be a function of the component surface energies of its mineralogical constituents as:

$$Se_{aggregate} = \sum (Se_{Mineral} \cdot SA) + \sigma$$

where Se is surface energy, SA is surface area, and σ is the error term. A visual inspection of rock mineralogy based on percent of constituents can accurately predict total surface energy of the sample.

Table for Decision Points & Deliverables

Date	Deliverable	Description
03/30/09	Decision Point	Validate preliminary model based upon characterized samples
06/30/09	Draft Report	Report on findings from subtasks M3a-1
09/30/09	Final Report	Final Report on findings from subtasks M3a-1
12/01/09	Journal Paper	Surface Energies of Minerals and Aggregates

CATEGORY M4: MODELING

Work Element M4a: Micromechanics Model (TAMU)

Major Findings & Status

A detailed literature review was conducted to identify the modeling aspects related to moisture induced damage at adhesive interfaces. The review focused on research conducted in areas other than bituminous materials such as the adhesive, thin film packaging, and electronics industries. The key findings from this review were presented in the second quarterly report.

The review was used as a basis for the development of a finite element model to simulate the loss of adhesive bonds in the presence of moisture at aggregate – binder interface with idealized geometry. The model was developed in the commercial finite element package ABAQUS®. The finite element model relies on coupling moisture diffusion and fracture at adhesive interfaces to account for two deterioration processes: 1) degradation of the mastic properties due to the presence of moisture, and 2) deterioration of the aggregate-mastic interface as a function of moisture content (figure M4a.1).

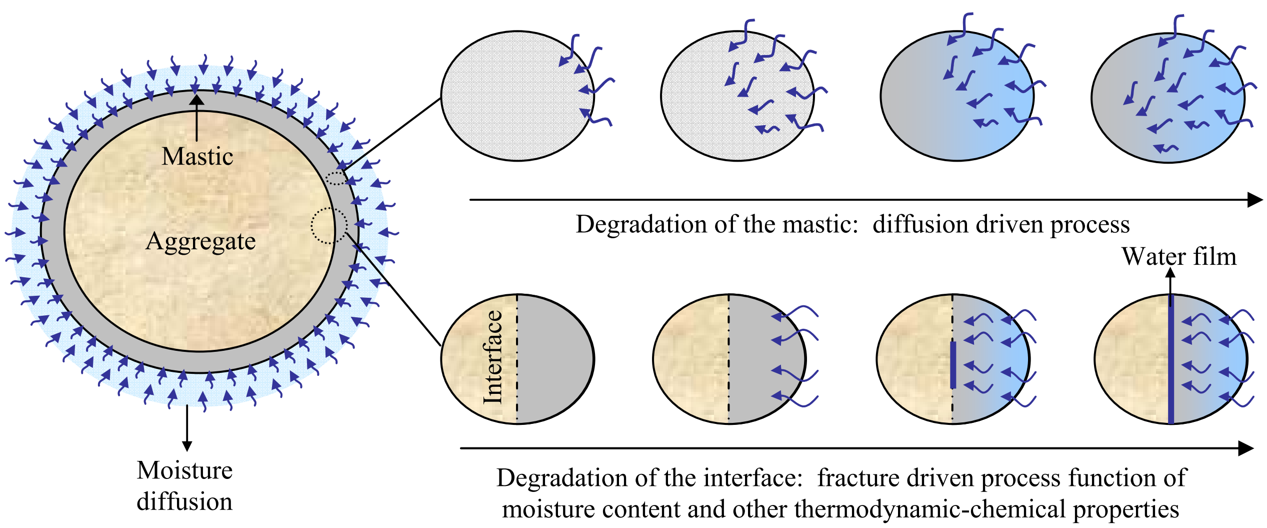

Figure M4a.1. Schematic of the moisture degradation processes considered in the model.

The aggregate-mastic interface was modeled using the cohesive zone elements of zero nominal thickness available in the ABAQUS® software. The constitutive behavior of these cohesive (or adhesive) elements is dictated by a traction-separation law, i.e. fracture nucleation at the interface occurs when the maximum traction capability of an element is overcome. The maximum traction capability is a function of the interface strength, which is a function of moisture content. In addition, the fracture model accounts for the thermodynamic potential and is controlled by the absolute rate of hydrolysis reaction (displacement of interfacial bonds by the presence of water molecules) at the interface.

This model was then extended to analyze the response of a two-dimensional portion of a real asphalt mixture that was subjected to the combined effects of moisture vapor diffusion and mechanical loading. The sample composed two aggregates with realistic shapes embedded in a mastic matrix (figure M4a.2.). The model was implemented in the finite element software ABAQUS® using the sequentially coupled moisture-mechanical scheme described in the last quarterly report. This model captures the adverse effect of water on the linear viscoelastic properties of the mastic and simulates the adhesive fracture at the aggregate-mastic interface by using a Cohesive Zone Model (CZM) technique.

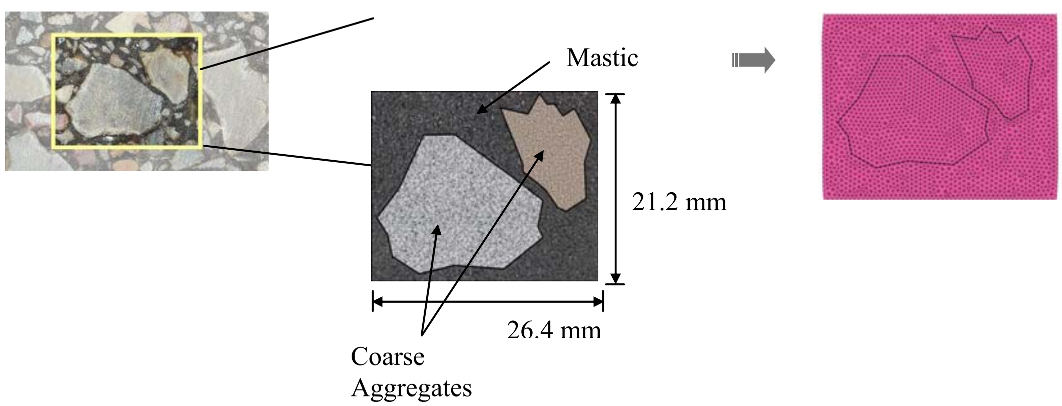

Figure M4a.2. Geometry and finite element implementation of a micromechanical model from a real asphalt mixture.

The simulations conducted were useful to:

- Corroborate the coupling abilities of the model,
- Cnalyze the effects of moisture on: the type of failure within the sample as a function of moisture content (cohesive vs. adhesive), the time required for adhesive fracture (i.e., time for crack initiation at the aggregate-mastic interface), the rate of adhesive-crack propagation, and the different adhesive-bond failure patterns (figure M4a.3.),
- Identify potential research activities involving the application of the model, and
- Identify the aspects that should be incorporated in order to improve the quality of the current model.

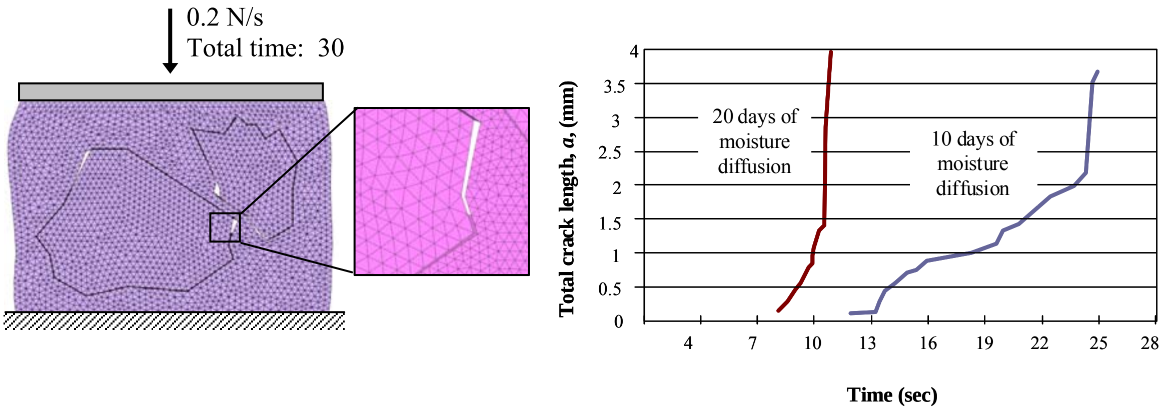

Figure M4a.3. Crack length at the interface vs. time during the mechanical test conducted on a sample subjected to 20 days of moisture diffusion and a sample subjected to 10 days of moisture diffusion (same boundary conditions).

A more detailed description of the above methodology can be found in the previous quarterly reports and Caro et al. (2009).

<u>Year Three Work Plan</u>

The tasks on numerical micromechanical model of moisture damage in asphalt mixtures for next year include:

- Study the impact of the internal void structure of asphalt mixtures on the development of moisture-induced damage,
- Use thermodynamic principles to simulate the saturation of water occurring at the aggregate-mastic interface
- Calibrate the fracture properties used in the model by using the experimental results obtained from mechanical adhesive tests.

The impact of air voids on the development of moisture damage will be analyzed from different perspectives: 1) assuming the bulk matrix acts as a continuum material (e.g., mastic or fine aggregate matrix), 2) including the presence of air voids directly into the model based on the probabilistic distribution of sizes and location of the internal void structure of asphalt mixtures (Masad et al. 2006a), and 3) using random fields theory to locally assign different physical properties to the continuum bulk matrix in order to achieve a better representation of the micro-scale behavior of this material.

Researchers at TAMU have developed techniques to measure the surface free energy of aggregates, asphalt binders and mastics. This information has been used to demonstrate that the work of adhesion computed from the surfaces free energies of the individual components of a mixture can be used as an indicator of the potential level of moisture susceptibility of the composite (Bhasin and Little 2007; Bhasin et al. 2006; Masad et al. 2006b, Caro et al. 2008).

Currently, the micromechanical model of moisture damage includes this thermodynamic potential indirectly by means of the mechanical and fracture properties of the adhesive zones (i.e., interfaces representing the aggregate-mastic bond). However, this potential should be also used to simulate the moisture diffusion process occurring at the interface. The researchers will explore the possibilities of including this aspect into the model.

Experimental work has been conducted during the last year to determine the adhesive properties of asphalt-metal interfaces and the effect that moisture has on such properties (work element F1a). The experimental program also includes determining the effect of moisture on the adhesive-fracture properties of aggregates-asphalt binder systems and on the bulk viscoelastic properties of different asphalt binders. The results obtained from this experimental program are expected to provide the information required to calibrate the fracture properties of the adhesive zones (i.e., aggregates-mastic interfaces) that are currently used in the model.

Cited References

Bhasin, A., and D. N. Little, 2007, Characterization of Aggregate Surface Energy Using the Universal Sorption Device. *Journal of Materials in Civil Engineering, ASCE*, 19(8): 634-641.

Bhasin, A., E. Masad, D. Little, and R. Lytton, 2006, "Limits on Adhesive Bond Energy for Improved Resistance of Hot Mix Asphalt to Moisture Damage." Transportation Research Board 85th Annual Meeting, TRB, Washington D.C.

Caro, S., E. Masad, A. Bhasin, and D. Little, 2008, Moisture Susceptibility of Asphalt Mixtures, Part I: Mechanisms. *International Journal of Engineering Pavements*, 9(2): 81-98.

Caro, S., E. Masad, A. Bhasin, and D. N. Little, 2009, "A coupled micromechanical model of moisture induced damage in asphalt mixtures." *Journal of Materials, ASCE,* (In Review).

Masad, E., A. Castelblanco, and B. Birgisson, 2006a, Effects of Air Void Size Distribution, Pore Pressure, and Bond Energy on Moisture Damage. *Journal of Testing and Evaluation*, 34(1): 1-9.

Masad, E., C. Zollinger, R. Bulut, D. Little, and R. Lytton, 2006b, Characterization of HMA Moisture Damage Using Surface Energy and Fracture Properties. *Journal of the Association of Asphalt Paving Technologists*, 75, 713-754.

Table for Decision Points and Deliverables

Date	**Deliverable**	**Description**
03/31/08	Journal Paper	Parametric analysis of the influence of coupling between mechanical loads and moisture on resistance to fracture.

Work Element M4b: Analytical Fatigue Model for Mixture Design

Major Findings & Status

The initial development of this work element is the same as sub-task F3c.1 The development of a method to separate the viscoelastic response from fatigue damage and the development of a model to analyze resistance to fatigue cracking under both dry and wet conditions is provided under subtask F1b.1

Year Three Work Plan

The plan is to analyze DMA specimens using the analysis approach described under subtask F1b.1. DMA specimens for three different mixtures will be tested under wet conditions using stress controlled and strain controlled testing conditions as shown in table F3c.1. The testing protocol follows the methods presented by Branco (2008).

Cited 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.

Work Element M4c: Unified Continuum Model

Major Findings & Status

Work element F3c presents the development of the mechanical damage formulation as part of the TAMU continuum model. The TAMU ARC team worked during the last quarter on the development of the moisture damage formulation. The degrading effect of moisture manifests in two physical phenomena: (1) adhesive moisture damage, ϕ_a^M, which is the degradation of the bond strength between the aggregates and the asphalt mastic due to the existence and diffusion of moisture through the thin films surrounding the aggregate particles and along the aggregate-mastic interfaces; and (2) cohesive moisture damage, ϕ_c^M, which is the degradation of the cohesive strength of the asphalt mastic itself. Both (1) and (2) may ultimately lead to erosion of the mastic film due to water flow imposed by passing traffic (scouring effect). The work in this quarter focused on modeling these phenomena independently, which allows one to introduce fundamental mechanical properties (e.g. bond strength and cohesive strength) and model the transition between adhesion and cohesion damage. We are currently preparing a journal paper that will document the modeling of the mechanical damage and moisture damage as part of the TAMU continuum model.

Year Three Work Plan

The work will incorporate the moisture damage formulation as part of the main formulation of TAMU continuum model. We will also conduct parametric analysis of the continuum model in order to verify that the model is capturing the main effects of moisture on the response of asphalt mixtures. The experimental verification of the moisture damage component of the continuum model will be initiated by conducting the tests outlined in table F3c.2 after subjecting the specimens to moisture conditioning.

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 for Deliverables & Decision Points

Work Element	Date	Deliverable	Description
M1a	9/09	Presentation	Presentation on progress of binder testing.
M1a	3/10	Presentation	Presentation on progress of correlation between mixture and binder moisture-damage test results.
M1b-1	09/30/09(1)	Journal Paper	Use of micro calorimeter to measure total energy of adhesion
M1b-1	09/30/10	Journal Paper	(2) See note below
M1b-1	09/30/10	Final Report	(2) See note below
M1c	09/30/09	Journal Paper	Moisture damage resistance of select FAM mixtures subjected to different moisture conditioning procedures
M1c	12/31/10	Draft Report	
M1c	03/31/10	Final Report	
M2a-1	09/30/11	Journal Paper	Surface properties of saturated asphalt binders
M2b	09/31/09(1)	Journal Paper	Measurement of diffusion of water through thin films of asphalt binders
M2b	12/31/09(1)	Draft Report	
M2b	01/31/10(1)	Final Report	
M2b	09/30/11(2)	Journal Paper	Kinetics of debonding at the binder-aggregate interface
M2b	12/31/11(2)	Draft Report	
M2b	03/31/12(2)	Final Report	
M2b	09/30/11	Journal Paper	Modeling moisture transport through a asphalt mixture composite
M2b	12/31/11	Draft Report	
M2b	03/31/12	Final Report	
M2c	6/09	Standard Protocol for PATTI Testing	Deliver a report on the results and details of the standard testing procedure in ASTM/AASHTO format. The report will include information about contacts with manufacturers of PATTI.
M2c	9/09	Journal Paper	Submit to AAPT or TRB highlighting findings from this task.
M2c	1/10	Report on Comparison Between DSR Tackiness and PATTI Results	Deliver a project report on the possibility of using modified PATTI as a surrogate for measuring adhesion and cohesion with and without water conditioning.
M3a	03/30/09	Decision Point	Validate preliminary model based upon characterized samples
M3a	06/30/09	Draft Report	Report on findings from subtasks M3a-1
M3a	09/30/09	Final Report	Final Report on findings from subtasks M3a-1
M3a	12/01/09	Journal Paper	Surface Energies of Minerals and Aggregates
M4a	03/31/08	Journal Paper	Parametric analysis of the influence of coupling between mechanical loads and moisture on resistance to fracture.

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

(2) The journal papers and report were intended to document the development of the test method in this subtask. However, portions of the test method were developed in conjunction with another FHWA project. The effort saved in the development of this method is redirected towards the development of models that utilize the results from these tests. Although we do not envision any further development of the test method, this task is crucial as it will provide data for the modeling efforts in other subtasks. Consequently, items marked as (2) will not appear as stand-alone deliverables. Instead, the data generated from this task will be incorporated into the reports and journal papers from other sub-tasks.

Budget

		Year 1	Year 2	Year 3	Year 4	Year 5
M1a	Affinity of Asphalt to Aggregate - Mechanical Tests (UWM)	75,000	75,000	75,000	75,000	
M1b	Work of Adhesion (TAMU)	75,000	75,000	50,000	50,000	25,000
	Work of Adhesion (WRI)		134,500	146,000	152,500	126,500
M1c	Quantifying Moisture Damage Using DMA (TAMU)		75,000	75,000	100,000	75,000
M2a	Work of Cohesion Based on Surface Energy (TAMU)	75,000	75,000	75,000		
	Work of Cohesion Based on Surface Energy (WRI)		134,500	146,000	152,500	126,500
M2b	Impact of Moisture Diffusion in Asphalt (TAMU)	75,000	150,000	150,000	175,000	
M2c	Thin Film Rheology and Cohesion (UWM)	75,000	100,000	100,000	75,000	
M3a	Impact of Surface Structure of Aggregate (TAMU)	75,000	100,000	125,000		
M4a	Development of Model (TAMU)		125,000	125,000	125,000	150,000
M5a	Moisture Damage Prediction System*				150,000	150,000
TOTAL		450,000	1,044,000	1,067,000	1,055,000	653,000
		4,269,000				

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

Moisture Damage Year 3

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

LEGEND

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[x]	Indicates completion of deliverable x

Work planned
Work completed
Parallel topic

PROGRAM AREA: FATIGUE

CATEGORY F1: MATERIAL AND MIXTURE PROPERTIES

The testing plan using ARC Core materials are listed in Tables F3c.1 and F3c.2 under the Fatigue program area. This plan is for evaluation of test methods and analysis procedures. The testing for purpose of verification and validation will start in year 4.

Work Element F1a: Cohesive and Adhesive Properties

Major Findings & Status

Literature review

A 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, respectively from the University of Nottingham and Imperial College in the United Kingdom. This discussion was as a 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. For elasto-plastic materials the relatively high magnitude of energy dissipated due to irreversible processes such as plastic deformation is one of the primary reasons for this difference. However, evidence in the literature indicates that there exists a relationship between the energy dissipated due to plastic deformation and the work of fracture due to surface free energy. The presence of this relationship has been implicitly verified for asphalt materials in the past. The ARC and other researchers have found consistent agreement between predictions based on models that rely on surface free energy (ideal work of fracture) and expected performance, despite the large difference in magnitudes of ideal and practical work of fracture. In fact, the work element of F1a was specifically designed to determine this relationship for asphalt materials as described in the year 1 and year 2 work plans. The aforementioned findings were documented in the form of a white paper.

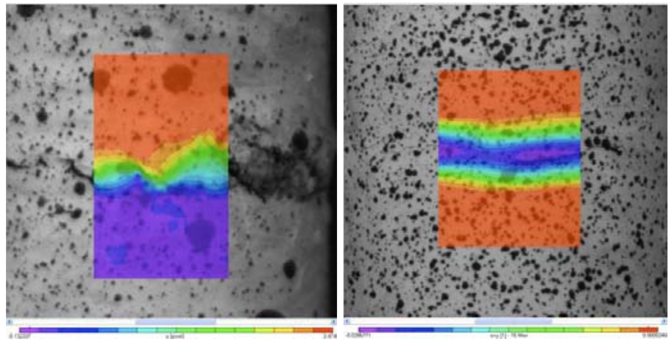
The findings from the aforementioned white paper were discussed in person with Dr. Kinloch and his colleagues from the Imperial College, London and Dr. Scarpas and his colleagues from TU-Delft. The proposed white paper was further reviewed and digested during a joint discussion at TU-Delft with Dr. Scarpas and his group. While this white paper is still a work in progress, the most recent version was transmitted to FHWA for internal use.

It is also important to note that part of the fatigue fracture process is healing. In fact members of the current ARC team have focused on understanding the mechanism of healing for about 15 years and in the past five to 10 years other researchers have taken up this task with considerable interest. One noteworthy effort is the continuing NCHRP project on the fatigue endurance limit which considers healing as a part of the reason for the endurance limit. The current form of the ARC's material characterization model addresses healing as a convolution of the processes of wetting and diffusion. The wetting function incorporates work of cohesion in the process zone that precedes the crack tip. The point to be made here is that even if one were convinced that work of cohesion and ostensibly surface energy are overpowered by plastic deformation or energy dissipated via plastic flow, this would not be the case in the crack closure process or the healing process.

Development of the Test Method

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 inputs such as the traction-separation behavior between binder/mastic-aggregate interface for inputs in the modeling effort.

Several techniques were attempted to create thin films with consistent thickness that could be subjected to transverse tensile loading. We have recently developed the final protocol to prepare these thin film specimens using the gap control feature on a DMA/DSR. The tests to measure the tensile strength of thin films in the transverse mode were conducted using a 5kN universal testing machine with conventional Linear Variable Deflection Transducers (LVDTs). However, these LVDTs were mounted to the loading frame. Consequently, the measured deformation in this mode of testing is the sum of the deformation due to the loading frame and the deformation of the specimen. The deformation of thin films (about 100 microns) at the time of failure is of the order of just a few microns, which is significantly large compared to the deformation within the loading frame itself. Therefore, the deformation recorded using these LVDTs has a very large bias and resulted in unrealistic stress-strain relationships. To rectify this situation, researchers changed to the use of laser or optical LVDTs that use specimen end plates as a datum or reference point. However, due to the specimen end plate geometry, the laser LVDTs amplified even the slightest distortion in the specimen geometry resulting in unrealistic strain measurements. Finally, a high-resolution camera was successfully used to record and measure the strain in the thin film during loading and failure. The final test protocol is now near finalization. Examples of horizontal displacement and shear strain fields in an asphalt binder are shown in figure F1a.1.



(a) Horizontal displacement (b) Shear strain

Figure F1a.1. Examples of (a) horizontal displacement and (b) shear strain in an asphalt binder specimen in the pull-off test.

Test Program and Preliminary Results

Tests have been conducted with films ranging from 50 micron to 5 micron in thickness (figure F1a.2). The tests were conducted with films prepared over a metal substrate instead of an aggregate. This is because metal is a high energy surface similar to aggregates, and it can be used to prepare control surfaces with a very high degree of uniformity. The use of aggregate substrates will be added at a later stage.

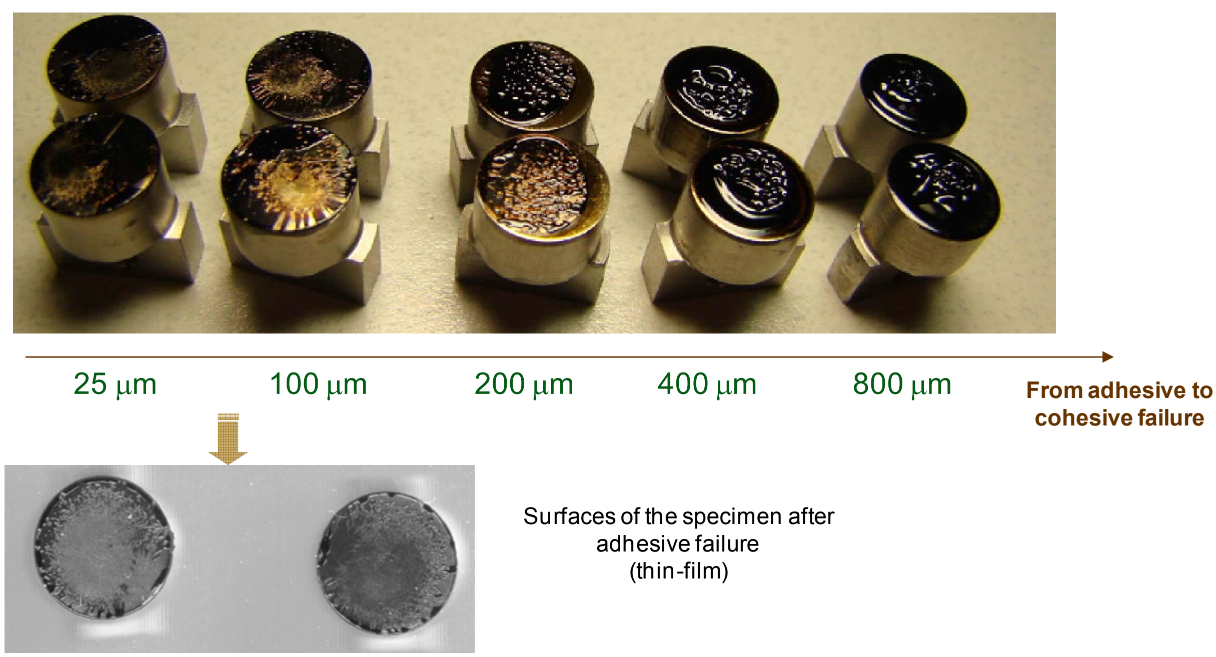


Figure F1a.2. Film thickness sweep using the transverse tensile test on thin films.

Based on some of the preliminary tests conducted on thin films of asphalt binder in the dry condition, a tentative test matrix was developed for this task. The findings from this task are also an integral part of the moisture damage work area, specifically the modeling effort in work element M4a. These test results and the model in work element M4a will be evaluated in conjunction with each other. The detailed test plan was presented in the 3rd quarterly report. Initially three different types of asphalt binders will be tested (AAD, AAB, and ABD). These binders were selected based on their use for method development and validation in other relevant components of this research. The tests will be conducted in two phases. In the first phase, the affect of moisture on the cohesive and adhesive properties will be evaluated (note that fatigue cracking of dry specimens is a special case with no extraneous moisture conditioning). Tests will be performed on all asphalt binders, room temperature, and one loading rate (0.025 mm/sec). In the second phase, the effect of changing the loading rate will be evaluated at one temperature using one asphalt binder.

Significant Problems, Issues and Potential Impact on Progress

Several experimental challenges were encountered during the development of this test procedure. While, we have developed a working test procedure the schedule of deliverables will have to be modified to accommodate these changes.

Year Three Work Plan

Table F1a.1 below shows the testing matrix for the dry tests to be run. Most tests in this matrix have already been completed; however, the data not yet analyzed. Completion of dry testing and data is scheduled for early spring.

Upon completion of the testing of dry samples, testing will begin on moisture conditioned samples. Two aggregates will be chosen with different mineralogy. Aggregate sample holders with the same dimensions as the current stainless steel sample holders will be manufactured using the two selected aggregates. Samples will be prepared from asphalts AAB, AAD, and ABD. These samples will be conditioned at 35^0C for different periods of time at different levels of humidity. Through this research it is hoped that the moisture sensitivity of the different aggregate-asphalt combinations can be determined mechanically and compared to the corresponding surface energy values.

Researchers will explore the effect of loading rate on the bond strength of thin films of asphalt binder and corresponding adhesive-cohesive transition point. We believe that the adhesive-cohesive transition point will shift to a thicker film, but the effect on the stress strain curve at this film thickness is not known. These tests will provide a better understanding of the viscoelastic effects of thin films of asphalt binder.

Table F1a.1. Pull-off tests for binder characterization in dry conditions for AAD, AAB and ABD.

AAD

Number of Tests to Run	Dry								
	Thin Film Adhesive - 15 um	Film Thickness Sweep						Cohesive Failure	Relaxation - DSR
		5 um	10 um	20 um	25 um	30 um	40 um		
Sample 1									
Sample 2									
Sample 3									
Sample 4									
Sample 5									
Sample 6									
Sample 7									
Sample 8									

AAB

Number of Tests to Run	Dry								
	Thin Film Adhesive - 15 um	Film Thickness Sweep						Cohesive Failure	Relaxation - DSR
		5 um	10 um	20 um	25 um	30 um	40 um		
Sample 1									
Sample 2									
Sample 3									
Sample 4									
Sample 5									
Sample 6									
Sample 7									
Sample 8									

ABD

Number of Tests to Run	Dry								
	Thin Film Adhesive - 15 um	Film Thickness Sweep						Cohesive Failure	Relaxation - DSR
		20 um	25 um	30 um	40 um	50 um	60 um		
Sample 1									
Sample 2									
Sample 3									
Sample 4									
Sample 5									
Sample 6									
Sample 7									
Sample 8									

Table for Decision Points and Deliverables

Date	Deliverable	Description
12/31/08	Journal Paper	A review of practical and thermodynamic work of cohesion and adhesion (1)
06/30/09	Journal Paper	Comparing practical and thermodynamic work of adhesion and cohesion
12/31/09	Draft Report	
03/31/10	Final Report	
09/30/11	Journal Paper	On the acid-base scale of surface energy components

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

Work Element F1b: Viscoelastic Properties

<u>Subtask F1b-1: Viscoelastic properties under cyclic loading</u>

The findings and plans reported here combine those for this subtask and subtask 3c.1: *Analytical Fatigue Model for Use During Mixture Design.* The method applies to M1c and M4b after moisture conditioning of specimens.

<u>Major Findings & Status</u>

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 summarizes the three important components of this methodology.

Table F1b.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

<u>Step 1:</u> 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 illustrates typical results from a stress sweep test. From Figure F1b.1, the limiting stress amplitude that generates a nonlinear viscoelastic response without causing damage was found to be approximately 4.5E+04 Pa.

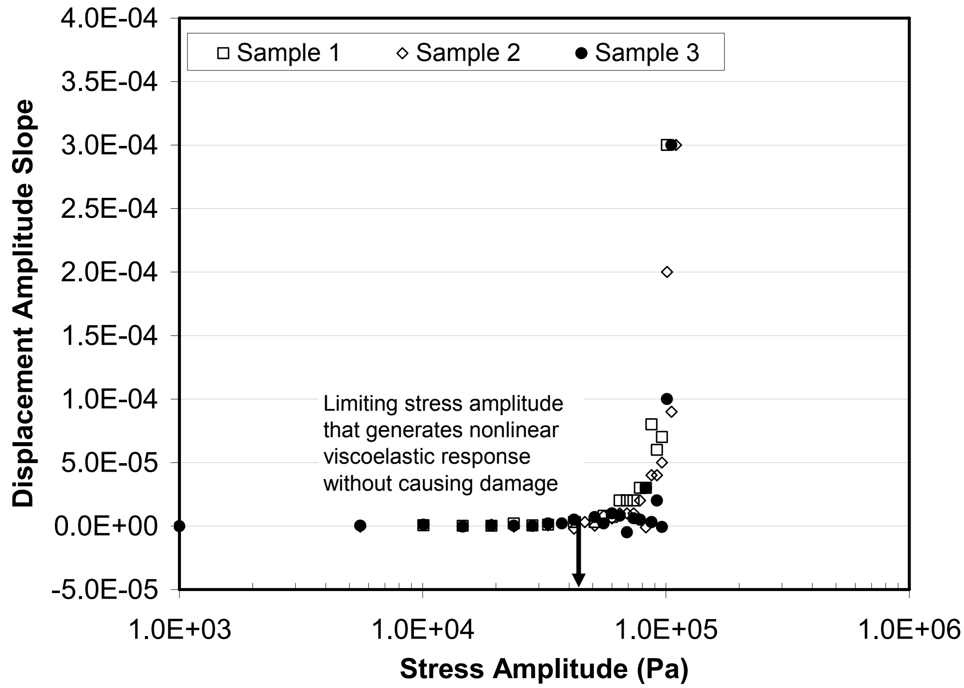


Figure F1b.1. Displacement amplitude slopes.

Step 2: Two different approaches were used to characterize damage evolution in fine aggregate matrix specimens subjected to cyclic loading. The first approach was based on the crack growth index which was improved to account 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 responses 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. The details of the findings from this study will be documented in the forthcoming detailed technical report and journal paper.

Step 3: In order to develop an analytical solution to characterize the response of non-linear viscoelastic materials subjected to dynamic loading, it is first necessary to express the four non-linear terms as a function of stress and then use these functions in the modified superposition principle. Initial work on this approach was carried out using available creep-recovery data for a non-linear viscoelastic adhesive material. The four terms that describe non-linearity, g_0, g_1, g_2, and a_σ were then expressed as bi-linear functions of stress (figure F1b.3.). These functions are now being used to determine an analytical formulation that expresses the non-linear viscoelastic response of the material subjected to dynamic loading. The key feature of this analytical formulation will be that the phase angle will vary within the load cycle and will be expressed as a function of time.

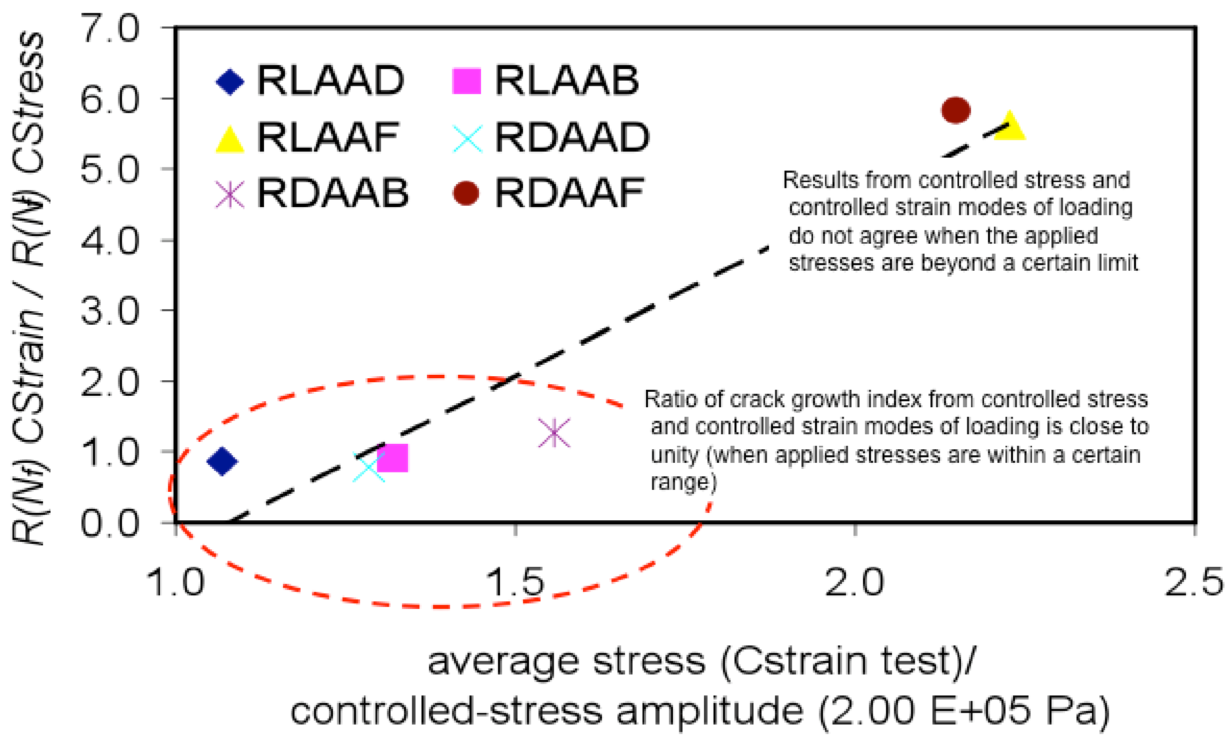


Figure F1b.2. Illustration of the uniformity of results from controlled stress and controlled strain modes of loading within a certain stress range.

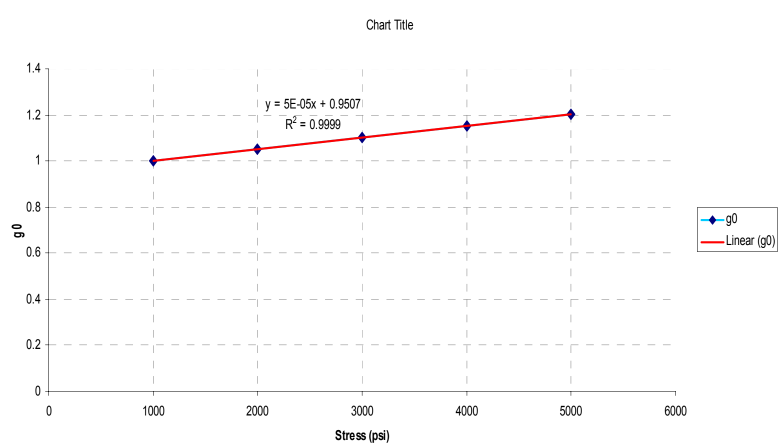


Figure F1b.3(a), g_0 as a bilinear function of stress.

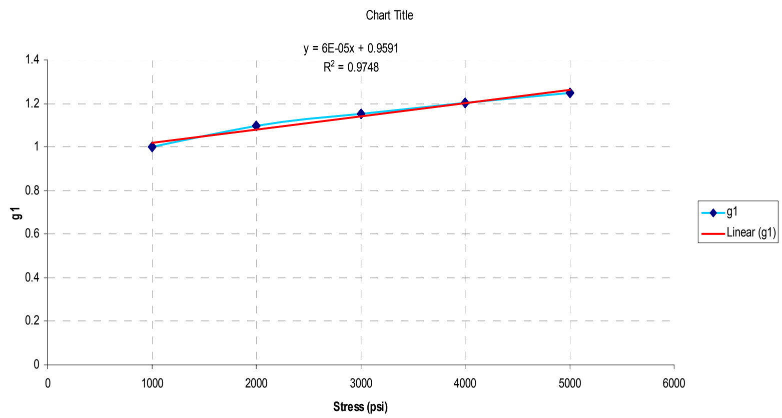


Figure F1b.3(b). g_1 as a bilinear function of stress.

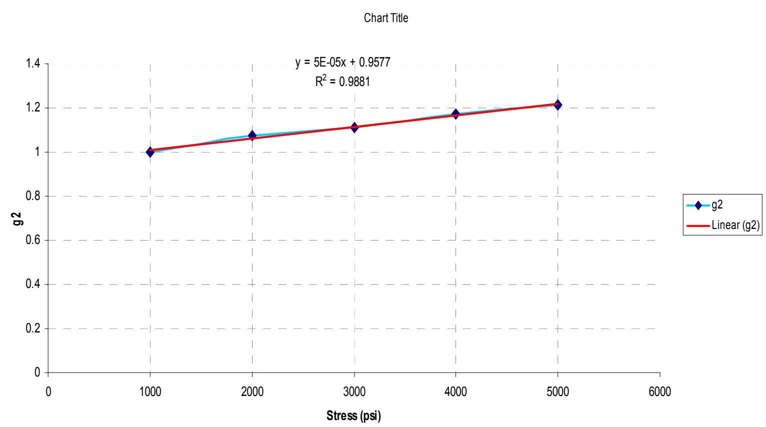


Figure F1b.3(c). g_2 as a bilinear function of stress.

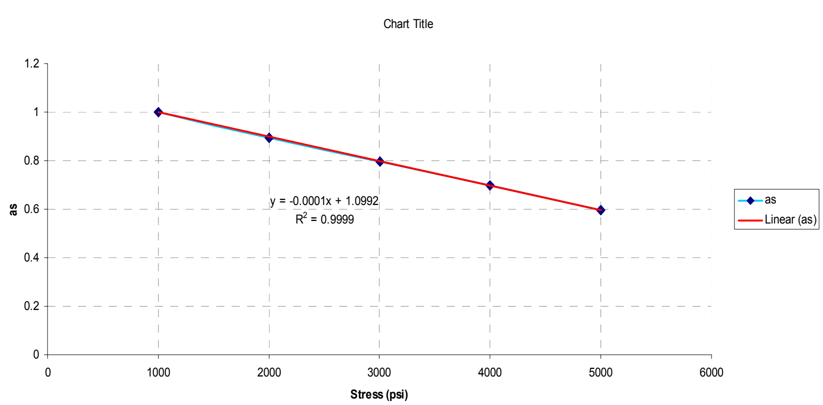


Figure F1b.3(d): a_σ as a bilinear function of stress.

For a more detailed discussion on steps 1 and 2 please refer to Castelo Branco (2008).

Year Three Work Plan

The work in year three will concentrate on validating the model in step three described above. The modeling effort will be based on testing of asphalt binders both in torsion and in normal tension. The following factors will be considered while developing and refining the test matrix to provide inputs for this model.

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, and
ii) repeated cyclic tests until failure (similar testing will be conducted for work element F1d to evaluate healing by incorporating a dwell time after each cycle during the repeated load test).

Table for Decision Points and Deliverables

Date	Deliverable	Description
12/31/08(1)	Draft Report	Use of non-linear viscoelastic properties to characterize fatigue damage and delineate non-linear viscoelastic response from damage
12/31/08(1)	Journal Paper	
03/31/09(1)	Mathematical model	
03/31/09(1)	Final Report	
03/31/10	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 draft report and the Microsoft Excel module that was developed will be submitted to FHWA by 03/31/2009.

Cited 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 for the separation of the nonlinear viscoelastic response from permanent deformation. This method was applied to monotonic tests from the Nottingham database. The main findings from this analysis were reported as part of the quarterly report submitted on January 2009 to FHWA.

The experimental results have shown that the Schapery (1969) nonlinear model can capture the mixture viscoelastic response when no damage is done to the sample. This was deemed necessary because previous studies showed that the nonlinear response of the binder can induce a nonlinear mixture without damage (Branco 2008). This nonlinear response can be mistakenly accounted for as damage if a linear viscoelastic mode is used to describe the undamaged state of the material. Schapery's nonlinear viscoelastic model has a simple formulation that is capable of accounting of time-temperature shift, time-stress shift, aging and other environmental factors. The study by Masad et al. (2008) presents preliminary results showing that this model is capable of describing the effect of binder aging, and the study by Huang et al. (2007) demonstrated the capability of the model to describe the nonlinear response of asphalt mixtures.

Year Three Work Plan

The method for separating the nonlinear viscoelastic and viscoplastic components will be used in the analysis of experimental measurements described in Sub-task F3c.2. Future plans for the continuum model are presented in Sub-task F3c.2.

Table for Decision Points and Deliverables

Date	Deliverable	Description
03/31/09	Journal Paper	The use of the method for separation of viscoelastic response from the viscoplastic response.

Cited 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."

Huang, C. W., E. Masad, A. Muliana, and H. Bahia, 2007, Nonlinearly Viscoelastic Analysis of Asphalt Mixes Subjected to Shear Loading. *Mechanics of Time Dependent Materials*, 11(2): 91-110.

Masad, E., C. W. Huang, G. Airey, and A. Muliana, 2008, "Nonlinear Viscoelastic Analysis of Unaged and Aged Asphalt Binders," *Construction and Building Materials*, (Accepted for Publication).

Schapery, R. A., 1969, Nonlinear Viscoelastic Solids. *International Journal of Solids and Structures*, 259-366.

Work element F1c: Aging

Major Findings & Status

Year two 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 journal paper has been prepared 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, a detailed aging experimental design was prepared and submitted to the FHWA. This design presents the planned mixture and recovered binder tests that are to be done at different levels of binder aging for the purpose of developing a fundamental understanding of the effect of binder oxidation on mixture fatigue resistance properties, including binder healing.

Year Three 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 3 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.

Subtask F1c-2: Develop Experimental Design

A 63 page experimental plan was recently completed and submitted. The Year 3 effort will carry out this plan. The plan is further discussed under Subtask F1c-4.

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 more formal validation and calibration. This effort will begin in Year 3 by testing field cores, obtained from the WRI test pavements in Arizona, Kansas, Nevada, Minnesota, and Wyoming, and the binder, recovered from several depths.

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

This subtask will comprise the major effort of the F1c task in year 3. Details are given in the recently submitted extensive experimental plan. The effort is summarized in this Year 3 plan in tables F1c.1 and F1c.2.

Table F1c.1 provides a summary of the experimental design, consisting of a pilot experiment, field-mixed-field-compacted (FMFC) cores, and an expanded experiment. The purpose of these tests will be to determine the effect of binder oxidation on mixture properties that relate to fatigue and healing.

Table F1c.1. Summary of Experimental Design to Evaluate Aging

	Pilot Experiment	**FMFC Cores**	**Expanded Experiment**
Purpose	Propose testing and analysis method to examine fatigue resistance & effect of aging	Verify testing and analysis method proposed in the pilot experiment with actual mixtures	Determine parameters that influence fatigue resistance & aging with the testing protocol proposed in the pilot experiment
Materials	Two unmodified binders + TX limestone + Tx DOT type C gradation	**-To be coordinated with larger ARC project**	4 core binders & 4 polymer-modified binders +2 core aggregates (CA granite & AR/TX Gravel or NV Andestie) + dense graded
Specimen	SGC compaction & core to 4" ϕ x 4" cylindrical	Cut prismatic from 6" ϕ core & saw to 5'' x 3'' rectangular, thickness varies with the asphalt layer under examination	SGC compaction & core to 4" ϕ x 4" cylindrical
Aging Period	0 & 6 months at 60 °C	multiple field aging periods	Dense-Graded
Binder Content	Optimum	-	Optimum, Optimum ± 0.5%
AC Content	4% & 7%	-	Low (< 5%), Medium (5-9%), high (>9%)
Lab Testing	CMSE* – TS @ 20°C Viscoelastic Characterization @ 10. 20. & 30°C RDT* @ 20 °C for 1000 cycles with multiple healing period Surface Energy of binder (WPT) & aggregate (USD) X-ray CT – AV distribution, interconnected AV CoreLok – total AV, accessible AV DSR Function, FT-IR, SEC – binder stiffening of neat & recovered binders		

Table F1c.2 summarizes the tests that will be conducted on the laboratory mixtures and field cores. The tests and their analyses are described in detail in the experimental plan. CMSE* is a modified calibrated mechanistic with surface energy test that uses tensile strength (TS) testing, viscoelastic characterization (VEC), a modified repeated direct tension test (RDT*), and Wilhelmy plate (WP) and universal sorption device (USD) for surface energy measurements of the binder and aggregate. Additionally, X-ray CT testing (for mixture air voids analysis) and binder tests (dynamic shear rheometry, DSR; Fourier transform infrared, FTIR; and size exclusion chromatography, SEC) as the binder ages will be used for complete materials characterization.

Table F1c.2. Summary of testing input and ouput for aging experimental design.

Test		**Input**	**Output**
CMSE*	**TS**	Tensile load Measured load (stress) Measured deformation (strain)	Tensile strength, σ_f Strain @ maximum stress, ε_f
	VEC	Tensile load Temperature: 10, 20, 30°C Measured load (stress) Measured axial and radial deformation (strain)	Elastic relaxation modulus Viscoelastic Poisson's ratio Complex modulus Phase angle Master curve
	RDT*	Controlled strain: 300 $\mu\varepsilon$ Continuous cyclic haversine load Multiple rest periods Measured load (stress) Measured deformation (strain)	Pseudo strain energy Rate of fracture damage accumulation Average crack radius Paris' Law coefficients Healing index
	WP	Loading force, F Dynamic contact angle, θ	Surface energy components: Γ_i^{LW}, Γ_i^{+}, Γ_i^{-} Total surface energy, Γ
	USD	Vapor pressure @ aggregate surface Adsorbed gas mass Testing time	Surface energy components: Γ_i^{LW}, Γ_i^{+}, Γ_i^{-} Total surface energy, Γ
X-ray CT		Test parameters Specimen dimension	Total air voids content Air voids size & distribution Water accessible air voids
DSR, FTIR, SEC		Complex viscosity @ 60°C Dynamic viscosity @ 45°C Storage modulus & loss modulus @ 20, 40, 60°C	Master curve DSR function Level of oxidation

<u>Subtask F1c-5: Polymer Modified Asphalt Materials</u>

This subtask will be begun during Year 3 as part of the experimental design that includes polymer-modified materials.

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

Date	**Deliverable**	**Description**
07/09	Presentation	Present early results on binder oxidation and fatigue (F1c-4)
08/09	Presentation	Present pavement oxidation transport model, Qindao (F1c-3)
01/10	Presentation, Journal Paper	Present field comparison of oxidation model (F1c-3, F1c-4). Submit for publication 8/09.
01/10	Presentation, Journal Paper	Results on binder oxidation and fatigue (F1c-4). Submit for publication 8/09.
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)

Major Findings & Status

Literature Review

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 of last year and was also summarized as a book chapter (Little and Bhasin 2007).

Development of a healing model

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:

i) wetting of the two faces of a nano crack,
ii) instantaneous strength gain due to interfacial cohesion between the crack faces, and
iii) 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). In this case, wetting of the crack faces is due to closing of the crack. Therefore, the rate of wetting can be obtained from the crack closing speed. Schapery (1989) developed a relationship between the crack closing speed and material properties such as the work of cohesion and compliance parameters. Based on this relationship, the wetting distribution function or rate of wetting of a crack surface can be shown as follows:

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

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.

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.

$$R_h(t) = R_0 + p(1 - e^{-qt^r}) \qquad \text{(F1d.3)}$$

Equation F1d.3 represents the sum effect of: i) instantaneous strength gain due to interfacial cohesion at the crack interface, represented by the parameter R_0 , and ii) time dependent strength gain due to inter diffusion of molecules between the crack surfaces, represented by $p\left(1 - e^{-qt^r}\right)$, where, p, q, and r are material related parameters that define the time dependent strength gain at the interface.

Development of a test method

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 is 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. Figure F1d.1 presents a schematic of this test procedure. Figure F1d.2 illustrates the differences in intrinsic healing function for different asphalt binders as well as the repeatability of this test method. The test method was partially validated by comparing the work of cohesion to the instantaneous component of the intrinsic healing fucntion (figure F1d.3).

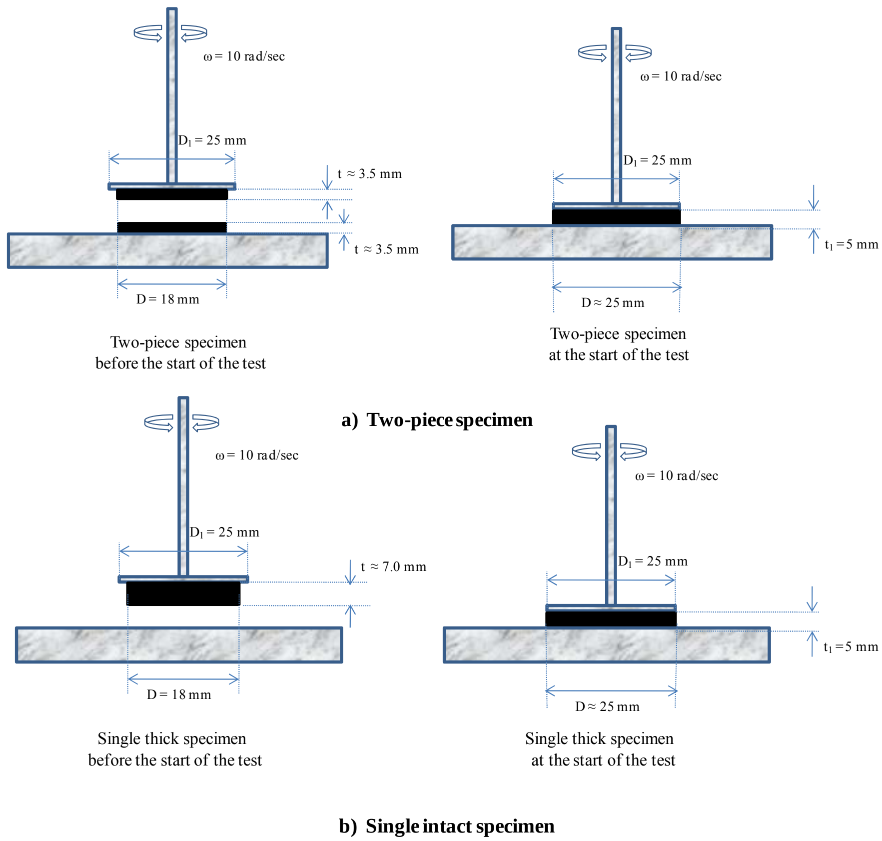


Figure F1d.1. Schematic illustration of the two pieces and intact test specimens used to determine the intrinsic healing function.

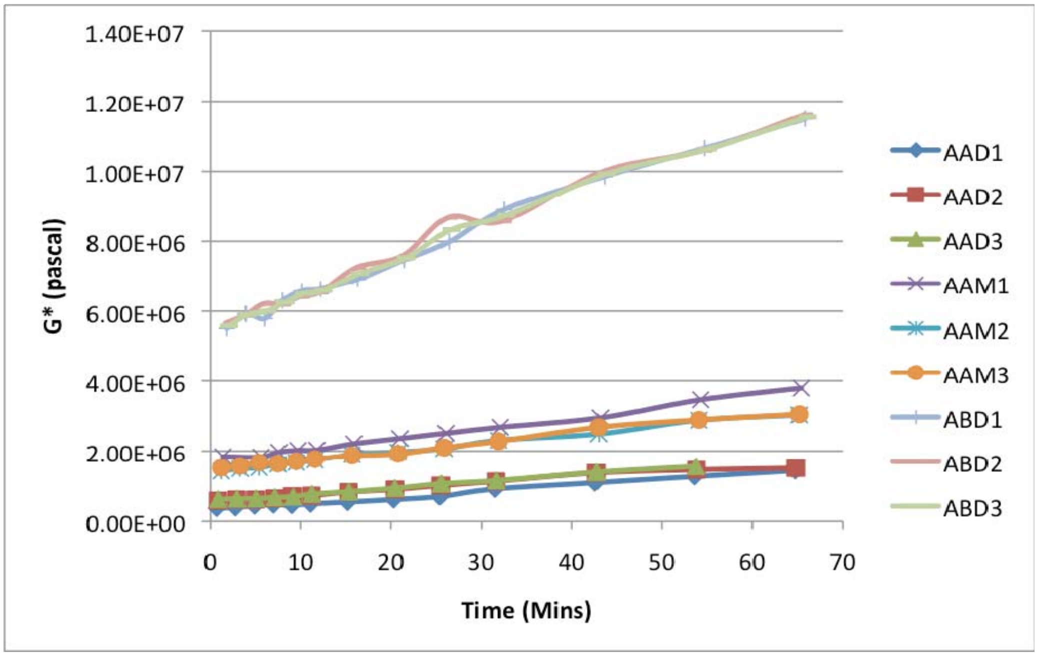


Figure F1d.2. Repeatability of the test results.

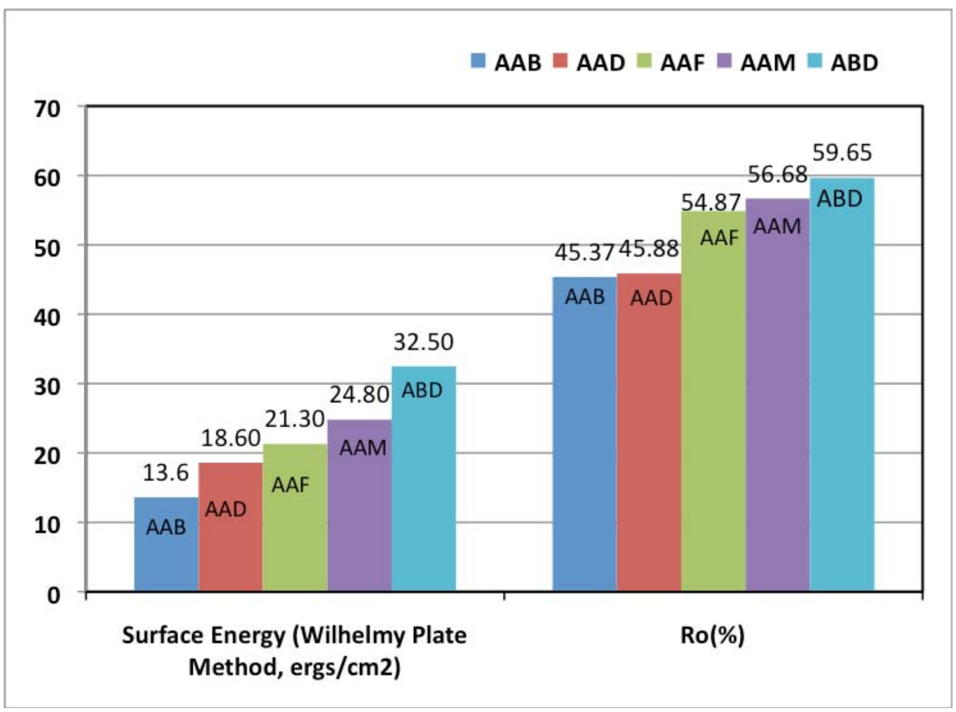


Figure F1d.3. Surface free energy vs. parameter of instantaneous healing (Ro) from DSR data.

Partial validation of the healing hypothesis

Kim et al. (1990) provide evidence that relates the rate of healing for different asphalt mixture to the molecular characteristics of their respective asphalt binders. They determined the rate of healing by introducing rest periods during a repeated load fatigue test on notched beam specimens. They quantified healing in terms of an index based on the relative increase in the dissipated pseudo strain energy immediately after the rest period relative to the dissipated pseudo strain energy just before the rest period. They then investigated the relationship between molecular morphology of the asphalt binders used in these mixtures to the measured healing index. They 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. The MMHC ratio identifies the amount of branching of the aliphatic or chain structures and the CH_2/CH_3 ratio is indicative of the length of chains. In this context chains refer to individual saturate structures as well as appendages to larger polar aromatic molecules and asphaltenes. 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. The hypothesis for proposing these two parameters was that longer chains with fewer branches would be able to migrate more freely across a crack interface and promote healing. 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, 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 example figure F1d.4 illustrates the relationship between diffusivity of hypothetical asphalt binders measured using molecular simulations to the computed CH_2/CH_3 ratio based on the molecular structure of these binders.

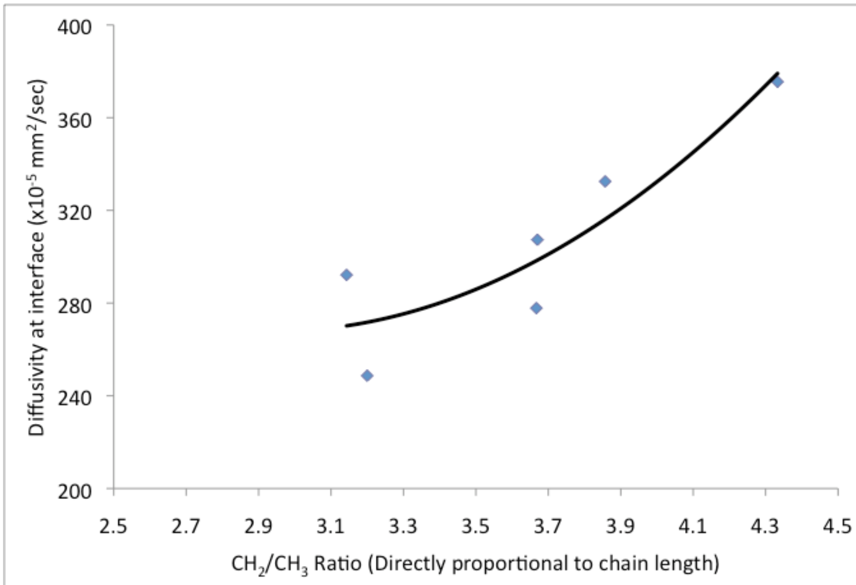


Figure F1.4. Comparison of CH_2/CH_3 ratio of binders created using average molecules to the self-diffusivity of molecules at the crack interface

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).

<u>Year Three Work Plan</u>

During year three the focus will be on the following two aspects.

i) develop a macroscopic healing model for materials subjected to rest periods. The model will be in a form that is compatible with models developed under work element F1b. In other words, the same parameters that are used to characterize non-linear viscoelastic response will also be used to characterize healing in the material.

ii) complete the development of the micro-mechanics healing model (described above) to predict healing as a function of material properties including intrinsic rate of healing and viscoelastic properties. During the year two, the focus was on the development of the intrinsic healing portion of this model. However, in year three the focus will be on the development of the second half of this model, namely the wetting function.

Item (i) will be addressed in the first half of year three. This will involve development of the model and some trial test methods that are related to obtaining and/or validating model parameters. Once the model development is complete, a more detailed test plan for validation will be developed during the second half of year three.

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
03/31/10	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
09/30/09	Final Report	
09/30/09	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)

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Bhasin, A., D. N. Little, R. Bommavaram, and K. Vasconcelos, 2008, A Framework to Quantify the Effect of Healing in Bituminous Materials using Material Properties. *Road Materials and Pavement Design,* 9 (Special Issue): 219-242.

Bommavaram, R., A. Bhasin, and D. N. Little, 2009, "Use of Dynamic Shear Rheometer to Determine the Intrinsic Healing Properties of Asphalt Binders." *Transportation Research Record,* TRB, National Research Council (Accepted for publication).

Kim, Y. R., D. N.Little, and F. C. Benson, 1990, Chemical and Mechanical Evaluation on Healing Mechanism of Asphalt Concrete. *Proc. Association of Asphalt Paving Technologists*, 59: 240-275.

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

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

Year 2 work found that the repeatability of the repeated cyclic testing with rest periods on binders is a major obstacle to obtaining meaningful data. Adjustments to the sample preparation procedures have been implemented and appear to have a significant impact, as detailed in the ARC April–June 2008 report. However, this improvement in repeatability needs to be verified. The research team also found that a new proposed test method, detailed in the ARC July–September 2008 report, can be applied to the Plateau Value/Rest Period concept introduced by Carpenter and Shen. However, difficulties were encountered in applying Kim and Roque's approach to quantify healing of asphalt binders because plastic deformation does not typically show any change in complex modulus or phase angle in the Dynamic Shear Rheometer (DSR).

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

There has been difficulty achieving repeatability in testing that involves first incurring fatigue damage followed by healing rest periods. This has caused delays in using the test protocols to evaluate healing characteristics. Work will continue to address these problems with current protocols while trying to develop alternatives. However, it is unclear if the resolution of these issues will lead to the ultimate goal of relating binder healing to endurance limit.

The research team will thoroughly review the results of this task at the end of Year 3, and if the objectives cannot be met, it will be discontinued.

Year 3 Work Plan

F1d-6.i: Develop protocols from literature on mixture healing and apply to asphalt binders

Protocols have been developed and are described in previous quarterly technical progress reports.

F1d-6.ii: Evaluate testing protocols and develop an efficient testing procedure

Work will continue on testing protocol evaluation for repeatability as well as ability to differentiate the healing behavior between different materials. The tests that are being evaluated follow:

- Repeated cyclic loading (time sweep) as a control.
- Repeated cyclic loading with multiple short-duration rest periods.
- Repeated cyclic loading with a single long-duration rest period.
- A new proposed Damage Healing Test based on Carpenter and Shen's concepts as well as Texas A&M University's concepts on nonlinearity versus damage. The experimental plan is shown in table F1d-6.1.

Table F1d-6.1. Experimental plan for healing protocol evaluation.

Binder	PG 64-22
	PG 58-28
Test Procedure	Time Sweep
	Time Sweep with Multiple Short Rest Periods
	Time Sweep with Single Long Rest Period
	Damage Healing Test
Temperature	19 °C
	25 °C
Replicates	Three

F1d-6.iii: Evaluate factors affecting healing of binders

The testing plan shown in table F1d-6.1 will be expanded to include modifiers (styrene-butadiene-styrene, or SBS; terpolymer; polyphosphoric acid, or PPA) and an additional temperature (13°C) using the healing test protocol identified as the best in terms of its ability to differentiate between binders, cost as it relates to time and effort, repeatability and simplicity of analysis.

F1d-6.iv: Evaluate role of mineral surface on binder healing

Pending recommendations from work performed under NCHRP 9-45, three types of mineral filler will be selected and evaluated using the test procedure from Subtask F1d-6.iii. The testing plan will be the same as shown in table F1d-6.1, only with one test procedure and the inclusion of the filler types.

F1d-6.v: Evaluate possible surrogate procedures

Concurrent with Subtasks F1d-6.iii and F1d-6.iv, test results from the following procedures on the same materials will be evaluated for correlations to the results from healing evaluation:

- DSR: $|G^*|$; phase angle; Yield Energy/Strain at Maximum Stress from Binder Yield Energy Test (BYET); τ_{50} and γ_{50} from stress and strain sweep, respectively.
- Bending Beam Rheometer (BBR): S(60) and m(60).
- Chemical separation.

F1d-6.vi: Make final recommendations on binder healing test and specification parameter

No work is planned for this during Year 3.

Table for Decision Points and Deliverables

Date	Deliverable	Description
6/30/09	Decision Point	Decide on best testing procedure to proceed with healing evaluation.
9/1/09	Journal Paper	Submit summary of testing and analysis to a journal or a conference.
12/31/09	Decision Point	Decide whether to continue with Subtask F1d-6.

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

Major Findings and Status

The detailed work plan was prepared as the initial part of the Year 2 Work Plan. The detailed plan was approved by FHWA in August 2008. 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.

Year Three Work Plan

The Year 3 plan is to continue to analyze the backlog of AFM images and data since the Year 2 work time was shorter than anticipated. The work in *F1d-7i and F1d-7ii* will be continued.

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.

CATEGORY F2: TEST METHOD DEVELOPMENT

Work Element F2a: Binder Tests and Effect of Composition

Major Findings and Status

In Year 2, the team found that samples of polyphosphoric acid (PPA) modified asphalts with high area-to-volume (A/V) ratio stored at 135°C could oxidize significantly. This resulted in an increase in stiffness with storage time. The stiffness increase was shown to be nonlinear with A/V ratio. For samples with A/V values smaller than 50 m^{-1} (that is, for larger samples), the increase in stiffness with time was negligible.

While it was observed that the presence of PPA seemed to diminish oxidation for some asphalts, it was determined that PPA did not have a significant influence on oxidation. The trends in oxidation were similar for neat and PPA-modified binders. The initial data collected for filled asphalts and polymer modified asphalts indicated that interaction between PPA and fillers and between PPA and polymer is significant and has to be considered in analysis of PPA effects on binders.

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

The effect of small samples gave misleading results that led to delays in understanding the cause of very rapid increase in stiffness as a function of storage time. The discovery of the effect of sample sizes required repeating many of the tests and required a delay to decide on an appropriate sample size.

Year Three 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

Samples from both the modified and unmodified types of binders will be subjected to lab aging techniques. This will be done to enable the study of aging as a determining factor in the fatigue life of binders. Modified and unmodified binder samples will undergo rolling thin film oven (RTFO) aging and one or more pressure aging vessel (PAV) treatments.

Subtask F2a-4: Collect fatigue test data

Stress sweep tests will be performed on these materials to assess their fatigue properties. In addition, the new Binder Yield Energy Test (BYET) developed at the University of Wisconsin–Madison will be performed. This will help the research team understand the influence of different modifiers on fatigue properties of binders and will also help further validate this new test. A summary of the tests to be performed in this subtask are presented in table F2a.1. All tests will be run in duplicate or triplicate to ensure consistency of data collected.

Table F2a.1. Summary of tests for Subtask F2a-4.

Binder	Polymer Modifier	Acid Modifier	Filler	Tests
CRM Flint Hills	AM 4170 LSBS RSBS	105 PPA 115 PPA 085 OPA	Limestone Sandstone	DSR G* and sin(δ) MSCR Amplitude Sweep BYET Frequency Sweep

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

The investigation of rheological properties will serve as a tool to classify and rank starting materials. It will also be a monitoring tool during the modification and conditioning process. This will be accomplished by measuring parameters such as $G^*/\sin(\delta)$, an indication of the rutting resistance of binders, as well as performing Multiple Stress Creep Recovery (MSCR) tests on the binders. This will provide important information about how the modification of binders affects not only fatigue but also rutting performance of binders. The rheological properties will also be investigated on laboratory-aged binders (RTFO and PAV aged) to cover the entire service temperature range for these materials. This will be performed with the understanding that aged binders usually have a shorter fatigue life than un-aged binders.

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

Subtask F2a-5: Analyze data and propose mechanisms

The objective of this subtask will be to analyze all 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.

Table for Decision Points and Deliverables

Date	**Deliverable**	**Description**
9/09	Presentation	Present preliminary fatigue testing data.
12/09	Presentation	Present progress on developing new mechanism to analyze fatigue in binders.
3/10	Presentation	Present results of the fatigue testing collected to date and confirm the direction for the mechanism developing process.

Work Element F2b: FAM Testing Protocol

<u>Major Findings & Status</u>

A method to fabricate specimens using the SGC was developed. In this method, the asphalt binder content is taken to be equal to that used in preparing the mixtures. In essence, the fine aggregate matrix (FAM) represents portion of the full mixtures without the coarse aggregates. Due to the high binder content in this mix design procedure, the compaction temperature had to be reduced by 30°C in order to prepare specimens using the SGC. It is important to note that the mixing and short term aging temperatures were not changed in this procedure. This ensured proper wetting of the fine aggregate particles by the asphalt binder in the mix, comparable to the full asphalt mixture. Since, the FAM does not contain coarse aggregate particles; it requires lower temperature to achieve the same workability as the full asphalt mixture. Hence, reduction in the compaction temperature can be justified to prepare SGC compacted samples. This procedure does not introduce change to the mix design and at the same time allows preparation of SGC compacted samples to obtain FAM specimens by coring with uniform geometry.

A method to test and analyze the FAM specimens was also developed. The specimen fabrication and test procedures were documented following the AASHTO format. The analysis tools are discussed in F1b.

<u>Year three work plan</u>

Researchers will coordinate with the technology development work area to further develop the test protocols.

Work Element F2c: Mixture Testing Control

<u>Major Findings and Status</u>

The Year 2 Milestones mentioned two major items: developing protocols for repeated load direct tension testing of full mixtures and developing protocols for tension and compression testing of prismatic samples taken from cores of HMA pavement layers. In the first of these, there were several practical problems that had to be overcome in order that the test results would prove to have repeatable means and low variances. These problems were with the non-uniform air void distributions in all samples, eccentricity of axial loading, and the non-symmetric response of the radial LVDT's. X-Ray Computed Tomography helped in making these evaluations. Any sample will have an outer layer along its top, bottom and sides with a higher level of air voids. In order to get a more uniform sample and thus achieve the desired consistency in means and variances of test results, it was necessary to trim off the high air void parts of each sample.

Eccentricity of sample axial loading, together with a high level of air voids at the top and bottom of a sample produced a failure in the material near the end caps. The eccentricity can be reduced considerably by using a gluing jig that aligns the end caps concentrically with the centroid of the sample cross-section. In addition, a computational method was developed and implemented to use three axial LVDT's to find the mean axial strain in the sample and the rotation of the plane cross-section of the sample under load. The non-symmetric response of the radial LVDT's required the determination of the mean axial strain under load and the centroid of the radial motion. In the later stages of our testing, the movement of the centroid of radial motion became very small. Because it is a measure of how well we had succeeded in curing the problems of the non-uniform air void distribution and the eccentricity of axial loading, the calculated movement of the centroid of radial motion is an important quality assurance indicator of the test data.

We also found that the displacement control of the MTS machine that we were using was setup to control larger displacements than we were calling for in our asphalt mixture samples. We found that setting up the machine to load under tensile displacement control actually resulted in the stress leading the strain and the repeated loading varying from tension to compression. This allowed us to develop an analytical data reduction method that took into account the tensile stress and its lagging strain and the compressive stress and its lagging strain. We ran repeated loading followed by a rest period to allow healing and then repeated the repeated loading sequence and a shorter healing period. Within the data reduction analysis, we derived and implemented the distinction between the dissipated pseudo-strain energy that produces cracking (W_{R1}) and the dissipated pseudo-strain energy that produces plastic deformation (W_{R2}). And in the course of these tests, we were able to measure and characterize both kinds of damage, and the effects on both the stiffness and lag angle in tension and compression of the healing rest periods. We also found that the stress control was not precise enough to reliably produce the same stress amplitude with each load cycle. So we used the mean stress amplitude for ten consecutive cycles as the recorded stress amplitude. We also instituted a Student's T-test to determine if the mean stress amplitudes in tension and compression were the same or different and if the lag angles in tension and compression were the same or different. They usually were not the same and this was largely due to the damage that had occurred up to that point. So what started out as a serious problem with the testing apparatus proved to be a blessing in disguise as it allowed us to develop software to capture all of the effects that were the objective of this work element.

We also found that the use of the UTM Testing machine using the Rapid Triaxial Test cell was the best way to run tests to determine the undamaged properties of a mix. The tests that were run in tension at different levels of temperature and the method of characterizing the master curves of the complex modulus magnitude and phase angle is the subject of a paper that has been submitted for review and publication. Another paper on the use of the same RaTT cell in compression is in preparation at present.

At a presentation of the tensile test results at the TRB Annual Meeting, it was pointed out by Dr. Jacob Uzan that there is no level of strain below which there is no damage. We had arranged not to strain the samples higher than 80$\mu\epsilon$. In subsequent discussion, he stated that in his carefully run tests the damage that was done at low levels of strain, such as we were using, healed almost immediately. This is no doubt due to the short-coupled non-polar Lifshitz-van der Waals forces in the mastic. Because of this, we believe that this observation of Dr. Uzan's is valuable but does not constitute a serious limitation to our "undamaged" characterization of mixtures.

The efforts we have applied to the handling and testing of cores taken from the field revolved around the ability to form a representative sample on which end caps could be mounted concentrically with the centroid of the sample cross-section. The cores are sawn by parallel saw blades 3-inches apart leaving a curved end on each end of the sample. After toying with curved end caps to see if eccentric loading could be reduced or eliminated, we concluded that it was better to cut the sample once more to produce flat ends. Then we had to work out a way of mounting LVDT's vertically and horizontally on the sample and to develop data reduction software that could determine the mean vertical and horizontal strain and the departure of the cross-section from concentric loading. Once more, the use of X-Ray Computed Tomography helped in showing whether non-uniformity of air void distributions would prove to be a problem. Fortunately, an axial load on these samples is a load within the plane of the HMA layer and non-uniformity of the sample air void distribution is less of a problem unless the sample is taken near a zone of segregation.

Year Three Work Plan

This coming year, testing of a variety of mixture compositions will be conducted using the testing and data analysis protocols described above. It is expected that several different stress states will be applied to companion samples to determine the effects of temperature and loading frequency on linear and nonlinear viscoelastic response, plastic deformation, fracture and healing. The different stress states include tension and compression, confining pressure, and variations of stress invariants. These tests will be to determine the sensitivity of the characterization properties of a mixture in seeking testing efficiencies that emphasize those properties with more significant influence on the mixture performance. It will also provide input parameters to the models of pavement performance that are being developed in this project.

The composition variables will be grade of asphalt, percent of asphalt and air voids. Three temperatures will be used as will three different loading frequencies. Using the RaTT cell, it will be possible to have three different confining pressures and three levels of octahedral stress applied to each mixture. With each sample that is tested, the full range of repeated loading, rest periods, and computed tension and compression stress amplitudes, dissipated pseudo-strain energies, fracture and plastic deformation will be measured or computed. This will not be a full factorial experiment design.

Table for Decision Points and Deliverables

Date	**Deliverable**	**Description**
04/31/09	Journal Paper	Viscoelastic tensile characterization of undamaged asphalt mixtures
08/31/09	Final Report	Final Report on Testing Protocols
07/31/09	Journal Paper	Viscoelastic anisotropic compressive characterization of undamaged asphalt mixtures
07/31/09	Journal Paper	Material response in direct tension and compression of asphalt mixtures using dissipated pseudo-strain energy
07/31/09	Journal Paper	Fatigue damage and plasticity evaluation of asphalt mixtures with dissipated pseudo-strain energy
07/31/09	Journal Paper	Bond energy and dissipated pseudo-strain energy in fatigue crack modeling

Work Element F2d: Tomography and Microstructural Characterization (TAMU)

Nano Scale Measurements Using AFM

<u>Major Findings & Status</u>

A protocol to measure viscoelastic properties of the binder at nano-scale was developed. One of the objectives of this research is to determine the distribution of viscoelastic properties within the different phases present in the asphalt binder using the Atomic Force Microscopy (AFM). The ultimate objective is to relate this distribution to the damage and healing characteristics of the asphalt binder. A protocol was developed to use the AFM to obtain creep-recovery curves using the AFM tip at select locations. This protocol is currently being refined and calibration procedures are being developed. Figure F2d.1 illustrates the typical creep-recovery data obtained using the AFM tip on the surface of the asphalt binder.

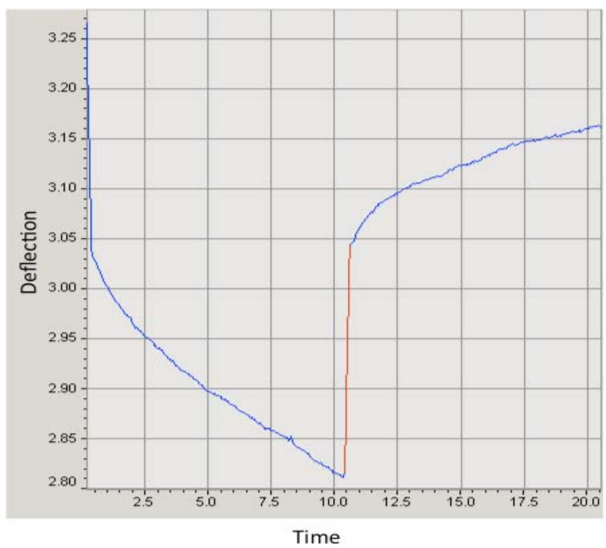

Figure F2d.1. Creep-recovery data obtained by applying a constant force for 10 seconds and removing it thereafter using the AFM tip

<u>Year three work plan</u>

The protocol to determine the creep-recovery curve for different phases present within the asphalt binder will be developed. Also, preliminary data documenting the distribution of viscoelastic properties on the surface of the asphalt binder will be collected. The important milestones that will be targeted for year three include:

1. Finalizing the procedure to obtain creep-recovery data for the different phases present in thin films of asphalt binder.

2. Finalizing the procedure to calibrate the creep-recovery data to obtain absolute measures of force and strain.
3. Using computational tools to correct for the various errors associated with the use of AFM tips (tip geometry, indentation etc.) and apply these corrections to the creep-recovery data.

Based on the results obtained from this work element, a test plan will be developed to relate the growth of fatigue cracking and mechanical properties at the micro-scale.

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

Date	Deliverable	Description
09/30/09	Journal Paper	Distribution of viscoelastic properties on a thin film of asphalt binder
09/30/10	Journal Paper	Distribution of viscoelastic properties and relationship to fatigue damage on thin films of asphalt binders
12/30/10	Draft Report	
03/31/11	Final Report	

X-ray Computed Tomography

<u>Major Findings & Status</u>

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. The main finding of this task is the development of an approach for the characterization of the directional (anisotropic) distribution of damage.

<u>Year Three Work Plan</u>

X-ray CT will be used to evaluate the anisotropic distribution of damage in asphalt mixtures. The use of the directional distribution functions proposed by Kanatani (1984, 1985) requires cutting the material with equally spaced sections parallel to three orthogonal planes. Stereology principles along with the assumption of randomness (homogeneity) are then used to obtain the 3-D distribution components from the 2-D measurements. The use of X-ray CT instead of orthogonal cutting of specimens will be used in this study to directly obtain the three dimensional distribution of damage, and consequently, there is no prior assumption in regard to the homogeneity (random distribution) of the material.

The 3-D directional distribution of damage is expressed in a Cartesian tensor form as follows (Kanatani 1984):

$$f(h) = n_a \left[1 + \phi_{ij} h_i h_j\right] \qquad \text{(F2d.1)}$$

where n_a represents the isotropic distribution of damage density, h_i's are the components of the unit vector h = (sin θ cos ϕ, sin θ sin ϕ, cos θ), and ϕ's are deviatoric tensors that represent the deviation from the average in the direction of the unit vector h.

In reality, cracks form a three dimensional network in asphalt mixtures cannot be described as discrete features. Therefore, vectors cannot be assigned to discrete cracks to describe their distribution. In order to overcome this limitation in quantifying damage, an inverse stereological procedure will be developed and used. A two dimensional illustration of the method is shown in figure 2d.2. In this method, a cube (a square in 2-D) will be placed at a point and a three-dimensional arrays of lines will be created in different directions (figure 2d.2c). Then, image analysis techniques will be used to measure the intersection of these lines with the air void and damage network medium. This will yield an image of segments that identify damage in that direction (figure 2d.2d). The average length of these segments and its direction will define a vector describing the damage in this direction. This step will be repeated at various angles of θ and ϕ (representing the vector *h* in equation F2d.1). For example, the damage in the vertical direction is determined using the segments shown in figure 2d.2e and damage in the vertical direction is given in Figure 2d.2f.

The, average damage density (n_a) at a point is determined by the volume of damage divided by the total volume within a cube. The function f(h) will be used to mathematically describe the deviation form the average damage in all directions designated by the vector h. The result will be the components of the deviatoric tensor ϕ_{ij} that describe the measured damage distribution at a given point.

Table for Decision Points & Deliverables

Date	Deliverable	Description
09/30/09	Journal Paper	Paper on the characterization of the directional distribution of damage using X-ray Computed Tomography

Cited References

Kanatani, K., 1984. Stereological Determination of Structural Anisotropy. *International Journal of Engineering Science*, 24(2): 207-222.

Kanatani, K., 1985, Procedures for Stereological Estimation of Structural Anisotropy. *International Journal of Engineering Science*, 23(5): 587-598.

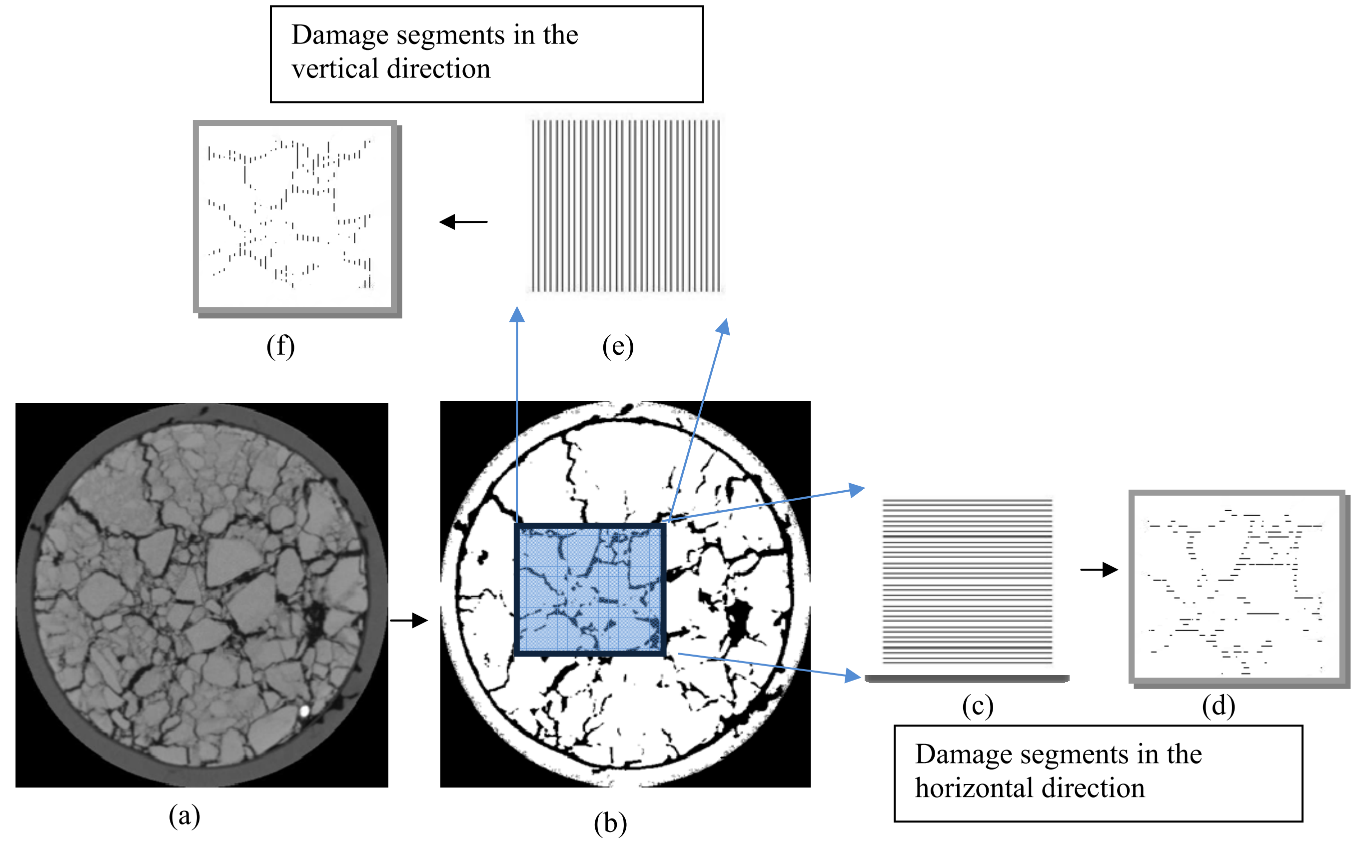

Figure 2d.2. Two Dimensional Illustration of the Procedure to Quantify Damage Anisotropy.

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

Major Findings and Status

Year 2 work for this element showed that linear viscoelastic modeling for use in the viscoelastic continuum damage (VECD) analysis framework is insufficient, and nonlinear approaches are needed as described in the ARC April–June 2008 report for this work element. Also, VECD characterization (figure F2e.1) was successfully applied to show that binder fatigue at low strains can be predicted using higher strains under the time sweep strain-controlled tests, thus reducing test time requirements. However, further investigation is required to determine if time sweep and amplitude sweep conditions can be predicted and compared using VECD characterization.

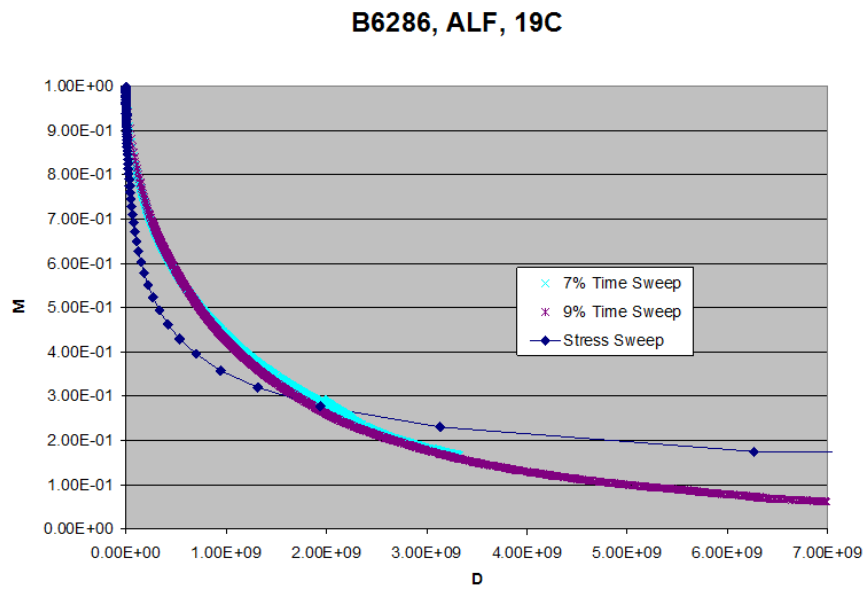

Figure F2e.1. Graph. Plot of material integrity *M* versus damage intensity *D* from VECD analysis of time sweep and stress sweep test results. More details can be found in the ARC October–December 2008 report.

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

Due to the findings during Year 2, some additional testing needs to be carried out to obtain a more complete characterization of the material behavior:

- Direct relaxation in the Dynamic Shear Rheometer (DSR): Currently, frequency sweep test results are used to estimate relaxation modulus curves based on viscoelastic constitutive relations between material response on frequency scale and time scale. However, limitations in DSR capabilities require some extrapolation of the frequency sweep data to cover the time scale used during the Binder Yield Energy Test (BYET). To more accurately characterize damage accumulation in asphalt binders, it is proposed that relaxation modulus be measured directly in the DSR. This can minimize possible errors caused by the estimation from frequency sweeps and allows using the directly measured modulus in the VECD analysis to relate binder fatigue characteristics to those of mixtures.
- The nonlinear frequency sweep test method will be also included in the testing plan in Year 3. The results of nonlinear characterization can be included in the continuum damage analysis for relating binder fatigue to mixture fatigue.
- For the VECD analysis of time sweep data was performed on strain-controlled test results, the addition of a strain-controlled amplitude sweep is planned for not only for consistency in applied loading type, but also because strain-controlled loading greatly reduces the possibility for drift of displacement measurements during testing. Stress-controlled amplitude sweep will still be included in the testing plan to evaluate the effect of loading type on test results. Results from this work will be used to determine the most

promising accelerated binder fatigue test to use to correlate to fatigue performance of mixtures.

To have an early validation of the value of binder testing and to start the process of establishing binder specification limits, limited beam fatigue testing of mixtures at one temperature and loading level will be conducted using samples that are readily available. This is intended to evaluate the suitability of the beam geometry for validation of the proposed binder fatigue test procedures.

Year 3 Work Plan

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

Collaboration with Professor Emin Kutay at Michigan State University will begin to evaluate binder fatigue data collected for binders used in the FHWA Accelerated Load Facility (ALF) fatigue experiments. Professor Kutay has extensive data on the mixture performance test results for those materials, so comparison between binder and mixture fatigue analysis will be investigated for any relationship between the two. The data available for analysis are listed in table F2e.1.

Table F2e.1. Binder data collected for ALF fatigue experiment.

<table>
<tr><th>Temp [°C]</th><th>Test Type</th><th>Loading Condition</th><th>Replicates</th></tr>
<tr><td rowspan="6">19</td><td rowspan="3">Time Sweep</td><td>3%</td><td rowspan="3">2</td></tr>
<tr><td>5%</td></tr>
<tr><td>7%</td></tr>
<tr><td rowspan="3">BYET</td><td>0.0050/s</td><td rowspan="3">3</td></tr>
<tr><td>0.0075/s</td></tr>
<tr><td>0.0100/s</td></tr>
<tr><td>10</td><td rowspan="6">Freq. Sweep</td><td rowspan="6">0.10%</td><td rowspan="6">1</td></tr>
<tr><td>16</td></tr>
<tr><td>19</td></tr>
<tr><td>22</td></tr>
<tr><td>25</td></tr>
<tr><td>30</td></tr>
</table>

Subtask F2e-2: Selection of testing protocols

Work will continue under this subtask to evaluate the applicability of strain sweep testing to fatigue characterization. Materials and test conditions being evaluated under this subtask as described in the Year 2 work plan will include strain sweep evaluation as well. However, the three main testing protocols in general remain as the BYET, time sweep and amplitude sweep. The testing tables F2e.2 and F2e.3 are broken out into fatigue tests and viscoelastic characterization tests necessary for VECD modeling.

Table F2e.2. Proposed binder fatigue testing matrix.

<table>
<tr><td rowspan="11">Test Temps:
19 °C
25 °C</td><td rowspan="4">Time Sweep</td><td rowspan="3">Strain Level</td><td>3%</td></tr>
<tr><td>5%</td></tr>
<tr><td>7%</td></tr>
<tr><td>Frequency</td><td>1 Hz</td></tr>
<tr><td rowspan="3">BYET</td><td rowspan="3">Shear Strain Rate</td><td>0.0050/s</td></tr>
<tr><td>0.0075/s</td></tr>
<tr><td>0.0100/s</td></tr>
<tr><td rowspan="2">Amplitude Sweep</td><td>Strain-Controlled</td><td>10 Hz</td></tr>
<tr><td>Stress-Controlled</td><td>10 Hz</td></tr>
</table>

Note: At least two replicates of each test will be performed.

Recently, work has also been performed by Laboratoire Central des Ponts et Chaussées (LCPC) in France using a new geometry and test equipment to apply uniaxial tension and compression on asphalt binders. Fatigue studies are currently under way, and the research team at the University of Wisconsin–Madison will contact LCPC to investigate whether the new protocol is suitable for inclusion in this work element.

Table F2e.3. Proposed binder viscoelastic properties testing matrix.

<table>
<tr><th>Test Procedure</th><th>Load Condition</th><th>Temp. °C</th></tr>
<tr><td rowspan="3">Nonlinear Freq. Sweep</td><td rowspan="6">1.0% Strain</td><td>4</td></tr>
<tr><td>10</td></tr>
<tr><td>16</td></tr>
<tr><td rowspan="3">Direct Relaxation</td><td>19</td></tr>
<tr><td>25</td></tr>
<tr><td>30</td></tr>
</table>

Note: At least two replicates of each test will be performed.

Subtask F2e-3: Binder and mixture fatigue testing

Table F2e.4 is the testing plan for mixture fatigue testing performed at UW–Madison to begin during Year 3.

Table F2e.4. Mixture fatigue testing plan.

Mixture Fatigue	Cyclic Push-Pull Test	Strain Level	600 microstrain
			1000 microstrain
			1400 microstrain
		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.

Note: At least two replicates of each test will be performed.

One initial mix design based on locally available aggregate sources will be used to begin testing. This will consist of one aggregate type but incorporate the various binders in use for binder fatigue characterization.

Additionally, the beam fatigue testing described above will be started and completed during the first half of Year 3.

Subtask F2e-4: Verification of surrogate fatigue test

This subtask is ongoing. As binder surrogate test results become available, they will be compared to available results from time sweep testing as well as mixture fatigue results. The surrogate tests are listed in table F2e.2 as the amplitude sweep and BYET procedures.

Subtask F2e-5: Interpretation and modeling of data

This subtask is ongoing. Efforts will be focused on incorporating the results from the nonlinear characterization of binders into VECD analysis of BYET results. Selected runs of the BYET procedure will be performed at 4°C and analyzed for possible visco-plasticity effects using the data collected under tables F2e.2 and F2e.3, specifically BYET and relaxation data.

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

As noted in the Year 2 work plan, incorporating the recommendations from this work element into the unified model is not scheduled to begin until Year 4.

Table for Decision Points and Deliverables

Date	Deliverable	Description
06/30/09	Decision Point	Finalize accelerated binder fatigue procedure candidates.
06/30/09	Draft Report	Report on findings from Subtasks F2e-1 and F2e-2.
08/01/09	Journal Paper	Focus on the VECD analysis of accelerated procedures.
09/30/09	Final Report	Issue final report on findings from Subtasks F2e-1 and F2e-2.
02/15/10	Presentation	Present binder fatigue progress at TRB, ETG or similar.

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. The detailed plan was approved by FHWA in August 2008. The complete work plan is included in the Revised Year 2 Work Plan that 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 Technological 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 is a substantial amount of contractual information and documentation required by the FHWA to establish the subcontracts with these parties which has been ongoing from the time of the work plan approval. It is anticipated that the subcontracts will be initiated in the last quarter of Year 2.

Year three Work Plan

The bulk of the planned work in this work element is to begin the research stated in the Revised Year 2 Work Plan.

Work Element F3b: Micromechanics Model

Subtask F3b-1: Model Development

Cohesive Zone Micromechanical Model

Major Findings & Status

Work during the 2nd year at the University of Nebraska for the development of micromechanics model has focused on the integration between experimental efforts and computational modeling. Experimentally, laboratory tests to obtain key model input parameters such as the linear viscoelastic (LVE) properties and the cohesive zone (CZ) fracture properties of asphalt matrix phase (referred to as the fine aggregate matrix (FAM) in other tasks related: M1c, F1b, F2b) and to define proper dimensions of representative volume elements (RVEs) of various asphalt concrete mixtures (dense-graded and stone-matrix-asphalt) have been performed.

The linear viscoelastic properties of FAM phase have properly been identified by using cylindrical specimens (12-mm diameter and 50-mm long) mounted in a dynamic mechanical analyzer (DMA) which induces torsional loading mode. Testing protocols have been developed and modified by many researchers and a series of progresses has been published in a number of studies (Kim et al. 2002, 2003, 2006a; Song et al. 2005; Masad et al. 2006; Castelo 2008). However, a more articulate and scientific protocol in mixing and compaction of the FAM specimens needs to be developed for the more accurate micromechanical modeling. Two researchers (Dr. Amit Bhasin at UTA and Dr. Yong-Rak Kim at UNL) are currently working together on the development of the FAM specimen fabrication protocol. New protocols developed will be circulated by ARC modeling members for their additional inputs.

To determine appropriate dimensions of asphalt concrete RVEs, three widely-used asphalt concrete mixtures (two dense-graded Superpave mixtures with different nominal maximum aggregate sizes and one stone matrix asphalt mixture) were selected and evaluated during the 2nd year without considering damage events such as cracking in the mixture. With no damage involved, RVE dimensions of each mixture could be successfully identified by simply integrating two approaches: (1) geometrical analyses of mixture heterogeneity to seek statistically homogeneous RVEs, and (2) numerical simulations of mixtures to find effective mixture properties of RVEs. Analysis results indicated that typical dense-graded Superpave asphalt concrete mixtures can be characterized for their non-damage effective properties with the approximately 50-mm by 50-mm RVE, while property measurements of stone matrix asphalt mixtures, where larger aggregates are involved, need to be performed at a larger scale for better accuracy. Details are presented in a journal article (TRB Compendium CD, 2009).

For the computational modeling, several activities have been pursued during the 2nd year. First, we investigated various CZ models developed by researchers 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. Then, several CZ models such as the 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. 2006b, 2006c, 2007) were implemented into the finite element (FE) framework.

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, intrinsic model 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.

Model validations via comparison to analytical solutions, numerical convergence issues of the model to the size of time increment and the cohesive zone element, artificial compliance issue due to the use of intrinsic CZ model (such as the bilinear model), and the effects of material viscoelasticity were studied and presented in the last two quarterly reports. Although computational simulations performed during the 2nd year were mostly preliminary pursuing a better understanding of CZ models and their appropriate application to asphalt concrete fracture predictions, some findings could be obtained. Simulation results indicate that intrinsic cohesive zone models introduce artificial compliance which should be addressed properly for a more accurate modeling of asphalt concrete mixtures, and the use of bilinear CZ model (elastic hardening-softening model) incorporated with bulk material viscoelasticity can potentially model rate-dependent fracture behavior of asphalt concrete mixtures with relatively reduced modeling efforts.

Year Three Work Plan

Work will begin to develop a more articulate and scientific protocol in mixing and compaction of the FAM specimens. Advanced image analysis techniques and FE 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.

The development of fracture testing system to determine CZ fracture parameters of FAM phase will be completed through repeated testing of various different materials at different testing conditions (temperatures and loading rates). As a follow-up to the effort of RVE determination of asphalt concrete mixtures without damage, we have initiated a testing set-up that will possibly identify asphalt concrete RVEs when damage events (such as cracking) are included. For this subtask, we have initiated a digital image correlation (DIC) testing system as presented in the last quarterly report. We will continue the development, testing, and data analyses for the next year.

Linear elastic properties of coarse aggregates will also be evaluated by the nanoindentation technique (Khanna et al. 2003). In the indentation process, a record of the depth of penetration is made, and then the area of the indention is determined using the known geometry of the indentation tip. Load and depth of penetration during the test are plotted on a graph to create a load-displacement curve which will result in mechanical properties of the material such as modulus of elasticity.

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 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 are then integrated into the FE 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 which are prepared and tested by NCSU researchers. 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 for Decision Points & Deliverables

Date	Deliverable	Description
06/30/09	Journal Paper	CZ fracture testing and modeling

Cited References

Allen, D. H., and C. R. Searcy, 2001a, A Micromechanical Model for a Viscoelastic Cohesive Zone. *International Journal of Fracture*, 107: 159-176.

Allen, D. H. and C. R. Searcy, 2001b, A Micromechanically-based Model for Predicting Dynamic Damage Evolution in Ductile Polymers. *Mechanics of Materials*, 33: 177-184.

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Espinosa, H. D., and P. D. Zavattieri, 2003, A Grain Level Model for the Study of Failure Initiation and Evolution in Polycrystalline Brittle Materials. Part I: Theory and Numerical Implementation. *Mechanics of Materials*, 35: 333-364.

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Song, S. H., G. Paulino, and W. G. Buttlar, 2006, A Bilinear Cohesive Zone Model Tailored for Fracture of Asphalt Concrete Considering Viscoelastic Bulk Material, *Journal of Engineering Fracture Mechanics*, 73: 2829-2848.

Xu, X. P., and A. Needleman, 1993, Void Nucleation by Inclusion Debonding in a Crystal Matrix. *Modelling and Simulation in Materials Science and Engineering*, 1: 111-132

Xu, X. P., and A. Needleman, 1994, A Numerical Simulations of Fast Crack Growth in Brittle Solids. *Journal of the Mechanics and Physics of Solids*, 42(9): 1397-1434.

Lattice Micromechanical Model

Major Findings & Status

The multiscale virtual fabrication and lattice modeling (MS-VFLM) software has been completely streamlined and efficient rank-k down dating algorithm is implemented for the purposes of efficiency. Software testing is in progress. Work is also in progress with respect to changing time-dependence of the material during the scale-up procedure.

Year Three Work Plan

One of the issues related to scaling up using lattice modeling is that the predicted time-dependence does not match with the time-dependence of the mixture. This issue is being investigated carefully and is expected to be resolved in the third year. Another improvement that is required for existing lattice modeling procedure is that the failure model is elastic, while the deformation is viscoelastic. In this year, a viscoelastic failure model will be developed and incorporated into lattice models.

Work element F3c: Development of Unified Continuum Model

Major Findings & Status

Subtask F3c-1 Analytical Fatigue Model for Use during Mixture Design

The method for determining the viscoelastic properties is integrated in the analytical fatigue model. Therefore, the findings and plans for this subtask are combined with those for Subtask F1b-1: Viscoelastic properties under cyclic loading.

Subtask F3c-2 Unified Continuum Model

The TAMU continuum model was developed to be general enough to describe the response and performance of asphalt mixtures without damage and with damage due to permanent deformation, fatigue cracking and moisture. The model includes nonlinear viscoelastic and viscoplastic components to represent the recoverable and irrecoverable responses, respectively. The nonlinear viscoelastic component is modeled using Schapery's model; while the irrecoverable component is represented using Perzyna's viscoplasticity theory with a Drucker-Prager yield surface that is modified to capture the influence of stress state on material response. In the past two years, the nonlinear viscoelastic-viscoplastic model was converted into a numerical formulation and implemented in a finite element (FE) code in the user-defined subroutine (UMAT) of the ABAQUS software.

The TAMU model's results have been verified mostly using laboratory experiments and limited field experimental measurements of various mixtures. A systematic procedure was developed to determine the model parameters, which were found to be related to properties and characteristics of mixture components such as aggregate angularity, texture and shape. Finite element analyses of pavement structures have demonstrated that the pavement performance is related directly to the material characteristics and model parameters.

Subtask F3c-3 Multi-Scale Modeling

The first step of the multi-scale modeling is the development of the micromechanics models. Therefore, the progress and plans for this sub-task are presented under Work Element F3b: Micromechanics Model.

Year Three Work Plan

The ARC researchers developed a plan for a joint testing program that will initiated during the third year of this project. This testing program is directly related to the modeling efforts in work elements F3b, F3c and M4a. Table 3c.1 gives the overall testing plan, and table F3c.2 presents the experiment for the calibration of the unified continuum model (Subtask 3c.2 and Subtask M4a.3).

Table F3c.1. Testing plan for determining parameters of micromechanical and continuum models.

Material	Test	Group in Charge of Experiment						Materials	Work Plan Task
		TAMU	UTA	UWM	UNL	WRI	NCSU		
Binder	Chemical Characterization							4 core binders	F3a
	Superpave Tests +Master Curve							4 core binders	F2e
	MSCR							4 core binders	F2e
	Tensile Strength and fatigue (with and without rest periods)							4 core binders +AAM+AAD+ABD	F1a, F1b, F1d
	Tensile Creep Recovery							4 core binders	F1a, F1b, F1d
	Surface Energy							4 core binders	F1a
	Atomic Force Microscope							4 core binders	F2d
	FTIR							4 core binders +AAM+AAD+ABD	M2b
	Aging Tests							4 core binders	F1c
Aggregate	AIMS							4 core aggregates	

	Micro-Deval							4 core aggregates	M3a
	Surface Energy							4 core aggregates	F1a
	Petrographic analysis							4 core aggregates	M3a
Mastic	Strength and fatigue (with and without rest periods)							6 binder - filler combinations using core materials (See Note 3)	F1b, F2b
	Creep Recovery								F1b, F2b
	Fracture properties								F1b, F2b
FAM	Strength and fatigue (with and without rest periods)							6 binder - fine aggregate comibnations using core materials	F1b, F2b
	Creep Recovery								F1b, F2b
	Fracture properties								F1b, F2b
	Master curve								F1b, F2b
Mixture	X-ray CT							1 mixture design will be used for the first round of experiments to develop the model and fine tune the test protocol; 2 additional mixtures will be tested after model development	F2d
	Full Characterization Dry and Wet in Tension						See Note4		F2c
	Tensile Creep Recovery Dry and Wet						See Note 5		F2c
	Full Characterization Dry and Wet in Compression	See Note 4							F2c
	Compression Creep Recovery Dry and Wet	See Note 6							F2c
	Nano indentation				See Note 7				F2d
	Double Endge Notched Dry (fracture test)								F2c
	Double Endge Notched Wet (fracture test)								F2c

Table F3c.2 Full Mixture Characterization for Calibration of Unified Continuum Model.

Mode of Loading	Test	Temp °C					Conf. Pressure (kPa)		
Tension	VE Properties (Master Curve)	-10	5	20	40	54	0		
	Monotonic		5		40		0	140	250
	Creep and Recovery		5		40		0	140	250
Compression	VE Properties (Master Curve)	-10	5	20	40	54	0	140	500
	Monotonic		5				0	140	500
	Creep and Recovery				40	54	0	140	500

Notes:
- The full mixture characterization will be conducted on three mixtures.
- The creep and recovery experiments will be conducted at multiple stress levels.

Subtask F3c-1 Analytical Fatigue Model for Use during Mixture Design

The method for determining the viscoelastic properties is integrated in the analytical fatigue model. Therefore, the findings and plans for this subtask are combined with those for Subtask F1b-1: Viscoelastic properties under cyclic loading.

Subtask F3c-2 Unified Continuum Model

The development of TAMU's continuum damage model will focus on the following:

- Complete the development of the damage formulation of the model by including (1) Kinematic viscoplasticity hardening function which is needed for modeling fatigue damage at high stress levels and for incorporating memory and strain-amplitude effects; (2) Anisotropic damage (i.e. different degradation in different directions) for realistic description of damage evolution in pavement systems; and (3) Viscodamage (i.e. rate-dependent damage) which is very important for modeling the degradation effect at various loading frequencies.
- Change the hardening function of the model to account for cyclic loading. The current hardening function has limitations in describing cyclic loading. In simple terms, during creep loading the model would predict the development of a maximum strain level (saturation level). If this stress level is removed and reapplied, the model would not predict further strain accumulation. However, experimental results have shown that the asphalt mixture would develop more deformation. Based on the literature review that the researchers have conducted, we believe that incorporating a dynamic yield surface with kinematic hardening would capture the actual response of the mixture under cyclic loading.
- Most of the current modeling efforts include simplistic loading conditions (circular and uniform stress distribution). 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 moving loads and nonuniform stress distribution that is supported by experimental measurements of time-pavement contacts.

- Incorporate the effect of temperature in the viscoplastic component of the model.
- 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.

The work at NCSU will focus on extending the continuum damage model to fracture. The work will focus on developing a model framework and experimental design to characterize damage during localization. Specifically, various models will be evaluated to incorporate the length-scales associated with localization and a model framework will be finalized through careful balance of flexibility and experimental effort required to characterize the models. Experimental program will be carefully designed and initiated to characterize the model. In parallel to the experimental program, the model form will be implemented into finite element program so that a framework would be ready once experimental characterization is complete.

Table F3c.2 University of Nottingham Database of Compression Tests (all stresses are in kPa).

Mixture Type: DBM					
Temp.	Repeated loading	Triaxial	Creep recovery	Constant load	Constant strain rate
10			Stress=2000,2500	Stress=2000,2500	Strain rate= 0.00005, 0.0005, 0.005
20	Stress=1500 (Loading Time=60 sec with Rest time=50,100,1500 sec Loading Time =1200 with Rest time= 1500)		Stress=1000,1500, 2000	Stress=1000,1500, 2000	Strain rate= 0.00005, 0.0005, 0.005
35		Axial stress=500,750, 1000,1500 with stress ratio=0.33,0.56, 0.462			
40			Stress=500,750	Stress=500,750	Strain rate= 0.0005, 0.005
Mixture Type: HRA					
10			Stress=1500,2000	Stress=1500,2000	Strain rate= 0.00005, 0.0005, 0.005
20	Stress=1000 (Loading Time=30 sec with Rest time=50,100,1500 sec Loading Time =60 with Rest time= 1500)		Stress=1000,1500, 2000	Stress=1000,1500, 2000	Strain rate= 0.00005, 0.0005, 0.005
35		Axial stress=300,500, 700 with stress ratio=0.33,0.7, 0.562			
40			Stress=400,500	Stress=400,500	Strain rate= 0.0005, 0.005

Table F3c.2 University of Nottingham Database of Tension Tests (all stresses are in kPa).

Mixture Type: DBM				
Temp.	Repeated loading	Creep recovery	Constant load	Constant strain rate
5				
10			Stress=500,1000,1500	
20	Stress=300 (Loading Time=60 sec with Rest time=50,100,1500 sec Loading Time =120 with Rest time= 100)	Stress=100	Stress=100,300, 500,700	Strain rate=0.00167,0.0167
35			Stress=50,100, 150	
Mixture Type: HRA				
5		Stress=1500	Stress=1000,1500	
10			Stress=300,500, 1000	
20	Stress=200 (Loading Time=30 sec with Rest time=50,100,1500 sec Loading Time =60 with Rest time= 50) Stress=300 (Loading Time=30 sec with Rest time=50,100 sec Loading Time =60 with Rest time= 50)	Stress=100	Stress=100,200, 300,500	
35			Stress=50,75,100	

Table F3c.2 University of Nottingham Database of Wheel Tracking Tests
(all stresses are in kPa).

Mixture Type: DBM			
Temperature	Small Scale Wheel Tracking	Large Scale Wheel Tracking	Full Scale Wheel Tracking
35	Stress= 540, 770	Stress=510	Stress= 675,740,885,1000
Mixture Type: HRA			
20	Stress= 540,770		
35	Stress= 540, 770	Stress=510	Stress= 675,740,885,1000

Table for Decision Points & Deliverables

Date	**Deliverable**	**Description**
07/31/09	Decision Point	Finalize the model framework and experimental design for continuum damage to fracture.
09/30/09	Journal Paper	Paper on TAMU continuum model development and verification using laboratory data from subtasks F3c-2

Subtask F3c-3 Multi-Scale Modeling

The first step of the multi-scale modeling is to develop the micromechanics models. Therefore, the progress and plans for this subtask are presented under Work Element F3b: Micromechanics Model.

Table for Decision Points & Deliverables

Work Element	Date	Deliverable	Description
F1a	12/31/08	Journal Paper	A review of practical and thermodynamic work of cohesion and adhesion (1)
F1a	06/30/09	Journal Paper	Comparing practical and thermodynamic work of adhesion and cohesion
	12/31/09	Draft Report	
	03/31/10	Final Report	
F1a	09/30/11	Journal Paper	On the acid-base scale of surface energy components
F1b-1	12/31/08(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	03/31/09(1)	Mathematical model	
F1b-1	03/31/09(1)	Final Report	
F1b-1	03/31/10	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	
F1b-2	03/31/09	Journal Paper	The use of the method for separation of viscoelastic response from the viscoplastic response.
F1c	07/09	Presentation	Present early results on binder oxidation and fatigue (F1c-4)
F1c	08/09	Presentation	Present pavement oxidation transport model, Qindao (F1c-3)
F1c	01/10	Presentation, Journal Paper	Present field comparison of oxidation model (F1c-3, F1c-4). Submit for publication 8/09.
F1c	01/10	Presentation, Journal Paper	Results on binder oxidation and fatigue (F1c-4). Submit for publication 8/09.
F1c	03/10	Draft Report	Draft Report on findings to date from subtasks F1c-4.
F1d	12/31/08(1)	Journal Paper	Test method to determine intrinsic healing properties of asphalt binders
F1d	03/31/10	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	09/30/09	Final Report	
F1d	09/30/09	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	
F1d-6	6/30/09	Decision Point	Decide on best testing procedure to proceed with healing evaluation.
F1d-6	9/1/09	Journal Paper	Submit summary of testing and analysis to a journal or a conference.
F1d-6	12/31/09	Decision Point	Decide whether to continue with Subtask F1d-6.
F2a	9/09	Presentation	Present preliminary fatigue testing data.
F2a	12/09	Presentation	Present progress on developing new mechanism to analyze fatigue in binders.
F2a	3/10	Presentation	Present results of the fatigue testing collected to date and confirm the direction for the mechanism developing process.
F2c	04/31/09	Journal Paper	Viscoelastic tensile characterization of undamaged asphalt mixtures
F2c	08/31/09	Final Report	Final Report on Testing Protocols
F2c	07/31/09	Journal Paper	Viscoelastic anisotropic compressive characterization of undamaged asphalt mixtures
F2c	07/31/09	Journal Paper	Material response in direct tension and compression of asphalt mixtures using dissipated pseudo-strain energy
F2d	09/30/09	Journal Paper	Distribution of viscoelastic properties on a thin film of asphalt binder
F2d	09/30/10	Journal Paper	Distribution of viscoelastic properties and relationship to fatigue damage on thin films of asphalt binders
F2d	12/30/10	Draft Report	
F2d	03/31/11	Final Report	
F2d	09/30/09	Journal Paper	Paper on the characterization of the directional distribution of damage using X-ray Computed Tomography
F2e	06/30/09	Decision Point	Finalize accelerated binder fatigue procedure candidates.
F2e	06/30/09	Draft Report	Report on findings from Subtasks F2e-1 and F2e-2.
F2e	08/01/09	Journal Paper	Focus on the VECD analysis of accelerated procedures.
F2e	09/30/09	Final Report	Issue final report on findings from Subtasks F2e-1 and F2e-2.
F2e	02/15/10	Presentation	Present binder fatigue progress at TRB, ETG or similar.

F3b	06/30/09	Journal Paper	CZ fracture testing and modeling
F3c	07/31/09	Decision Point	Finalize the model framework and experimental design for continuum damage to fracture.
F3c	09/30/09	Journal Paper	Paper on TAMU continuum model development and verification using laboratory data from subtasks F3c-2

Budget

		Year 1	Year 2	Year 3	Year 4	Year 5
Category F1: Material and Mixture Properties						
F1a	Cohesive and Adhesive Properties (TAMU)	60,000	100,000	90,000		
F1b	Viscoelastic Properties (TAMU)	70,000	75,000	30,000	25,000	
F1c	Aging (TAMU)	70,000	100,000	110,000	110,000	75,000
F1d	Healing (TAMU)	60,000	105,000	100,000	100,000	75,000
	Healing (UWM)	75,000	75,000	75,000	75,000	50,000
Category F2: Test Method Development						
F2a	Binder Tests and Effect of Composition (UWM)	75,000	100,000	100,000	100,000	50,000
F2b	Mastic Testing Protocol (TAMU)	20,000				20,000
F2c	Mixture Testing Protocol (TAMU)				20,000	20,000
F2d	Tomography and microstructure characterization (TAMU)		70,000	50,000	50,000	
F2e	Verification: DSR fatigue & Mixture performance (UWM)	75,000	100,000	100,000	100,000	75,000
Category F3: Modeling						
F3a	Asphalt Microstructure Model (WRI)		316,000	321,000	321,000	319,000
F3b	Micromechanics Model (TAMU)	60,000	125,000	125,000	125,000	110,000
F3c	Unified Continuum Fatigue Model (TAMU)	60,000	125,000	125,000	125,000	110,000
F3d	Calibration and Validation*			90,000	95,000	140,000
TOTAL		625,000	1,291,000	1,316,000	1,246,000	1,044,000
		5,522,000				

	Fatigue Year 3	Year 3 (4/09-3/10)											
		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						JP			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												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		F										
F1c-3	Develop transport model for binder oxidation in pavements					P					P, JP		D
F1c-4	Effect of binder aging on properties and performance				P	JP	D			F			
F1c-5	Polymer modified asphalt materials										P		D
F1d	**Healing**												
F1d-1	Critical review of literature												
F1d-2	Select materials with targeted properties												
F1d-3	Develop experiment design												
F1d-4	Test methods to determine properties relevant to healing												JP
F1d-5	Testing of materials												
F1d-6	Evaluate relationship between healing and endurance limit of asphalt binders			DP			JP			DP			
F1d-7	Coordinate with AFM analysis												
F1d-8	Coordinate form of healing parameter with micromechanics and continuum damage models												
Test Methods													
F2a	**Binder tests and effect of composition**												
F2a-1	Analyze Existing Fatigue Data on PMA												
F2a-2	Select Virgin Binders and Modifiers and Prepare Modified Binder												
F2a-3	Laboratory Aging Procedures												
F2a-4	Collect Fatigue Test Data						P						P
F2a-5	Analyze data and propose mechanisms									P			
F2b	**Mastic testing protocol**												
F2b-1	Develop specimen preparation procedures												
F2b-2	Document test and analysis procedures in AASHTO format												
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			DP, D			F						
F2e-3	Binder and Mixture Fatigue Testing												
F2e-4	Verification of Surrogate Fatigue Test												
F2e-5	Interpretation and Modeling of Data					JP					P		
F2e-6	Recommendations for Use in Unified Fatigue Damage Model												
Models													
F3a	**Asphalt microstructural model**												
F3b	**Micromechanics model**												
F3b-1	Model development			JP									
F3b-2	Account for material microstructure and fundamental material properties												
F3c	**Develop unified continuum model**												
F3c-1	Analytical fatigue model for mixture design												
F3c-2	Unified continuum model									JP			
F3c-3	Multi-scale modeling												

LEGEND

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

Work planned

Work completed

Parallel topic

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

LEGEND

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

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 destructive test using ablative laser mass spectroscopy that there was 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.

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.

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 pseudo-strain energy that generates microcracking and to differentiate it from the dissipated pseudo-strain energy that causes plastic deformation.

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 Three 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.

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.

This 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 strain formulation and the more difficult controlled stress 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.

Table for Decision Points and Deliverables

Date	Deliverable	Description
04/31/09	Journal Paper	Viscoelastic tensile characterization of undamaged asphalt mixtures
07/31/09	Journal Paper	Viscoelastic anisotropic compressive characterization of undamaged asphalt mixtures
07/31/09	Journal Paper	Material response in direct tension and compression of asphalt mixtures using dissipated pseudo-strain energy
07/31/09	Journal Paper	Fatigue damage and plasticity evaluation of asphalt mixtures with dissipated pseudo-strain energy
07/31/09	Journal Paper	Bond energy and dissipated pseudo-strain energy in fatigue crack modeling
03/31/10	Journal Paper	Self-consistent micromechanics model of binder-mastic relations
07/15/09	Presentation	Presentation of results of E1a-3 at the Pavement Performance Prediction Symposium in Laramie, Wyoming
07/15/09	Presentation	Presentation of results of E1a-1 and E1a-2 at the Pavement Performance Prediction Symposium in Laramie, Wyoming
01/31/10	Presentation	Presentation of results of E1a-1 and E1a-2 at the Transportation Research Board Meeting
1/31/10	Presentation	Presentation of results of E1a-3 at the Transportation Research Board Meeting
1/31/10	Presentation	Presentation of results of E1a-4 at the Transportation Research Board Meeting
3/31/10	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 2 activities for this work element initially focused on the encountered discrepancies between equipment geometries (parallel-plate versus cone-and-plate) in the Dynamic Shear Rheometer (DSR). Results show that the testing geometry in the DSR has a significant effect on the results, particularly at high stress or long testing time. They also show that the nonlinear behavior of asphalt binders plays a major role in the nonlinear stress dependency of mixtures. The stress sensitivity of binders and mixtures is highly dependent on modification type and aggregate gradation. Following stress, temperature was identified as the second most important factor controlling the binder behavior. A model was developed for the effects of stress and temperature on permanent strain as a function of number of cycles or loading time.

As shown in figure E1b-1.1, permanent strains in asphalt mixtures and binders can increase significantly with increasing stresses. The increases seen in permanent strain are not proportional to the stress and follow a nonlinear trend, meaning higher stresses can cause disproportionately higher rutting. Binder type and modification as well as aggregate gradation have important effects on the rate of increase in permanent strains and the nonlinearity of binders and mixtures.

It can be seen in figure E1b-1.2 that the binder has an evident influence on the normalized initial strain for the mixtures. Both coarse and fine gradations show an increase in the initial strain when the B5 binder was used. The figure shows that increasing the stress results in increasing strain; however, the increase in strain does not occur in a clear or consistent manner. Despite this lack of trend in figure E1b-1.2, a correlation can be observed between mixtures tested at 0.689 MPa and binders tested at 0.1 kPa. Figure E1b-1.3 depicts this correlation separated by aggregate gradation and binder type. The correlation proves that tertiary flow of mixtures can be explained by the behavior of the binder in the mix and appears independent of the aggregate gradation. These trends prompted further investigation.

Additional investigation is needed to determine the connection between binder resistance characterization, mastic behavior and the actual pavement performance as verified with mixture test results.

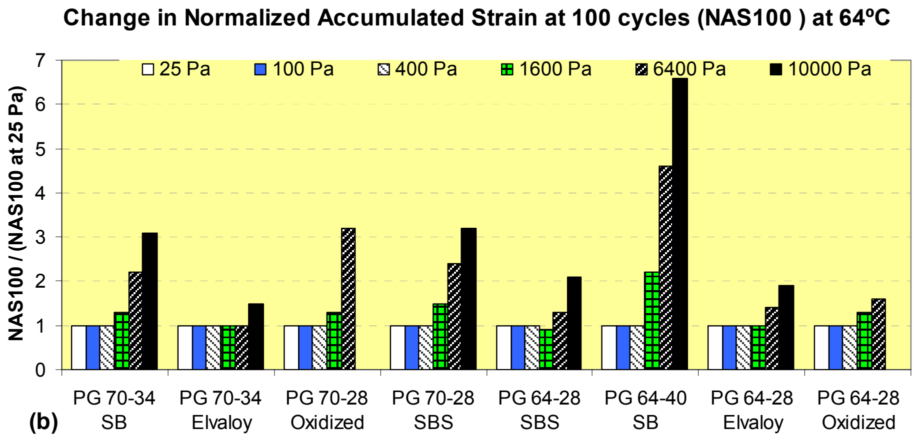

Figure E1b-1.1. Graph. Change in normalized accumulated strain at 100 cycles (NAS_{100}) and 64 ºC for binders.

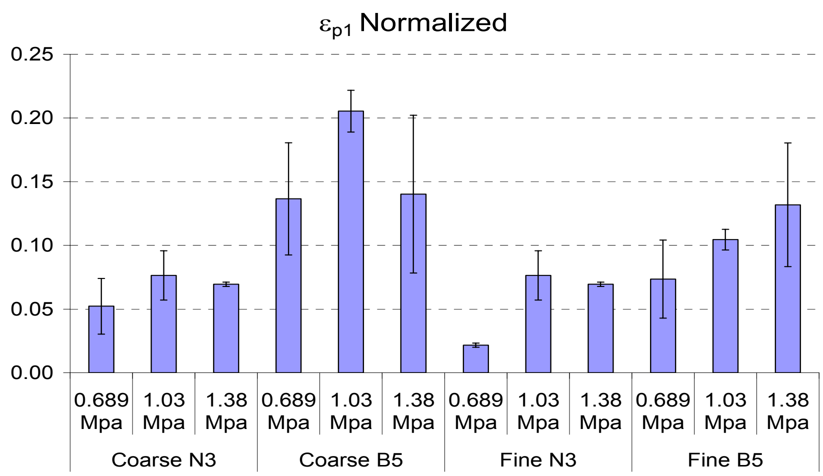

Figure E1b-1.2. Graph. Normalized initial strain for mixtures.

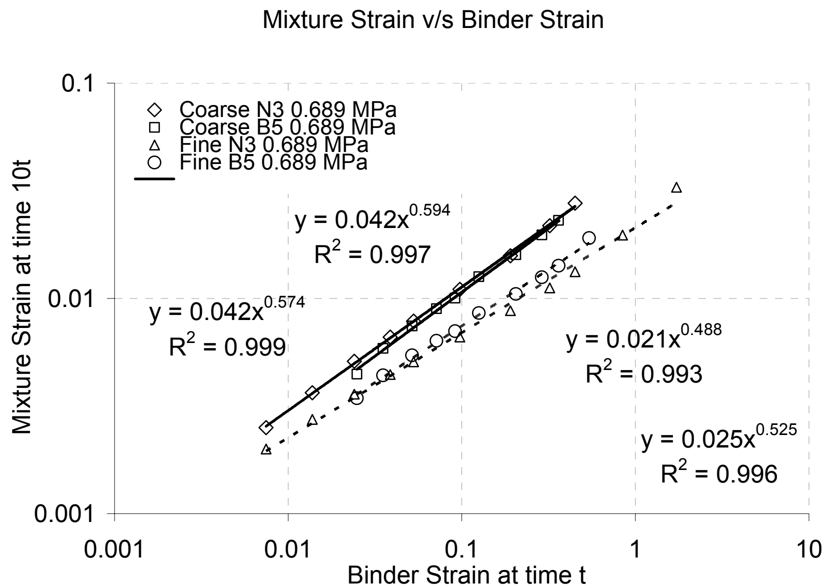

Figure E1b-1.3. Graph. Correlation between mixtures (tested at 0.689 MPa) and binders (tested at 0.1 kPa).

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

Initial laboratory testing indicated that asphalt mastic testing with the DSR is more difficult than binder testing. This is not expected to have a significant impact on progress. Also, while Multiple Stress Creep and Recovery (MSCR) testing has been successful, Repeated Creep and Recovery (RCR) and frequency sweep (FS) tests have not generated reasonable results. The results are under evaluation, and the work plan may be adjusted accordingly.

Year 3 Work Plan

Subtask E1b-1-1: Literature review

The projected Year 2 milestone of completing literature review is on schedule and completed.

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

The asphalt binders, asphalt fillers and mineral aggregates were selected for this subtask. These are described here.

The asphalt binders are:

- PG 76-XX SBS-FH (76SBS-FH).
- PG 76-XX Elvaloy®-FH (76EL-FH).
- PG 70-XX SBS-FH (70SBS-FH).

- PG 70-XX Elvaloy-FH (70EL-FH).
- PG 64-XX FH Unmodified (64UM-FH).
- PG 64-XX EM Unmodified (64UM-EM).
- PG 64-XX SBS-FH (64SBS-FH).
- PG 58-XX Unmodified SS (58UM-SS).
- PG 58-XX SBS-SS (58SBS-SS).

The asphalt fillers are:

- Pulverized limestone (LS).
- Pulverized granite (GN).
- Hydrated lime (HL).

The mineral aggregates are:

- Crushed limestone.
- Crushed gravel.

The prediction of actual performance of pavements as determined by rutting of asphalt binders has been expanded from a two-part (binder-mixture) to a three-part (binder-mastic-mixture) relationship. The inclusion of this middle phase, mastic, may be the link for correlation between binders and mixtures. In Year 3, binder testing will continue, bulk mastic testing will start, and preparation of mixture testing will conclude. Data analysis and interpretation will continue as testing progresses. In particular, the relationship between binder and mastic rheological properties will be examined when new data become available. Development of standard testing procedures and recommendations for specifications will be considered with continued data analysis and interpretation.

<u>*Subtask E1b-1-3: Conduct testing*</u>

Asphalt Binder Testing
The controlled variables in the asphalt binder testing plan are:

- Temperatures: high temperature (HT), 58 °C and 46 °C (also 34 °C when HT = 58 °C).
- Equipment: DSR with cone-and-plate, 20 mm in diameter, 100 µm in gap between cone tip and plate, and 4° in cone angle.
- FS test (AASHTO T 315-06): 0.01 to 100 Hz, 10 data points per logarithm decade, at a constant strain of 3%.
- MSCR test (AASHTO TP 70-07).
- RCR test (AASHTO TP 70-07):
    - Loading pattern: 1 s loading + 9 s unloading.
    - Stress levels: 100, 1000, 10000, 20000 and 30000 Pa.

- Number of cycles: 300 or that at which the specimen fails.

Asphalt Mastic Testing
The controlled variables in asphalt mastic testing plan are:

- Asphalt mastics:
  - Binder 1 + LS (76SBS-FH+LS).
  - Binder 3 + LS (70SBS-FH+LS).
  - Binder 5 + LS (64UM-FH+LS).
  - Binder 6 + LS (64UM-EM+LS).
  - Binder 7 + LS (64SBS-FH+LS).
  - Binder 5 + GN (64UM-FH+GN).
  - Binder 5 + HL (64UM-FH+HL).
- Dust-to-binder ratio (DTBR): 0.6, 1.0, 1.4 and 1.8.
- Temperatures: Same as in binder testing.
- Equipment: Same as in binder testing.
- FS test (AASHTO T 315-06): 0.01 to 100 Hz, 10 data points per logarithm decade, at strains shown in table E1b-1.1
- MSCR test (AASHTO TP 70-07).
- RCR test (AASHTO TP 70-07): Same as in binder testing.
- Only selected asphalt mastics with selected DTBRs will be tested in selected conditions.
- The mastic testing is an addition from the Year 2 work plan because mastic is the actual binder in the asphalt mixture holding the aggregate particles.

Table E1b-1.1. Strains for FS test.

DTBR	**Frequency (Hz)**			
	0.01-0.1	**0.1-1**	**1-10**	**10-100**
0.6	**0.3%**	**0.3%**	**0.3%**	**0.3%**
1.0	**0.3%**	**0.3%**	**0.3%**	**0.3%**
1.4	**0.2%**	**0.2%**	**0.2%**	**0.2%**
1.8	**0.2%**	**0.2%**	**0.2%**	**0.2%**

Asphalt Mixture Testing
The controlled variables in the asphalt mixture testing plan are:

- Asphalt binders:
  - PG 76-XX SBS-FH (76SBS-FH).
  - PG 70-XX SBS-FH (70SBS-FH).

    - PG 64-XX FH Unmodified (64UM-FH).
    - PG 64-XX EM Unmodified (64UM-EM).
    - PG 64-XX SBS-FH (64SBS-FH).

- Mineral filler: LS.
- Aggregate gradations: Superpave 12.5 mm fine-graded and coarse-graded (AASHTO M323-07).
- Other mixture variables:
    - Asphalt contents: Design (AASHTO M323-07).
    - DTBR: 1.0.
- Basic testing 1: Repeated load in uniaxial compression (Flow Number, or FN) test (NCHRP 465 Appendix B).
    - Temperature: 46 °C.
    - Load magnitudes: 22, 100 and 200 psi.
    - Confining pressure: 0.
- Basic testing 2: Dynamic modulus for permanent deformation (E*) test (AASHTO TP 62-07; also NCHRP Report 465 Appendix A and NCHRP Report 547).
    - Temperatures: 40, 70, 100 and 130 °F.
    - Frequencies: 25, 10, 5, 1, 0.5 and 0.1 Hz.
    - Confining pressure: 0.
    - Mixtures: Selected on basic testing 1.
- Additional testing based on results of basic testing 1 and 2:
    - FN and E* tests at other DTBRs: 0.6, 1.4 and 1.8.
    - FN test at other temperatures: HT and 58 °C.
    - On limited mixtures to be selected.

Subtask E1b-1-4: Analysis and interpretation

This subtask is ongoing and the previously collected data from binder test results will be analyzed in conjunction with the results from the aforementioned mastic testing as well as asphalt mixture testing.

Subtask E1b-1-5: Standard testing procedures and recommendations for specifications

Standard testing procedures will be followed in accordance with those listed previously in the individual testing sections of asphalt binders, mastic and mixtures. Recommendations for specifications may be made as the data collected increases.

Table for Decision Points and Deliverables

Date	Deliverable	Description
08/01/09	Journal Paper	Submit to AAPT and TRB.
01/01/10	Presentation	Prepare up-to-date results for TRB.
03/01/10	Presentation	Prepare relevant and up-to-date results for AAPT.

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

Major Findings and Status

Year 2 work included a detailed literature search on the existing technology of measuring response of binders and mastics using nano-indentation. In addition, preliminary nano-indentation tests were run on the mastics produced with a modified asphalt and a conventional limestone filler. Many problems were encountered, and the research team is proposing a change to the focus and plan for this task.

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

Although the literature search indicated that small-scale indentation has been used in the past for asphalt binders and mastics, the preliminary results indicated significant challenges regarding the stickiness between the binder and the nano-indenter and the need to heat the mastic to a higher temperature (135 ºC) to be within the range of the force available.

Researchers tried to solve this problem by adding a water film on the binder surface. However, questions remained about how the water film interacts with the binder and nano-indenter, and whether alternate solutions are possible. In addition to the technical problems, the small-scale indentation equipment is extremely expensive, and a controlled chamber to cool and heat samples is not readily available. The research team has, therefore, decided to change the focus of this task and follow a more practical approach for performing indentation tests on small asphalt samples to obtain rheological and fracture properties in a manner similar to nano-indentation experimental work.

Year 3 Work Plan

Overview

Exploratory work is proposed to investigate the possibility of obtaining fracture and rheological properties of asphalt materials based on small scale indentation or penetration tests performed on asphalt binders, mastics and mixtures. The goal is to identify the probe geometries (such as Vickers and Berkovich), loading configurations and data analyses that can be adopted within a reasonable amount of time and effort to characterize asphalt materials. Using existing instruments such as the Bending Beam Rheometer (BBR) or the Indirect Tensile Test, which allow researchers to apply vertical controlled loads to accommodate indentation tests with minimum costs, is a priority of this research. The work will be performed in collaboration with the University of Minnesota asphalt research experts and will be divided in four subtasks.

Subtask E1b-2i: Literature review

For more than a century, penetration tests based on simple indentation have been performed on asphalt binders, and many countries still have penetration-based specifications. The main objection to the penetration test is the lack of attention to the uniformity of the stress field and the use of a pointed needle that can result in a highly variable stress field.

Indentation tests are commonly used on other materials to measure surface hardness and to measure modulus of bulk or thin film materials. One of the challenges of running indentation tests (sometimes called surface hardness tests) is determining the indentation area. This problem is solved with the development of depth-sensing indentation instruments and analyses tools that provide much more information than just hardness.

In recent years, analysis methods have been extended to examining the time-dependent deformation of viscoelastic materials. A theory of linear viscoelastic indentation was first given for a spherical indenter; the elastic material constants were replaced with the corresponding differential operators in the viscoelastic constitutive equations. More complex solutions consisting of hereditary integral operators were also developed. These approaches were followed by others that produced creep and relaxation modulus data.

Indentation also provides a simple method to obtain toughness. The post-indentation radial crack size is measured as a function of load and toughness T_0, calculated as:

$$T_0 = \xi \left(\frac{E}{H} \right)^{1/2} \frac{P}{c_I^{3/2}}$$

where ξ is a dimensionless constant that depends on the geometry of the indenter; E is the elastic modulus and H is hardness, both determined in the indentation test; P is the peak indentation; and c_I is the post-indentation crack length.

In Year 3, the research team will continue its literature search on hardness tests and procedures for analyzing indentation results of viscoelastic materials.

Subtask E1b-2ii: Proposed Superpave testing modifications

The research team will propose modifications for Superpave equipment or other simple linear loading devices to measure the response of binders, mastics and mixtures.

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

The team will conduct preliminary testing and correlate results of indentation to rheological and fracture measurements.

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

The research team will submit a detailed report on the feasibility of indentation tests for lab and field measurements of the fracture and rheological properties of asphalt materials.

Table for Decision Points and Deliverables

Date	Deliverable	Description
8/1/09	Draft Report	Literature review of indentation and hardness tests, and their applicability to viscoelastic properties.
9/30/09	Presentation	Presentation on proposed modifications to Superpave tests to include indentation tests.
3/30/10	Draft Report	Report on the feasibility of indentation tests for asphalts and correlations to existing testing results.
2/10	Presentation	Presentation at the Binder ETG on the indentation testing of binders.

Work Element E1c: Warm and Cold Mixes

Subtask E1c-1: Warm Mixes

Major Findings and Status

The following points summarize the main findings from analysis of results collected in Year 2:

- The effect of water-bearing minerals and waxes claimed to allow reduction in mixing and compaction temperature are not easy to measure using the Superpave compaction method.
- Lowering the compaction pressure in the Superpave compaction to 300 kPa appears to increase sensitivity of mixture densification to the effects of warm mix additives.
- Use of surfactants and foamed asphalts as a warm mix technology is prevalent, warranting their inclusion in this work plan for further investigation.
- Capturing and quantifying the effect that warm mix additives have on the asphalt binders is difficult. For instance, the foaming effect of mineral-based additives has a very short duration, so it is not measurable using conventional means. Also, using the normal force method detailed in the ARC Q2 2008 report was unsuccessful and appears to be un-reliable.
- The measure of lubrication effect claimed in many publication is not simple and no standard binder or mixture testing methods exist today to quantify claimed lubrication.

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

In light of the findings from Year 2, this work element will focus on investigating the mixture coating and densification for the following three warm mix technologies:

- Water-based mineral additives.
- Surfactant-based additives.
- Injected water foaming.

Due to concerns over the detrimental effects of wax-based additives on low temperature stiffness and creep properties, no further investigation of these additives will be performed. This is a deviation from the Year 2 work plan, where originally wax, mineral and surfactant-based additives were included. For Year 3, the foaming technology will replace the wax-based additive in the testing matrix, so no effect on the schedule or budget is expected.

Year 3 Work Plan

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

The testing plan shown in table E1c-1.1 is expected to be completed by the end of Year 2. Materials are shown in table E1c-1.2.

Table E1c-1.1. Asphalt binder testing matrix.

Viscosity (OB)	Adhesion/Cohesion (OB)	Rutting (OB & RTFO)		Fatigue (PAV)		Low Temperature (PAV)	
ZSV	UW–Madison Tack Test (IT °C)	G*/sin(δ) (HT °C)	MSCR (HT °C)	G*sin(δ) (IT °C)	BYET (IT °C)	BBR (LT + 10 °C)	SENB (LT + 10 °C)

(HT = high temperature, IT = intermediate temperature, LT = low temperature, OB = original binder, RTFO = rolling thin film oven, PAV = pressuring aging vessel, ZSV = zero-shear viscosity, MSCR = Multiple Stress Creep and Recovery, BYET = Binder Yield Energy Test, BBR = Bending Beam Rheometer, SENB = Single-Edge Notched Bending)

Table E1c-1.2. Materials for Subtask E1c-1i.

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

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

Year 3 will continue work begun during Year 2 on mixture workability and stability. The updated experimental matrix shown in table E1c-1.3 reflects changes in the warm mix technologies.

Table E1c-1.3. Experimental matrix for subtask E1c-1ii.

Summary of Independent Variables				
	Control		WMA Additives	
Variable	**Values**	**Levels**	**Values**	**Levels**
Compaction Temperature (C)*	90 110 135	3	90 110	2
Compaction Pressure (kPa)	300 600	2	300 600	2
Binder Grade	PG 64-22 PG 76-22	2	PG 64-22 PG 76-22	2
Additive Type	Control	1	Mineral Surfactant Foaming	3
Aggregate Type	Granite	1	Granite	1
NMAS (mm)	19.0	1	19.0	1
Gradation	Fine Coarse	2	Fine Coarse	2
Replicates		2		
Summary of Progress	**Total Mixes - Control**	48	**Total Mixes- WMA**	96
	Mixes to Date	24	**Mixes to Date**	20
	% Complete	50%	**% Complete**	21%
Total Percent Complete	**31%**			

(NMAS = nominal maximum aggregate size.)

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 HT [°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.

The University of Wisconsin–Madison will prepare specimens in the Superpave Gyratory Compacter (SGC) where appropriate and ship to the University of Nevada, Reno. Otherwise the

University of Nevada, Reno will prepare specimens from virgin materials shipped from the UW–Madison.

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

Both WisDOT and local contractors will be contacted prior to and during the 2009 construction season to determine projects incorporating warm mix technology. The following parameters will be measured during construction:

- Mixing temperature.
- Compaction temperature.
- In-place density (nuclear gauge).
- Number of passes to achieve target density.
- Thickness.
- Thickness-NMAS ratio.

Loose mix will also be sampled for evaluation in the lab using the SGC with the pressure distribution analyzer (PDA) plate for determining the energy of densification.

Table for Decision Points and Deliverables

Date	Deliverable	Description
Jan.-March 2009	Presentation	Present journal paper at TRB/AAPT, ETG or similar.
3/31/09	Decision Point	Decide which WMA technologies are most promising and focus on development of best practices for those.
8/1/09	Journal Paper	Submit paper to TRB/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

Review of current national and international standards and practices showed similarities in using basic empirical methods to evaluate emulsions with many countries still using experience and judgment as surrogates for standardized tests. International standards included those from South Africa, New Zealand, Australia, and France. A detailed review of manuals and published papers from these countries was conducted. In addition, personal contacts with experts from these countries were established. The various uses of emulsions necessitate development of a general framework for emulsion testing supplemented by application-specific tests on both the materials used and performance of the entire surface treatment or cold mix system. An advisory group was formed in Year 2 to identify critical gaps in current practice and to prioritize applications in need of research. This input identified investigation of emulsion properties related to chip seals and selection of an appropriate residue recovery procedure as the first areas of research.

Figures E1c-2.1 and E1c-2.2 submitted in the ARC July–September 2008 report present data from a paper accepted for a poster session at TRB titled "Rheological Characterization of Emulsion Residues Using Newly Developed Evaporative Techniques." Further investigation determined that the recovered residue exhibits rheological properties resembling rolling thin film oven (RTFO)-aged conventional binders. Furthermore, percent recovery data from Multiple Stress Creep and Recovery (MSCR) testing presented in the TRB paper indicates that the proposed method produces residues that preserve the effects of polymer and latex modification. Details of this work are presented in the ARC October–December 2008 report. Both findings are consistent with other industry efforts presented through the Emulsion Task Force Subcommittee on Residue Recovery. These findings and coordination with national efforts led to the selection of the evaporative residue recovery procedure recently accepted by ASTM to produce materials for evaluation of residue properties.

Year 2 work focused on the construction properties of emulsions for chip seals, specifically, setting rate and development of adhesion. Efforts related to development of specific test methods to quantify these properties were presented in a paper submitted to the International Symposium on Asphalt Emulsion Technology (ISAET). The citation was provided in the ARC July–September 2008 report. In summary, initial testing showed that the Dynamic Shear Rheometer (DSR) and the Pneumatic Adhesion Tensile Testing Instrument (PATTI) tests show promise in measuring resistance to raveling and adhesion, respectively. Development of these tests methods allowed for identification and prioritization of materials properties such as emulsion type and aggregate mineralogy and environmental conditions in need of investigation. An experimental design was produced for both properties and will be executed in early 2009. Year 2 effort also included a review of energy savings that could be achieved when cold asphalt applications are used to replace HMA applications. An evaluation of the methods used in calculating energy and in modeling environmental and energy reduction impacts was conducted.

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

Significant differences were found between the rheological properties of the residue relative to the base binder. Subsequent testing identified aging of the residue during the recovery procedure as the main source of differences. Preliminary research showed that the residue produced is similar to that of an RTFO-aged conventional binder. To provide a frame of reference for establishing performance thresholds, the rheological properties of the base binders used in the experiment will be measured after being subjected to curing by the evaporative recovery procedure and to RTFO-aged materials. The additional testing is not expected to significantly delay future work.

Long-term aging of the residue also must be addressed. The current proposal is to recover emulsion residues using the draft ASTM recovery procedure and then subject the residue to conventional pressure aging vessel (PAV) aging. University of Wisconsin–Madison will work with the Emulsion Task Force to define correct conditions and provide adequate materials for characterization of the residue. Establishing these procedures is not expected to significantly affect the progress on emulsion residue characterization.

Logistical issues in terms of shipping emulsions cross-country and through cold climates were identified as an area of concern for shipping emulsions produced by suppliers to UW–Madison over the winter months. This concern was addressed by identifying a local material supplier.

The issue of curing emulsion in the presence of mineral surface in the testing fixture proved to be challenging. Some adjustments in testing protocols were needed to achieve relatively efficient curing that can mimic field conditions.

Year 3 Work Plan

E1c-2i: Review of literature and standards

Review of literature and standards will focus on the following:

- Design guidelines and aggregate requirements for chip seals and dense cold mixes.
- Emulsion properties relevant to dense cold mixes and tests to measure them.
- Performance tests for evaluation of cold in-place recycling and dense cold mixes, including workability, curing time and in-service performance.

A literature review report summarizing the current state of technology for chip seals and for dense cold mixes will be submitted as separate documents; the chip seal document will be submitted by April 30, 2009, and the cold mix document submitted by September 30, 2009.

E1c-2ii: Creation of advisory group

An advisory group has been established and engaged in the project. It will plan at a minimum two face-to-face meetings and one teleconference. A tentative schedule for the meetings is:

- Teleconference #1: Summer 2009.
- Face-to-face meeting #1: Fall 2009.
- Face-to-face meeting #2: January 2010 (TRB).

E1c-2iii: Identify tests and develop experimental plan

Tests will be developed related to construction and in-service properties of both spray grade and mixing grade emulsions. Applications investigated include chip seals, cold in-place recycling, and dense graded cold mixes. Specifically, the following activities will be performed:

- Construction properties of emulsions.

- Investigation of the use of the Brookfield Rotational Viscometer (RV) to evaluate emulsion viscosity and breaking rate.
- Evaluation of current storage stability tests and potential improvements to current practice.

Promising test methods will be incorporated into the experimental plans presented for evaluation of development of adhesion and setting rate specified in *E1c-2v*.

- Emulsion residue testing.
  - Performance testing will follow the modified version of the straw man specification for evaluation of emulsion residues published in a study funded by the Federal Lands Bureau (FLH). UW–Madison provided initial input for the testing protocols, and procedures will be revised based on recommendations in the draft version of the research report submitted to FLH. The finalized residue testing matrix will be implemented on all emulsions tested for this work element. The finalized testing protocol will be completed by April 30, 2009.

- Cold in-place recycling and dense cold mixes.
  - Construction considerations: Work will focus on relating emulsion and mixture properties to workability, development of density and curing time.
  - In-service performance: Work on relating residue tests to mixture performance.
  - Other pertinent aspects of construction or performance that arise from the results of the literature review will be considered.

An experimental design will be developed pending the results of the review of literature and initial laboratory testing. The preliminary due date for the design is September 30, 2009.

E1c-2iv. Develop material library and collect materials

Table E1c-2.1 provides a summary of the materials selected to execute the chip seal investigation specified in the Year 3 work plan.

Table E1c-2.1. Summary of materials used in investigation of emulsion properties for chip seal applications.

Material	Levels Selected	Supplier	Comments	Materials Collection Complete
Emulsion	CRS	Potential for HG Meigs*	Based on initial testing emulsion types of different viscosities will be requested	
	CRS-P			
	LM-CRS			
	RS			
	RS-P			
	LM-RS			
Asphalt Binder	PG 64-22	Flint Hills	High Asphaltenes	
	PG 58-28**	CRM	Low Asphaltenes	
Modifiers	SBS Polymer	Kraton		X
	Proprietary Polymer**	Proprietary	Investigate feasibility of applying this modifier to emulsions.	X
	Latex	Provided by Emulsion Supplier		
	Rubber**	TBD	Rubber modified emulsions already being used. Evaluate feasibility of use in cold climates.	
Aggregate Mineralogy	Granite	Mathy Inc.	Aggregate used in E1c-1.	X
	Diabase	Rocky Mountain Enterprises	Igneous Aggregate with different composition than granite.	X
	Hard Limestone	Michels Construction	Two limestone sources selected to investigate the effect of aggregate porosity	
	Soft Limestone	Northeast Asphalt		X

*Pending signature of the commitment letter.
**Indicates materials that will not be completely integrated into the full factorial experimental design.

A local emulsion supplier, HG Meigs Inc., was identified in hopes of overcoming the logistical issues related to shipping emulsions over long distances or in cold weather. UW–Madison is currently working with HG Meigs Inc. to establish a letter of commitment to help in supplying materials.

Initial investigation of dense cold mixes will use local materials procured by University of Nevada, Reno, the project lead on the work related to cold mix applications. Aggregates, emulsions, modifiers, and base asphalts will be specified as part of the preliminary experimental design for investigation of cold in-place recycling and dense cold mixes, which will be submitted as part of the literature review report by September 30, 2009.

The summary of materials and the quantities required to execute the Year 3 work plan will be established for the mixing applications and finalized for the surfacing applications. Required quantities will be broken out by application type. A database will be established, including the following:

- Aggregate: Physical and chemical properties.
- Emulsions: Results of standard quality control tests.
- Asphalts: Rheological properties of base binders and modified asphalts. Testing will be conducted using un-aged, aged using the evaporative residue recovery procedure, RTFO and PAV-aged materials.

The database will be created concurrently with *E1c-2v* and will be used to identify materials properties that significantly affect the performance of a chip seal, dense cold mix, or cold in-place recycling application.

E1c-2v. Conduct Testing Plan

Construction Properties of Emulsions

To identify significant material properties and the development of emulsion rheological properties over time, a full factorial experimental design was developed for the evaluation of setting behavior and development of adhesion. To ensure consistency in test results, construction properties of a given emulsion will be tested one month after the emulsion is received. The testing plans established for evaluation of these properties are provided in tables E1c-2.2 and E1c-2.3.

Table E1c-2.2. Experimental plan for adhesion testing.

Emulsions Selected		
Cationic	CRS LM-CRS CRS-P	3
Anionic	RS LM-RS RS-P	3
Total		**6**
Aggregate Properties		
Variable	**Values**	**Levels**
Surface Roughness	High Low	2
Mineralogy/Porosity	Soft Limestone (High Porosity) Hard Limestone (Low Porosity) Diabase Granite	4
Total	**8**	
Testing Variables		
Application Temp (Rock)	Rock (25C)	1
Application Temp (Emulsion)	Emulsion (70C)	1
Curing Humidity	Low (50%) High (95%)	2
Curing Temperature	Low (20C) High (35C)	2
Aggregate Moisture	Dry Wet	2
Total	**8**	
Testing Conditions		
Curing Time	6 24 30	3
Stub Temperature	Constant 45C	1
Film Thickness	Design (0.4 mm)	1
Total	**3**	
Combinations	**1152**	
Replicates	**3**	
Total Tests	**3456**	

The PATTI test will be used to evaluate the development of bond strength and the sensitivity to the materials and testing variables provided above. Evaluation parameters will include tensile strength at failure and the tack factor, defined as the area under pressure versus time curve. Sample preparation and testing do not require much time, allowing for a plan of 720 tests per month. Using this estimate and a safety factor, it is anticipated that testing will be completed in six months.

The testing matrix presented for the evaluation of bond strength was modified for consideration of the effects of emulsion type, material properties and testing variables on setting rate due to the increased time requirements of DSR testing. The modified testing plan is presented in table E1c-2.3.

Table E1c-2.3. Experimental plan for evaluation of setting rate.

Emulsions Selected		
Cationic	CRS	3
	LM-CRS	
	CRS-P	
Anionic	RS	1
Total		**4**
Parameter	**Values**	**Factors**
Aggregate Variables		
Surface Roughness	High	1
Aggregate Type	Soft Limestone	3
	Hard Limestone	
	Granite	
Total	**3**	
Testing Variables		
Application Temp (Rock)	Rock (25C)	1
Application Temp (Emulsion)	Emulsion (70C)	1
Curing Time	6 hrs	3
	24 hrs	
	30 hrs	
Curing Humidity	Low (50%)	2
	High (95%)	
Curing Temperature	Low (20C)	2
	High (35C)	
Total	**48**	
Combinations	**144**	
Replicates	**1**	
Total Tests	**144**	

Specific testing procedures for both the PATTI and rheological tests used to evaluate setting behavior and resistance to raveling are presented in the ARC October–December 2008 report. The time required to conduct each test is approximately two hours, allowing for the entire testing matrix to be completed in approximately six months. Replicates of the first two testing runs will be conducted to evaluate the reliability of the tests. After an initial level of reliability has been established, certain combinations at each curing time will be randomly selected and repeated. Initial results indicate coefficients of variation (COV) less than 10% when the emulsion has sufficiently cured.

Emulsions specified in table E1c-2.2 will be used to evaluate breaking rate, viscosity and storage stability using the tests developed under E1c-2iii. As specified in E1c-2iii, an experimental plan to evaluate the aforementioned properties will be submitted by April 30, 2009.

Emulsion Residue Properties
Emulsions will be recovered using the ASTM draft recovery procedure referenced in the ARC July–September 2008 report and tested using the protocol defined as part of the scope E1c-2iii.

Testing for construction and residue properties of emulsions and a report of the results will be submitted by October 30, 2009.

Dense Graded Cold Mixes
As specified in E1c-2iii, the experimental design submitted by September 30, 2009, will be executed in the second half of 2009.

E1c-2vi. Develop performance selection guidelines

Performance selection guidelines will be developed using the laboratory testing specified in the work described above and will be selected for the following properties:

- Construction properties.
  - Viscosity.
  - Breaking rate.
  - Storage stability.
- In-service properties.
  - Resistance to deformation.
  - Fatigue cracking.
  - Thermal cracking.
  - Resistance to long-term raveling.

In addition, the sweep test will be used as a performance test on the entire system to develop guidelines in terms of resistance to early raveling. Preliminary results of the adhesion and setting experiments will be used to select the emulsion and aggregate types for testing in the sweep test. The sweep test samples will be prepared per ASTM D7000 standards and cured at a temperature and humidity consistent with the conditions of the experiments conducted in *E1c-2v*. Sweep test results will be evaluated in terms of percent aggregate lost. In addition, emulsion residue from the sweep test sample will be collected and tested in the DSR using the aforementioned strain sweep and MSCR procedures. Results from the sweep test residues will be compared to results of emulsion cured directly on the aggregate surface to evaluate the effect of the compactive effort exerted in preparation of the sweep test samples and the feasibility of using emulsion cured directly on the aggregate surface to predict early raveling.

Sweep test procedures may be revised based on the outcomes of NCHRP 14-17: Manual for Emulsion-Based Chip Seals. UW–Madison is currently working with FHWA to obtain progress reports from this project.

Energy Analysis
Use of emulsions in surface treatment or cold mix applications necessitates consideration of the reduction in emissions and energy consumption associated with maintenance and rehabilitation activities using emulsion relative to conventional methods. As green technologies become more prevalent, there have been efforts to incorporate the eco-efficiency of different construction activities for consideration in pavement type selection and maintenance strategies. Efforts will be made in Year 3 to evaluate and select the most appropriate method for quantifying the environmental impacts of these applications and identify the relationships between environmental savings and cost/performance.

E1c-2vii. Validate guidelines

Guidelines established in E1c-2vi will be validated through selection of field sections. The goal is to have a testing plan and three to five field-constructed chip seal sites. The testing plan and summary of field sites will be completed by June 30, 2009. The following are potential sources for field projects:

- HG Meigs, Inc.
- City of Madison.
- Other regional cooperation.

The field sampling and testing procedures in NCHRP 14-17 will be used as a starting point for the development of a testing protocol for ARC field sites. The testing plan will also include methods for obtaining field values for energy consumption inputs.

E1c-2viii. Develop CMA mix design procedure

A mix design method will be developed for cold in-place recycled (CIR) mixtures and cold-mix asphalt (CMA) mixtures. The mix design method will be consistent with the Superpave volumetric mix design method for HMA. The Superpave gyratory compactor 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 CIR and 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.

E1c-2ix. Develop CMA performance guidelines

There are no planned activities for this work. This work will be re-evaluated in the Year 4 Work Plan.

Table for Decision Points and Deliverables

Date	Deliverable	Description
4/30/09	D1: Chip Seal Technical Progress Update	Literature review, testing protocols for emulsion construction, residue properties and performance tests. Preliminary experimental results.
6/30/09	D2: Validation Plan	List of test sections, plans and procedures for field and laboratory testing.
9/30/09	D3: Dense Cold Mix Literature Review Report	Summary of state of practice for CIR and dense cold mixes; preliminary materials election/experimental design.
10/30/09	D4: Emulsion Properties for Chip Seal	Report on data analysis and summary of path forward.
12/31/09	D5: CIR/Dense Cold Mix Experimental Design	Final experimental design for evaluation of CIR and cold mix performance properties.

CATEGORY E2: DESIGN GUIDANCE

Work element E2a: Comparison of Modification Techniques

Major Findings and Status

After discussions with the reviewers of this work element, the research team will not be producing the modified asphalts but instead will be requesting PG grades from suppliers, leaving to the manufacturers the selection of the base binder as well as the amount of modifier to be added. The research team will compare the collected materials based on target PG grades and type of additives used.

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

The work plan and the experimental design for this element have been changed significantly after discussions with manufacturers and experts in the field. The new work plan has been developed so that it will fit in the time left for the ARC project.

Year 3 Work Plan

Subtask E2a-1: Identify the possible binder modification targets and the additives to be included in the study

The work plan for this element includes manufacturer-prepared modified binders. The team will seek modifiers to provide both low and high levels of modification (one and two PG grade bumps). A minimum of three manufacturers will be solicited to provide materials so that three different modifiers at a minimum are included in this work plan.

The research team will recommend a base binder, but the ultimate binder selection will be left to the manufacturer's discretion. In the event that a manufacturer decides to use a different base binder than the one recommended, the manufacturer will be asked to provide a sample of its selected base binder along with the modified materials.

A Request for Materials letter will be sent out to several manufacturers to solicit their participation in this project. Once the participation offers have been collected, the modified and base binder will be collected.

Subtask E2a-2: Test and compare different binders and modifiers

The team will investigate the high temperature, low temperature and intermediate temperature properties for all binders (modified and unmodified) included in this work plan. This approach will allow for classification and comparison of the different modifiers to map their relative effects on binders.

The modified binders will be subjected to storage stability tests like the Cigar Tube Test or the Laboratory Asphalt Stability Test to evaluate their homogeneity and storage capability.

The team will also perform a data analysis focusing on the rheological properties and damage resistance characterization of modified binders.

The rheological properties investigation will serve as a tool both to classify and rank starting materials, and as a monitoring tool during the modification and conditioning process. The investigation will be accomplished by measuring parameters like $G^*/\sin(\delta)$, which is an indication of the rutting resistance of binders, as well as by performing Multiple Stress Creep Recovery (MSCR) tests. The team will also use time sweep tests at different frequencies to gather the information necessary to build master curves, which will highlight the impact of modification over a broader range of properties. Bending Beam Rheometer (BBR) testing will shed light on the effect of modification on binder behavior in low temperature conditions. These tests will provide important information as to how the modification of binders affects their properties.

The damage resistance investigation will focus on classifying and ranking different modifiers and modification techniques based on their impact on the binder's ability to resist damage. The team will focus on tests for fatigue damage control using the Binder Yield Energy Test (BYET), rutting damage control using the MSCR test, and low temperature damage control using the Single-Edge Notched Bending (SENB) test to maintain their perspective on monitoring the overall binder properties.

An overview of the tests to be included in this subtask is presented in table E2a.1.

Table E2a.1. Summary of tests.

Binder	Polymer Modification	Tests
A	Low level	Superpave Dynamic Shear Rheometer (DSR)
B	High level	Storage Stability ASTM D-5976
C	Unmodified (base)	MSCR
		Frequency Sweep
		BBR
		BYET
		SENB

All tests will be run in triplicates.

Subtask E2a-3: Develop models that allow estimation of level of modification and a costing 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 to provide a costing index.

Subtask E2a-4: Write an asphalt modification guideline

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**
7/09	Decision Point	Decide which modification targets and materials are to be included in the testing matrix.
3/10	Presentation	Give presentation on progress 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 2 focused on Subtask E2b-1.a, "Develop a System to Evaluate the Properties of the Recycled Asphalt Pavement (RAP) Aggregates."

The impact of the current extraction techniques (i.e. ignition, centrifuge, and reflux) on the properties of the extracted RAP aggregates was evaluated for two different sources of aggregates from the east and two sources from the west. Only the trichloroethylene solvent was used in the centrifuge and reflux experiment. The following physical properties of the extracted aggregates were measured: gradation, LA abrasion, soundness, absorption, specific gravity, fine aggregate angularity, coarse aggregate angularity, fractured faces, sand equivalent, durability index, Micro-Deval, and AIMS. Additionally, the impact of reflux and centrifuge on the properties of the recovered asphalt binder was evaluated. The generated data from the four different aggregate sources are under analysis for any statistical significant difference between the measured properties before and after extraction.

University of Wisconsin–Madison's efforts on this work element in Year 2 focused on Subtask E2b-1.b, "Develop a System to Evaluate the Properties of the Recycled Asphalt Pavement (RAP) Binder."

The major finding for this subtask was the establishment of a procedure to test beam samples of RAP mortar (Passing # 8) mixed with fresh binders. The beam samples were tested in the Bending Beam Rheometer (BBR) to measure mortar stiffness. An analysis procedure was established to use binder-mortar correlations to estimate stiffness of aged binder in the RAP without extraction. Examples of the mortar and binder stiffness correlations are shown in figure E2b.1 for the RAP aggregates mixed with fresh binders (fresh RAP) and for RAP aggregates mixed with binder artificially aged in the pressure aging vessel (artificial RAP). The binder-mortar stiffness correlations can be used to estimate the stiffness of the aged binder in the RAP by using a blending chart as shown in figure E2b.2. The blending chart inputs include the stiffness of the fresh binder and the stiffness of the aged binder blended with the fresh binder at a specific percentage. The outcome of the chart is the stiffness of the aged binder (the scale at left in figure E2b2).

Another important finding was that the implemented BBR modifications and new molding technique were suitable to obtain the stiffness of the binders and mortars. The BBR modifications and new molding technique are detailed in the ARC July–September and October–December, 2008 progress reports.

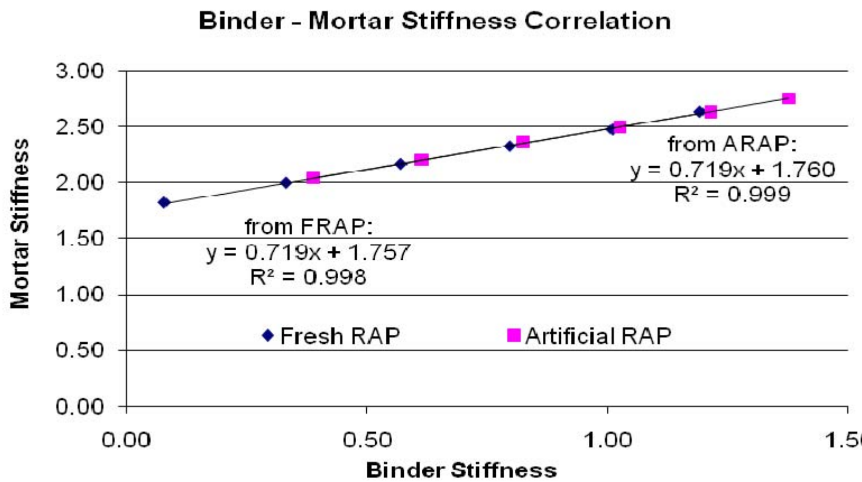

Figure E2b.1. Correlation and equation for binder-mortar stiffness.

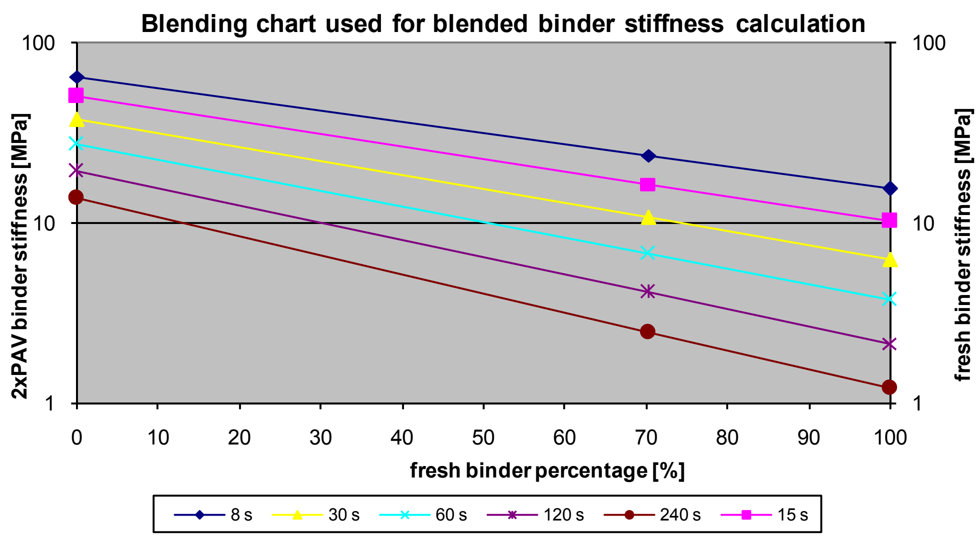

Figure E2b.2. Blending chart used to calculate blended binder or aged binder stiffness in RAP.

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

One of the objectives of this work element is to estimate the PG grade of the binder in RAP and determine if shifting of the new (fresh) binder grade is necessary when RAP is used in HMA. As explained earlier, the established method requires a blending chart to determine the stiffness of the aged binder (figure E2b.2). It appears that for some aged RAP binders the extrapolation to estimate the stiffness of the aged binder gives an erroneous distribution of stiffness as a function of loading time. An example is shown in figure E2b.3, where the blended binder shows a narrow distribution of stiffness as a function of time that extrapolation for the aged binder shows increasing stiffness with loading time. This is obviously not possible and more investigation is needed to understand what causes this problem for some RAPs.

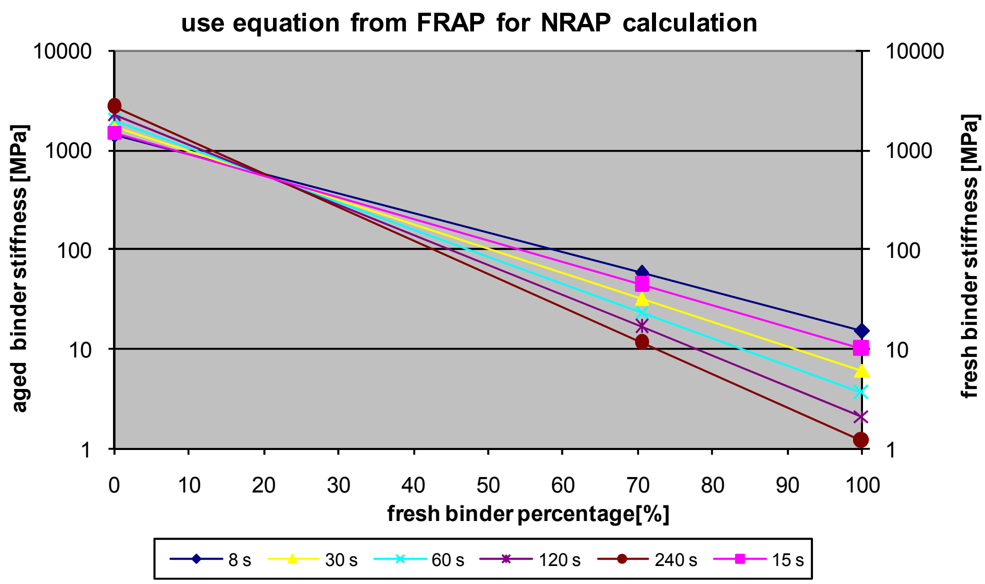

Figure E2b.3. Blending chart for natural RAP based on the calculation results in table E2b.1.

<u>Year 3 Work Plan</u>

<u>Subtask E2b-1: Develop a System to Evaluate the Properties of RAP Materials</u>

<u>E2b-1.a: Develop a System to Evaluate the Properties of RAP Aggregates</u>

Work for Year 3 will consist of analyzing the data generated for the four different aggregate sources. Additionally, the impact of mixing on the properties of the aggregates will be evaluated by mixing the virgin aggregate with water (no asphalt) in the mixer and then re-evaluate their properties. Once the best extraction procedure is identified the impact of solvent types on the aggregate properties will be evaluated. The materials that will be used in the experimental plan are shown in table E2b.1.

Table E2b.1. Materials for the evaluation of impact of mixing on aggregate properties.

Material	Tests
Nevada-andesite	Gradation, LA abrasion, soundness, absorption, specific gravity, fine aggregate angularity, coarse aggregate angularity, fractured faces, sand equivalent, durability index, AIMS, and Micro-Deval.
California-Handley Ranch	
NCAT-Source 1	
NCAT-Source 2	

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

Work for Year 3 will consist in reviewing the analysis methods used to obtain the stiffness of the binder. Special attention will be given to the calculation of the aged binder stiffness of the natural RAP and solving the problem discussed in the section on Findings and Status.

The materials that will be used in the experimental design are shown in table E2b.2. A complete set of testing will be conducted using these materials. The testing set consists of three replicas for each mortar and binder tested.

Table E2b.2. Materials for experimental design of E2b-1.b.

Virgin Binder Grades	RAP Sources
1. PG 64-22 2. PG 64-28 3. PG 58-34	1. Modified Stiff (Northern Nevada) 2. Modified Very Stiff 3. Unmodified Stiff (South Carolina) 4. Unmodified Very Stiff (Palmdale, S. California)

The following experimental plan will be conducted concurrently by UNR and UWM to validate the RAP mortar procedure:

- Evaluate the Properties of the Natural RAP:
  - Select two sources of RAP: S. Carolina RAP, and Palmdale-Southern California RAP.
  - For each RAP source, extract the aggregates and recover the RAP binder using the centrifuge extraction and the Rota-vap methods.
  - Calculate the RAP binder content for each RAP source.
  - Grade the recovered RAP binders according to the Superpave grading system and the guidelines provided by the NCHRP Research Results Digest No. 253.
- Prepare the Artificial RAP mortars:
  - Select two virgin binder grades: PG64-22 and PG58-28.
  - For each RAP source and selected binder grade, prepare artificial RAP mortars:
    - For each binder grade, mix the extracted RAP aggregates with the 2×PAV binder at the corresponding RAP binder content.
    - Mix the artificial RAP with 10% and 15% of the same grade fresh binder.
- Prepare the Fresh RAP mortars:
  - For each RAP source and for the same binder grades, prepare fresh RAP mortars:
    - For each binder grade, mix the extracted RAP aggregates with the fresh binder at the corresponding RAP binder content.
    - Mix the fresh RAP with 10% and 15% of the same grade fresh binder.

- Testing:
    - Test the artificial and fresh RAP mortars in the BBR at 4000 mN and two temperatures.
    - Conduct the BBR test on fresh and 2×PAV binders.

A standard protocol for the RAP mortar testing procedure will be prepared, and the necessity of PG grade shifting will be evaluated.

Subtask E2b-2: Compatibility of RAP and Virgin Binders

Work for Year 3 will continue working on developing methods to identify the degree of compatibility between virgin binder and RAP binder in the HMA mix. The WRI research will conduct the test matrix shown in table E2b.3.

Table E2b.3. Proposed Testing Matrix for RAP/virgin binder compatibility.

Material	Test Procedure	
	Rheological	Chemical
Virgin	Dynamic Shear Rheometer (G*, δ)	Automated Flocculation Titrimetry (AFT) Atomic Force Microscopy (AFM)
RAP		
Blended Binder		

Subtask E2b-3: Develop a Mix Design Procedure

Work on this subtask will begin in the second half of year 3. The experimental plan for this subtask calls for the development of a mix design procedure for HMA mixtures containing high RAP contents. The first step of this subtask will be to meet with the NCAT researchers who are working on NCHRP 09-46 to avoid any duplication of efforts. Based on the meeting with the NCAT researchers an experimental plan will be developed for this subtask and the work will begin shortly after.

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

No work on this subtask is planned for year 3.

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.

Year 3 Milestones

- Complete the testing on the impact of mixing on the aggregate properties.
- Complete the analysis on the impact of the extraction techniques on aggregate properties.

- Write a report summarizing the findings of E2b-1.a subtask.
- Evaluate the impact of solvent type on the properties of RAP aggregates and binders.
- Complete testing of four RAPs and three binders selected for the experimental plan.
- Write a standard protocol for the RAP mortar testing procedure.
- Evaluate PG grade shifting.
- Develop an experimental plan and start working on Subtask E2b-3.

Table for Decision Points and Deliverables

Date	Deliverable	Description
4/31/09	Draft Report	Report on findings from subtask E2b-1.a.
6/15/09	PG Grade Shifting Evaluation	For all the materials listed in the work plan, evaluate PG grade shifting. Evaluate the PG grade of aged binder in each kind of RAP.
9/15/09	Standard Protocol	Write a standard protocol for evaluating the PG grade of aged binder in the RAP.
12/15/09	Project Report	Finish the whole project report for Subtask E2b-1.b.
01/31/10	Draft Report	Experimental Plan for subtask E2b-3

Work element E2c: Critically Designed HMA Mixtures

Major Findings and Status

During Year 2, the focus of the work at UNR was on Subtask E2c-1, "Identify the Critical Conditions." The 3D-Move mechanistic analysis of the HMA pavements under a moving 18-wheel truck were undergoing according to the experimental plan. Table E2c.1 summarizes the analyses that have been completed for the PG64-22 and the PG52-22 mixes. The 3D-Move analyses were used in conjunction with the measured dynamic modulus (|E*|) data on the various mixes.

The stress states in the various HMA pavements were evaluated for the completed 3D-Move runs. The determined stress states in the pavements were analyzed and stress invariants were used to appropriately duplicate the state of stresses in the laboratory triaxial testing set-up of the HMA mixtures. The calculated octahedral normal and shear stresses (i.e. σ_{oct} and τ_{oct}, respectively) at any point within the pavement structure were related to the stress invariants at the same point which in turn were related to the deviator and confining stresses in a laboratory triaxial testing set-up. As a result, recommendations for the magnitude of the deviator and confining stresses in the triaxial test were provided. For further details refer to the Report entitled "Recommended Deviator and Confining Stresses for the Flow Number Test" that was submitted to the mix ETG for review and consideration in the new provisional AASHTO standard test method.

Table E2c.1. Completed mechanistic analyses for the PG64-22 and PG52-22 mixes.

Road geometry	Pavement structure	18-wheel traveling speed (mph)	Braking	Tire-pavement pressure distribution*	HMA Layer Temperature
Level road	4” HMA/6” Base & 6” HMA/8” Base & 8” HMA/10” Base	60	No	Uniform	40°C
					50°C
					60°C
					70°C
		40	No	Uniform	40°C
					50°C
					60°C
					70°C
		20	No	Uniform	40°C
					50°C
					60°C
					70°C

* An inflation pressure of 125 psi is used

In summary, the data showed only minor variations in the magnitude of the deviator and confining stresses due to vehicle speed. Therefore, it was decided to use the average values of the three speed levels at each pavement temperature. Figure E2c.1 shows the average total vertical, deviator, and confining stresses of the various pavement structures and temperatures. The total vertical stress is defined as the sum of deviator and confining stresses. The data presented in figure E2c.1 clearly showed that the deviator and confining stresses maintained steady values at temperatures higher than the high performance temperature of the corresponding asphalt binders’ grades.

Consequently, it is recommended to use a deviator stress and a confining stress of 80 psi and 32 psi, respectively, at the high performance temperature of the asphalt binder in question. The final recommended values for the deviator and confining stresses to be applied in the flow number (FN) test set-up are summarized in table E2c.2. It should be noted that the recommended values are for an 18-wheel truck travelling at a speed between 20 and 60 mph without braking and a tire inflation pressure of 125 psi. The recommendations will be further refined when the anticipated experimental plan is fully completed and all the data from the mechanistic analysis are analyzed.

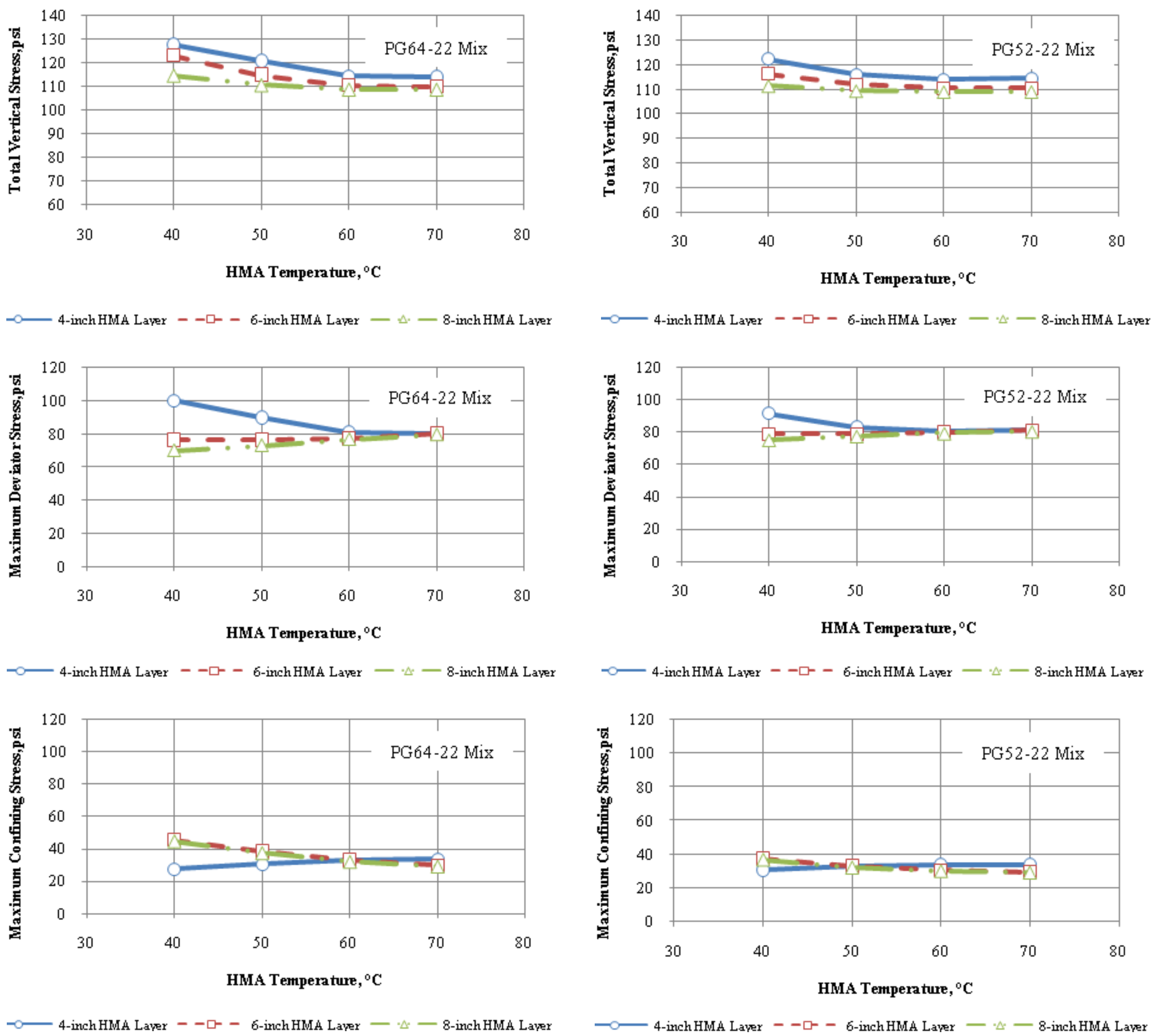

Figure E2c.1. Average total vertical, deviator, and confining stresses for vehicle speed between 20 and 60 mph.

Table E2c.2. Recommended deviator and confining stresses.

Asphalt binder grade	Testing Temperature (°C)	Max deviator stress, σ_d (psi)	Max confining stress, σ_c (psi)	Total vertical stress, $\sigma_d + \sigma_c$ (psi)
PG64-22	64	80	32	112
PG52-22	52	80	32	112
PGXX	XX	80	32	112

* recommended values for an 18-wheel truck traveling at a speed between 20 and 60 mph without braking and a tire inflation pressure of 125 psi.

Additionally, the time of loading in the HMA layer at 2 inches below the pavement surface was calculated for the PG64-22 mix and the PG52-22 mix. The time of loading was determined by best fitting a sinusoidal wave shape for the deviator stress pulse that was calculated from the octahedral shear stress (τ_{oct}) under a moving 18-wheel truck at different speeds and temperatures.

The data for the pulse time for each mix was combined and a general relationship between the loading time at 2 inches below the pavement surface and vehicle speed and temperature was established. The pavement thickness did not have a statistically significant impact on the pulse time at 2 inches below the pavement surface. The square of speed had a statistically significant impact on the pulse time. Fitting parameters (R^2) of 0.995 and 0.997 were found for the PG64-22 and the PG52-22 mixtures, respectively.

PG64-22 mix: $\log(t) = -0.57339 - 0.00504*Temp - 0.02311*Speed + 0.000147*(Speed)^2$ (1)

PG52-22 mix: $\log(t) = -0.74886 - 0.00253*Temp - 0.02338*Speed + 0.000151*(Speed)^2$ (2)

where,

t = deviator stress pulse time at 2 inches below pavement surface in seconds
Temp = pavement temperature in °C
Speed = vehicle speed in mph

Table E2c.3 shows an example of the estimated pulse time at 2-inch below the pavement surface for the PG64-22 and the PG52-22 mixtures under the driving tandem axles of an 18-wheel truck at a travelling speed of 20 and 60 mph. Table E2c.3 show the pulse time with a duration in the order of 0.017 to 0.057 second at 2-inch below the pavement surface whereas currently, laboratory triaxial testing on HMA specimens is performed using a haversine wave at loading duration of 0.1 second.

Table E2c.3. Estimated pulse time at 2-inch below pavement surface.

HMA Mix	HMA layer temperature (ºC)	18-wheel traveling speed (mph)	Loading time (seconds)
PG64-22	52	20	0.057
		60	0.020
	64	20	0.050
		60	0.018
PG52-22	52	20	0.052
		60	0.018
	64	20	0.048
		60	0.017

Field HMA mixtures from the WesTrack sections that experienced early rutting are requested from the material reference library (MRL) for laboratory evaluation. The requested material will be evaluated for permanent deformation characteristics under the repeated load triaxial test.

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

The 3D-Move runs are taking more time than anticipated because of limitations in the number of computers that can be used. Delay is expected to complete all the runs described in the experimental plan of this work element.

Year 3 Work Plan

Subtask E2c-1: Identify the Critical Conditions

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

Subtask E2c-2: Conduct Mixtures Evaluations

Work for Year 3 will consist of evaluating the permanent deformation characteristics of the three mixtures (i.e., PG64-22, PG58-22, and PG52-22 mix) that were designed under Subtask E2c-1. The permanent deformation curves under the repeated load triaxial (RLT) test will be developed for the various mixtures under the various combinations of temperature and rate of loading as determined in Subtask E2c-1.

Additionally, the identified field HMA mixtures from the WesTrack project will be evaluated in the laboratory for permanent deformation characteristics under the repeated load triaxial test.

Subtask E2c-3: Develop a Simple Test

Work for Year 3 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 3.

Subtask E2c-5: Evaluate the Impact of Mix Characteristics

No work on this subtask is planned for Year 3.

Table for Decision Points & Deliverables

Date	Deliverable	Description
8/31/09	Journal Paper	Regarding the magnitude of the deviator and confining stresses for the repeated load triaxial test.
8/31/09	Journal Paper	Regarding the duration of the deviator stress pulse time for the repeated load triaxial test.
10/31/09	Draft Report	Summarizing the findings of Subtask E2c-1
2/28/10	Draft Report	Summarizing the findings of Subtask E2c-2

Work element E2d: Thermal Cracking Resistant Mixes for Intermountain States

Major Findings and Status

During Year 2, the focus of the work at UNR was on Subtask E2d-1, "Identify Field Sections," Subtask E2d-3, "Identify an Evaluation and Testing System," and Subtask E2d-3.a, "Evaluate Long-Term Aging of Asphalt Binders Subjected to Free Atmospheric Oxygen."

Under Subtask E2d-1, the air and pavement temperature profiles for the identified fourteen LTPP Seasonal Monitoring Pavement (SMP) sections within the intermountain region of the U.S. were evaluated. The calculation for the maximum pavement temperature rates was completed. Additionally, the minimum air and pavement temperatures from the LTPP SMP sections were checked against the information provided by the LTPPBind software version 3.1. A difference was observed between the two sets of data (i.e. LTPP SMP and LTPPBind software). The difference is mainly related to the small number of years of collected data for the LTPP SMP sections (i.e. maximum 3 years of collected data) when compared to the LTPPBind information (i.e. 13 to 35 years of collected data). Additionally, the comparison between the two sets of data allowed for the identification of SMP sections with potential sensor reading problems.

Additionally, pavement temperature histories and profiles were collected for the NATC WesTrack project in Nevada. Similar analysis is undergoing for the WesTrack pavement temperature profile. A condition survey of the Westrack pavement sections was conducted on February 2008 and all their thermal cracking performance was documented.

The UNR team identified and summarized the available materials in the Material Reference Library (MRL) for the LTPP SPS-9 sections. Additionally, no asphalt materials were found for the LTPP SMP sections at the MRL.

Under Subtask E2d-3, the UNR and University of Minnesota (UM) researchers met and agreed for the need of an experiment to improve the current Thermal Stress Restrained Specimen Test (TSRST) method by improving the repeatability of the test results. This will be achieved by completing the following three objectives:

1. Investigate the effect of size and shape of the TSRST specimen.
2. Investigate the effect of cooling rate on the fracture properties of the asphalt concrete and develop correlations that allow for a rapid test procedure.

3. Investigate the behavior of asphalt mixtures subjected to multiple cooling and warming cycles.

Consequently, a joint experimental plan was developed to investigate the effect of specimen size and shape on TSRST test results:

- Select aggregates with different mineralogy from two different sources.
  - Nevada: Lockwood – andesite.
  - Minnesota aggregate source
- Obtain a neat and a polymer modified asphalt binders typically used in Nevada and Minnesota.
  - Nevada: PG64-22 (neat) and PG64-28NV (polymer modified)
  - Minnesota neat and polymer-modified binders
- Develop two intermediate Superpave gradations with ½ inch and ¾ inch nominal maximum aggregate size for each of the aggregate sources and binder type – total 4 mixes from Nevada and 4 mixes from Minnesota.
- Conduct the Superpave mix design for 6 million ESALs and for a top lift.
- Prepare specimens to test in the TSRST:
  - Compact 6 replicates of 2x2x10 inch beams.
  - Compact 2 sample of 6 inch diameter by 7 inch height using the Superpave Gyratory Compactor (SGC) and then core out of each of the specimen 3 replicates of 2.25 inch diameter and 6 inch height.
  - Compact 3 sample of 6 inch diameter by 7 inch height using the SGC and then core out of the center of one each of the specimens a 2.25 inch diameter and 6 inch height sample.
- Air-Voids: prepare compacted samples from each mixture at two levels of air-voids: 4% and 8%.
- Aging: prepare compacted samples from each mixture at two levels of aging:
  - Short term age the loose mixture following AASHTO R30, 4hr aging.
  - Long term age the compacted mixture following AASHTO R30, 5 days at 185°F.
- Cooling rate: 10°C/hr.
- Use a thermo-couple to measure the temperature inside a dummy sample having the exact dimensions as the tests sample to eliminate the impact of sample size on the mix temperature. This temperature will serve as the control temperature of the test.
- Compare and analyze the test results (stress-temperature relationship) of the TSRST fracture test to check for test repeatability.

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. Figure E2d.1 shows the results for the measured mass loss and gain of the PG64-22 asphalt binder when aged at different temperatures and periods in the forced convection (horizontal airflow) ovens.

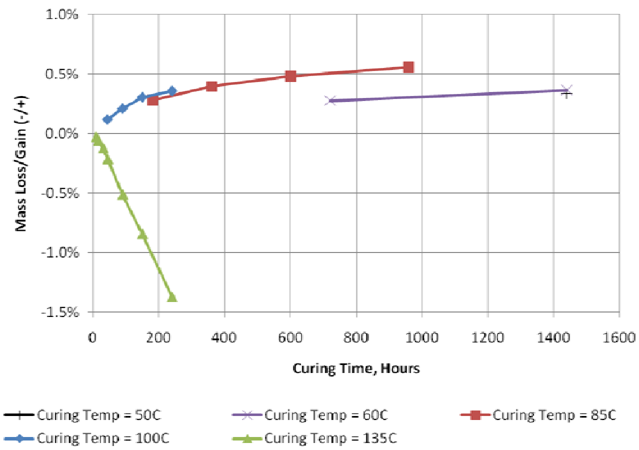

Figure E2d.1. PG64-22 Mass loss/gain at various curing temperatures and times

The multiple stress recovery (MSCR) test was conducted on the aged asphalt binders according to AASHTO TP70-07. Figure E2d.2 shows the average percent recovery for the PG64-22 asphalt binder aged at 85 and 100°C and for a creep stress of 0.1 and 3.2 kPa. The average percent recovery at 0.1 kPa did not show a consistent increasing trend as a function of aging whereas a consistent increasing linear trend was found for the average percent recovery at 3.2 kPa stress level as a function of aging. Additionally, the average percent recovery at 0.1 kPa was unexpectedly found to be less than the average percent recovery at 3.2 kPa. This is mainly due to the combination of both the aging effect of the asphalt binder and the level of the applied creep stress (i.e. 0.1 kPa). Therefore, it was decided to rerun the MSCR test at 3.2 kPa and 10 kPa creep stress levels.

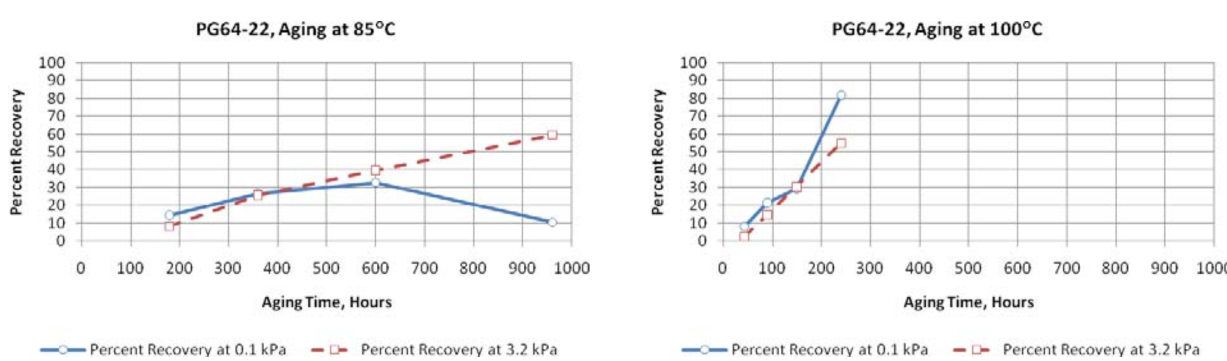

Figure E2d.2. Percent recovery of the PG64-22 asphalt binder from the MSCR test

During Year 2, the focus of the work at UW-M was on the improvement of the testing equipment. Particularly, a new device has been developed which will be used to conduct multiple types of testing:

- All binder thermal dilatometric testing
- Mixture thermal linear expansion and contraction
- Mixture Thermal Stress Restrained Specimen Test (TSRST)

Similarly, a modified version of the Bending Beam Rheometer (BBR) for Single-Edge Notched Bending (SENB) testing has been built. A detailed literature review was conducted to determine prior experience with the SENB and the potential for success in using the BBR to conduct the test. The equipment will make it possible to evaluate properties of asphalt binder, mastic and possibly mixtures at low temperatures using fracture mechanics.

Both devices are being finalized. The all-in-one glass transition temperature (Tg) apparatus is working and new cells have been manufactured to improve the sealing of the sample and to allow for more samples to be tested at once. The SENB equipment has been assembled and the correct functioning of individual components has been verified. A dedicated data acquisition system independent of the BBR software is being considered to capture the sample behavior during fracture testing.

The Fourier transform infrared spectroscopy (FTIR) machine in the Physics Department of the University of Wisconsin–Madison will be used for measuring the carbonyl peak growth. A working relationship has been established and the research group has been granted access to the equipment. A special support is necessary to hold samples in the machine and this fixture has been ordered.

One of the important findings during Year 2 is the thermo-volumetric behavior of some mixture samples during repeated cooling and heating. Detailed evaluation has shown that the thermal lag of the specimen temperature distribution; possible restructuring of aggregates could be the reason for this observation. Alternations to temperature change controls have been implemented to account for this behavior.

The analysis of data for many tested mixtures indicates that the glass transition temperature remains approximately constant throughout the loops, but the coefficients of contractions and the glass transition temperature during cooling cycles are different than those calculated during the heating cycles. The differences are considered significant and will be further investigated in future work. The research team is convinced that slower cooling and heating rates should be used to allow the temperature to homogenize within the specimen. Also, the non-homogeneity of the aggregates could be behind the asymmetrical behavior during cooling and heating.

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

The building and assembling of the new glass transition temperature (Tg) testing equipment has been significantly slower than expected due to delays on the manufacturing side due to adjustments in designs that had to be implemented. This has prevented the scheduled experimental plan from being carried out and will delay the expected timeline of the task by approximately two quarters. The research team will try to reduce the impact on the completion of the work plan for Year 3.

Year 3 Work Plan

Subtask E2d-1: Identify Field Sections

Work for Year 3 will consist of completing the analysis of the temperature rates for the various LTPP SMP and WesTrack sections.

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

Work for Year 3 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 UWM will continue testing samples for most of Year 3.

- Measurements of thermal contraction and expansion coefficients will be performed on binders and mixtures, focusing on glass transition temperature and cyclic behavior.
- The SENB tests for binders and mastics will be performed in order to measure fracture properties.
- An FTIR experimental plan will start as soon as the fixture for the equipment at the UW–Madison is ready.
- Some tests with the Asphalt Binder Cracking Device (ABCD) have been performed as part of a ruggedness test for the machine in collaboration with Dr. Kim of EZ Asphalt Technology. The opportunity of including this test in the work plan will be evaluated during the first quarter of Year 3.

The UNR and UM researchers will be conducting the TSRST joint experiment during year 3. The plan calls for UNR and UM to conduct several laboratory evaluations using materials from Nevada and Minnesota to improve the operational characteristics and measuring capabilities of the TSRST.

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.1

Table E2d.1. 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

Start the work on this subtask according to the experimental plan. Table E2d.2 shows the selected aggregates for the experimental design.

Table E2d.2. Materials for aggregate absorption experiment (E2d-3.b).

Aggregate Source	Mineralogy
California	will be determined
Colorado	will be determined
Montana	will be determined
Nevada	will be determined
Utah	will be determined

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

Work on this subtask will begin in the second half of year 3. The experimental plan for this subtask calls for the evaluation of the impact of intermountain region mixture characteristics on the long-term aging characteristics of the asphalt binder. The first step of this subtask will be to conduct the Superpave mix designs for all combinations of mixtures based on 6 million ESALs. The various mixtures will be designed using:

- Two aggregate sources selected based on the recommendations of E2d-3.b.
- An intermediate and fine Superpave gradation for each of the aggregate sources will be conducted.
- Three asphalt binders will be selected: two extremes and one intermediate as identified in subtask E2d-3.a.
- Three mineral fillers types will be used: none, lime, and regular limestone.

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

The development of a software program for prediction of critical cracking temperatures using the TSRT, SENB, and Tg results will be pursued in collaboration with the UNR research team.

Subtask E2d-5: Develop a Standard

No work on this subtask is planned for Year 3.

Table for Decision Points & Deliverables

Date	Deliverable	Description
4/31/09	Decision Point	Decide whether to include the ABCD test in the work plan.
5/31/09	Draft Report	Report on findings from subtask E2d-1.
8/31/09	Journal Paper	Regarding glass transition temperature, fracture properties and/or carbonyl peak growth.
8/31/09	Journal Paper	Regarding the aging characteristics of asphalt binders.
10/31/09	Decision Point	Decide what aggregate sources and asphalt binders to use in subtask E2d-3.c.
12/31/09	Draft Report	Report on findings from the TSRST experiment
01/31/10	Presentation	Present thermal cracking progress at TRB, ETG or a similar venue.

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. 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.

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

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

Year Three Work Plan

Subtask E2e-2: Design and Execute Laboratory Testing Program

Revised experimental designs that include the core materials are being developed during the fourth quarter of Year 2. Laboratory testing will be initiated in Year 3 and will continue throughout most of Year 4.

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

None. Work on this subtask has been delayed to Year 4 after a substantial portion of the laboratory testing is complete.

Subtask E2e-4: Validate Refined Models

None. Work on this subtask was planned for Year 4.

Subtask E2e-5: Prepare Design Guidance

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

Table for Decision Points & Deliverables

Date	Deliverable	Description
9/1/10	Journal Paper	Summarizing selected improved models
3/11	Draft Report	Draft report on findings from subtasks E2e-2 and E2e-3
3/11	Final Report	Final report on findings from subtasks E2e-2 and E2e-3
3/11	Presentation	At TRB or AAPT of 9/1/2010 journal paper.
9/1/11	Journal Paper	Summarizing results of model validation efforts
12/31/11	Models	Improved composition to engineering property models • Hirsch Model for Dynamic Modulus • Resistivity Model for Rutting Resistance • Continuum Damage Fatigue Model • Permeability
3/12	Draft Report	Draft report on entire Task E2e
3/12	Final Report	Final report on entire Task E2e
3/12	Presentation	At TRB or AAPT of 9/1/2011 journal paper

Table of Decision Points & Deliverables

Work Element	Date	Deliverable	Description
E1a	04/31/09	Journal Paper	Viscoelastic tensile characterization of undamaged asphalt mixtures
E1a	07/31/09	Journal Paper	Viscoelastic anisotropic compressive characterization of undamaged asphalt mixtures
E1a	07/31/09	Journal Paper	Material response in direct tension and compression of asphalt mixtures using dissipated pseudo-strain energy
E1a	07/31/09	Journal Paper	Fatigue damage and plasticity evaluation of asphalt mixtures with dissipated pseudo-strain energy
E1a	07/31/09	Journal Paper	Bond energy and dissipated pseudo-strain energy in fatigue crack modeling
E1a	03/31/10	Journal Paper	Self-consistent micromechanics model of binder-mastic relations
E1a	07/15/09	Presentation	Presentation of results of E1a-3 at the Pavement Performance Prediction Symposium in Laramie, Wyoming
E1a	07/15/09	Presentation	Presentation of results of E1a-1 and E1a-2 at the Pavement Performance Prediction Symposium in Laramie, Wyoming
E1a	01/31/10	Presentation	Presentation of results of E1a-1 and E1a-2 at the Transportation Research Board Meeting
E1a	1/31/10	Presentation	Presentation of results of E1a-3 at the Transportation Research Board Meeting
E1a	1/31/10	Presentation	Presentation of results of E1a-4 at the Transportation Research Board Meeting

E1a	3/31/10	Model and algorithm	Providing the model and algorithm for testing and analysis of undamaged asphalt mixtures in tension and compression
E1b-1	08/01/09	Journal Paper	Submit to AAPT and TRB.
E1b-1	01/01/10	Presentation	Prepare up-to-date results for TRB.
E1b-1	03/01/10	Presentation	Prepare relevant and up-to-date results for AAPT.
E1b-2	8/1/09	Draft Report	Literature review of indentation and hardness tests, and their applicability to viscoelastic properties.
E1b-2	9/30/09	Presentation	Presentation on proposed modifications to Superpave tests to include indentation tests.
E1b-2	3/30/10	Draft Report	Report on the feasibility of indentation tests for asphalts and correlations to existing testing results.
E1b-2	2/10	Presentation	Presentation at the Binder ETG on the indentation testing of binders.
E1c-1	Jan.-March 2009	Presentation	Present journal paper at TRB/AAPT, ETG or similar.
E1c-1	3/31/09	Decision Point	Decide which WMA technologies are most promising and focus on development of best practices for those.
E1c-1	8/1/09	Journal Paper	Submit paper to TRB/AAPT on findings from compaction and mechanical testing of WMA.
E1c-2	4/30/09	D1: Chip Seal Technical Progress Update	Literature review, testing protocols for emulsion construction, residue properties and performance tests. Preliminary experimental results.
E1c-2	6/30/09	D2: Validation Plan	List of test sections, plans and procedures for field and laboratory testing.
E1c-2	9/30/09	D3: Dense Cold Mix Literature Review Report	Summary of state of practice for CIR and dense cold mixes; preliminary materials election/experimental design.
E1c-2	10/30/09	D4: Emulsion Properties for Chip Seal	Report on data analysis and summary of path forward.
E1c-2	12/31/09	D5: CIR/Dense Cold Mix Experimental Design	Final experimental design for evaluation of CIR and cold mix performance properties.
E2a	7/09	Decision Point	Decide which modification targets and materials are to be included in the testing matrix.
E2a	3/10	Presentation	Give presentation on progress to date.
E2b	4/31/09	Draft Report	Report on findings from subtask E2b-1.a.

E2b	6/15/09	PG Grade Shifting Evaluation	For all the materials listed in the work plan, evaluate PG grade shifting. Evaluate the PG grade of aged binder in each kind of RAP.
E2b	9/15/09	Standard Protocol	Write a standard protocol for evaluating the PG grade of aged binder in the RAP.
E2b	12/15/09	Project Report	Finish the whole project report for Subtask E2b-1.b.
E2b	01/31/10	Draft Report	Experimental Plan for subtask E2b-3
E2c	8/31/09	Journal Paper	Regarding the magnitude of the deviator and confining stresses for the repeated load triaxial test.
E2c	8/31/09	Journal Paper	Regarding the duration of the deviator stress pulse time for the repeated load triaxial test.
E2c	10/31/09	Draft Report	Summarizing the findings of Subtask E2c-1
E2c	2/28/10	Draft Report	Summarizing the findings of Subtask E2c-2
E2d	4/31/09	Decision Point	Decide whether to include the ABCD test in the work plan.
E2d	5/31/09	Draft Report	Report on findings from subtask E2d-1.
E2d	8/31/09	Journal Paper	Regarding glass transition temperature, fracture properties and/or carbonyl peak growth.
E2d	8/31/09	Journal Paper	Regarding the aging characteristics of asphalt binders.
E2d	10/31/09	Decision Point	Decide what aggregate sources and asphalt binders to use in subtask E2d-3.c.
E2d	12/31/09	Draft Report	Report on findings from the TSRST experiment
E2d	01/31/10	Presentation	Present thermal cracking progress at TRB, ETG or a similar venue.
E2e	9/1/10	Journal Paper	Summarizing selected improved models
E2e	3/11	Draft Report	Draft report on findings from subtasks E2e-2 and E2e-3
E2e	3/11	Final Report	Final report on findings from subtasks E2e-2 and E2e-3
E2e	3/11	Presentation	At TRB or AAPT of 9/1/2010 journal paper.
E2e	9/1/11	Journal Paper	Summarizing results of model validation efforts
E2e	12/31/11	Models	Improved composition to engineering property models • Hirsch Model for Dynamic Modulus • Resistivity Model for Rutting Resistance • Continuum Damage Fatigue Model • Permeability
E2e	3/12	Draft Report	Draft report on entire Task E2e
E2e	3/12	Final Report	Final report on entire Task E2e
E2e	3/12	Presentation	At TRB or AAPT of 9/1/2011 journal paper

Budget

		Year 1	Year 2	Year 3	Year 4	Year 5
Category E1: Modeling						
E1a	Analytical & Micromechanics Models for Mechanical Behavior of Mixtures (TAMU)	140,000	240,000	200,000	120,000	120,000
E1b	Binder Damage Resistance Characterization (UWM)	75,000	110,000	165,000	150,000	
E1c-1	Warm Mixes (UWM and UNR)	75,000	75,000	262,500	262,500	312,500
E1c-2	Improvement of Emulsion Characterization and Mixture Design for Cold Mixtures (UWM and UNR)	75,000	120,000	175,000	275,000	299,000
Category E2: Design Guidance						
E2a	Comparison of Modification Techniques (UWM)		85,000	130,000	127,500	110,000
E2b	Design System for HMA Containing a High Percentage of RAP Material (UNR , UWM, WRI, and AAT)	295,000	345,000	335,000	280,000	280,000
E2c	Critically Designed HMA Mixtures (UNR)	50,000	140,000	150,000	130,000	160,000
E2d	Thermal Cracking Resistant Mixes for Intermountain States (UNR and UWM)	215,000	245,000	230,000	230,000	230,000
E2e	Design Guidance for Fatigue and Rut Resistant Mixtures (AAT)	74,000	75,000	76,000	77,000	69,500
TOTAL		999,000	1,435,000	1,723,500	1,652,000	1,581,000
		7,390,500				

Engineered Materials Year 3

	Year 3 (4/2009-3/2010)												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			JP			P			P			JP	
E1a-2: Analytical Micromechanical Models of Modified Mastic Systems			JP			P			P				
E1a-3: Analytical Models of Mechanical Properties of Asphalt Mixtures			JP			P			P			M&A	
E1a-4: Analytical Model of Asphalt Mixture Response and Damage			JP			P			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					JP						P		
E1b1-4: Analysis & Interpretation					JP						P		
E1b1-5: Standard Testing Procedure and Recommendation for Specifications													
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					D								
E1b-2ii. Proposed SuperPave testing modifications						P							
E1b-2iii. Preliminary testing and correlation of results										D			
E1b-2iv. Feasibility of using indentation tests for fracture and rheological properties				JP							P		
E2a: Comparison of Modification Techniques													UWM
E2a-1: Identify modification targets and material suppliers					DP								
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													
E2c: Critically Designed HMA Mixtures													UNR
E2c-1: Identify the Critical Conditions					JP		D				F		
E2c-2: Conduct Mixtures Evaluations											D		
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						F							
E2d-2: Identify the Causes of the Thermal Cracking		D											
E2d-3: Identify an Evaluation and Testing System	DP				JP		DP		D				
E2d-4: Modeling and Validation of the Developed System													
E2d-5: Develop a Standard													
E2e: Design Guidance for Fatigue and Rut Resistance Mixtures													AAT
E2e-1: Identify Model Improvements													
E2e-2: Design and Execute Laboratory Testing Program										P			
E2e-3: Perform Engineering and Statistical Analysis to Refine Models													
E2e-4: Validate Refined Models													
E2e-5: Prepare Design Guidance													
(2) Green Asphalt Materials													
E2b: Design System for HMA Containing a High Percentage of RAP Material													UNR
E2b-1: Develop a System to Evaluate the Properties of RAP Materials	D			F		D			D				
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													
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													
E1c-1iii. Mixture Performance Testing					JP					P		DP	
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	D1					D3							
E1c-2ii: Creation of Advisory Group													
E1c-2iii: Identify Tests and Develop Experimental Plan	D1								D5				
E1c-2iv. Develop Material Library and Collect Materials.													
E1c-2-v. Conduct Testing Plan					JP		D4			P			
E1c-2-vi. Develop Performance Selection Guidelines													
E1c-2-vii. Validate Performance Guidelines			D2										
E1c-2-viii. Develop CMA Mix Design Guidelines													
E1c-2ix. Develop CMA Performance Guidelines													

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

Work planned
Work completed
Parallel topic

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

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DP: Decision Point	Time to make a decision on two parallel paths as to which is most promising to follow througjh

Work planned
Work completed
Parallel topic
Delayed

PROGRAM AREA: VEHICLE-PAVEMENT INTERACTION

CATEGORY VP1: WORKSHOP

Work Element VP1a: Workshop on Super-Single Tires

Major Findings and Status

During Year 2, the UNR team published the minutes of the international workshop on the use of wide-base tires along with relevant presentations and reports on the Consortium website, www.ARC.unr.edu. The workshop was held at the FHWA Turner-Fairbank Highway Research Center (TFHRC) in McLean, VA on October 25 and 26, 2007.

Year 3 Work Plan

There is no activity planned for year 3.

CATEGORY VP2: DESIGN GUIDANCE

Work element VP2a: Mixture Design to Enhance Safety and Reduce Noise of HMA

Major Findings and Status

This work element focuses on evaluating and modifying mixture design procedures to enhance safety and noise-reduction properties of asphalt mixtures for flexible pavements. In particular, this work element will develop a laboratory test procedure or a prediction model for the evaluation of macro- and microtextures of asphalt pavements. It is also focused on comparing these measurements with field measurements of skid resistance and pavement-tire noise. Results from this work will evolve into the development of pavement mixture design protocols that will not only include structural strength and durability, but also traffic safety, comfort and reduced pavement-tire noise.

During Year 2 the research team completed the development of the waveguide sound absorption device (impedance tube) and continued work on measuring the effect of surface abrasion on the macro-texture of HMA slab specimens. Details of the waveguide device were finalized, and the current design and methodology of the equipment are described in the ARC July–September 2008 report. In addition, during Year 2 contacts with major centers in Europe working on noise mapping were established and a significant amount of recent relevant results were reviewed. The collaboration with such institution and sharing of ideas were initiated to enhance the understanding of possible methods to design mixtures for safety and noise reduction.

Dense and open-graded asphalt mixtures were subjected to laboratory tests to determine their skid resistance and acoustic properties. The sand patch method (SPM) was used to determine the mean texture depth to evaluate the surface texture characteristics of the asphalt specimens. In addition, the impedance tube was used to evaluate the acoustic absorption characteristics of asphalt mixtures. The team investigated gyratory (cylindrical) and roller (slab) compacted specimens.

As a part of an FHWA equipment loan program, the Circular Texture Meter (CTM) and Dynamic Friction Tester (DFT) were delivered to UW–Madison and were used in a demonstration test to evaluate the texture and frictional characteristics of pavement surface.

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

The work progress for this work element is consistent with the timeline described in the 5-year general work plan and is significant to the accomplishment of the objectives of this work element. The schedule for Year 2 involved work to be completed for Subtasks VP2a-1 and 2, and work to be continued for Subtasks VP2a-3, 4, 5 and 6. The work progress for Year 2 is somewhat behind the work plan proposed for Year 2 due to unforeseen problems that arose, especially with developing and calibrating the impedance tube. It is expected that in early 2009 work progress will catch up with Year 2 work plan.

Year 3 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 further collected to document the overall properties of asphalt pavements designs. Emphasis will be placed on aggregate properties and binder requirements for mixture types that improve not only frictional skid properties but also reduce cost and improve durability and comfort. Examples are open-graded, porous asphalts and pavement friction courses. NCHRP's most recent reports and literature worldwide will be covered.

Subtask VP2a-2: Evaluate pavement macro- and microtextures and their relation to tire and pavement noise-generation mechanisms

There are a number of tire-pavement noise-generation mechanisms (for example, thread vibration, air pumping, slip stick and stick snap) and noise-enhancement mechanisms. Quiet designs typically address these two issues and include surface textures of less than 10 mm, below-surface textures, increased porosity to reduce high-frequency noise and elastic surfaces. A complete literature review will be performed on both traffic noise-generation mechanisms and noise-reduction designs. Emphasis will be placed on technologies that reduce traffic noise by more than 5 dB and have a durability of more than 15 years. The results of this task will be compiled and evaluated along with the results from Subtask VP2a-1 to select best practices for pavement mixtures with enhanced skid friction behavior and reduced noise generation.

Subtask VP2a-3: Develop a laboratory testing protocol for the rapid evaluation of the macro- and microtexture of pavements

Currently there is no standard system capable of measuring texture profiles for a laboratory-prepared sample. The concepts of using the sand patch on lab samples and the method of using a simple laser profile meter are being studied by various researchers. Also, because of the difficulty in measuring microtexture profiles, a surrogate is required for measuring microtexture. The development of such procedures would enable researchers and engineers to estimate pavement macro- and microtexture to predict both the dry and wet frictional skid and/or noise-reduction designs of pavements.

In Year 3 the research team will expand and continue the laboratory testing of gyratory compactor (GC) cylindrical and roller-compacted slab specimens to determine the acoustic properties of asphalt mixtures. The impedance tube will be used for this purpose. Approximately 150 cylindrical specimens were obtained from 25 asphalt mixtures that were prepared at two pressures and three temperatures. In addition, about 20 slab specimens are available for testing. The influence of traffic in terms of polishing the asphalt pavement surface will be accounted for during testing. The GC cylindrical specimens will be saw-cut per the laboratory testing procedure for other work elements. The same specimens will also be tested as unpolished asphalt specimens (before saw-cutting), which will provide data on new asphalt mixtures, while testing of a saw-cut specimen surface will provide data for a largely polished asphalt surface. A procedure will be adopted to account for intermediate (quantified) levels of polished pavement surfaces. Since most of these asphalt specimens are related to actual field projects, testing will also be conducted on selected projects to obtain enough data to validate analyses. 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

[yellow] = to be tested

(NMAS = nominal maximum aggregate size, ESAL = equivalent single axle load)

The research team will continue laboratory and fieldwork on texture of asphalt mixtures to investigate friction/skid resistance characteristics using the CTM and DFT equipment obtained from FHWA. Attempts will be made to use the skid/friction test trailer of WisDOT (if available) on these field projects. Moreover, the British Pendulum (BP), widely recognized as a measure of the micro-texture, will be used to monitor skid resistance on different asphalt mixtures and to evaluate pavement texture. The instrument will be modified to accept the standard 150 mm diameter GC specimens. Other state-of-the-art methods will be investigated such as the use of imaging technology. Table VP2a.2 summarizes the proposed field and laboratory testing program.

Table VP2a.2. Proposed test matrix for Year 3.

Test environment	Test property	Specimen type	Test type	Number of specimens	Comment
Laboratory	Skid resistance/ friction	GC specimens (cylindrical)	BP CTM DFT SPM	120 (25 different mixtures)	Mixtures properties/ characteristics will be identified and related to the measured parameters
		Roller-compacted specimens (slab)		20	
	Noise absorption/ generation	GC specimens (cylindrical)	Waveguide device	120 (25 different mixtures)	
		Roller-compacted specimens (slab)		20	
Field	Skid resistance/ friction	Selected Wisconsin projects related to the laboratory specimens	BP CTM DFT SPM Inertial profiler Skid trailer	Based on field project data (not available)	
	Noise absorption/ generation		Waveguide device		

<u>Subtask VP2a-4: Run parametric studies on tire-pavement noise and skid response</u>

Using the data collected in Subtasks VP2a-1 and 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 microtextures and the skid resistance and pavement-tire noise levels. The pavement mixtures to be tested in this task will be selected in coordination with consortium research activities performed parallel to this work element. This will be done not only to evaluate noise-reducing pavement mixture design, but also to incorporate construction cost and durability in the pavement system design and help create a more holistic pavement mixture design protocol.

The laboratory and field testing program will provide a comprehensive database with various variables that can be used via statistical analysis to develop correlation models among asphalt textures, skid resistance and pavement-tire noise levels. Characteristics of asphalt mixtures will be included in these models so that an optimal mixture design can be achieved to produce safe, low-noise, cost-effective and durable asphalt pavements.

<u>Subtask VP2a-5: Establish collaboration with established national and international laboratories specialized in transportation noise measurements. Gather expertise on measurements and analysis</u>

To complement the capabilities of the consortium with other expertise available in the country, UW–Madison researchers will reach to nationally recognized laboratories and centers. A leading example is Purdue University's Institute for Safe, Quiet and Durable Highways. This institute's expertise on measurement and analysis will be leveraged to enhance the development of quiet pavement mixture designs. UW–Madison researchers will establish collaborative initiatives to allow measuring the pavement noise levels obtained with proposed holistic pavement mixture designs.

The research team will complement the capabilities of the consortium with other expertise available in the country and worldwide. Collaboration will be established with leading institutions such as Purdue University, the National Center for Asphalt Technology and Pisa University.

<u>Subtask VP2a-6: Model and correlate acoustic response of tested tire-pavement systems</u>

Results obtained in Subtasks VP2a-4 and 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 constrain numerical models for the evaluation of frictional skid, noise-generation mechanisms and pavement-tire noise-reduction designs. These results will be incorporated into a new asphalt mixture design protocol.

<u>Subtask VP2a-7: Proposed optimal guideline for design to include noise reduction, durability, safety and costs</u>

The parametric studies performed and the correlations and models obtained from previous tasks will be analyzed in combination with other work items in the consortium to maximize research resources and the use of the developed data and expertise. These parametric studies and designs will help in the development of improved frictional and noise-reducing mixture designs while maintaining 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 the merits of the holistic pavement mixture designs.

CATEGORY VP3: MODELING

Work element VP3a: Pavement Response Model to Dynamic Loads

<u>Major Findings and Status</u>

During year 2, the load distribution on the various axles of the 18-wheels tractor-trailer combination during braking was determined for leveled and sloped pavements. Braking decelerates the vehicle, which causes load to transfer to the front of the vehicle. The resulting axle load can be higher or lower than the initial static load, depending on the location of the axle. Figure VP3a.1 shows the major forces acting on an 18-wheels tractor-semitrailer during braking on a sloping pavement. Since Brakes are the primary source of deceleration, the aerodynamic drag and rolling resistance were neglected. The various axles include: the tractor steering axle, the tractor tandem axle (i.e. driving axle), and the semitrailer tandem axle (i.e. trailer axle).

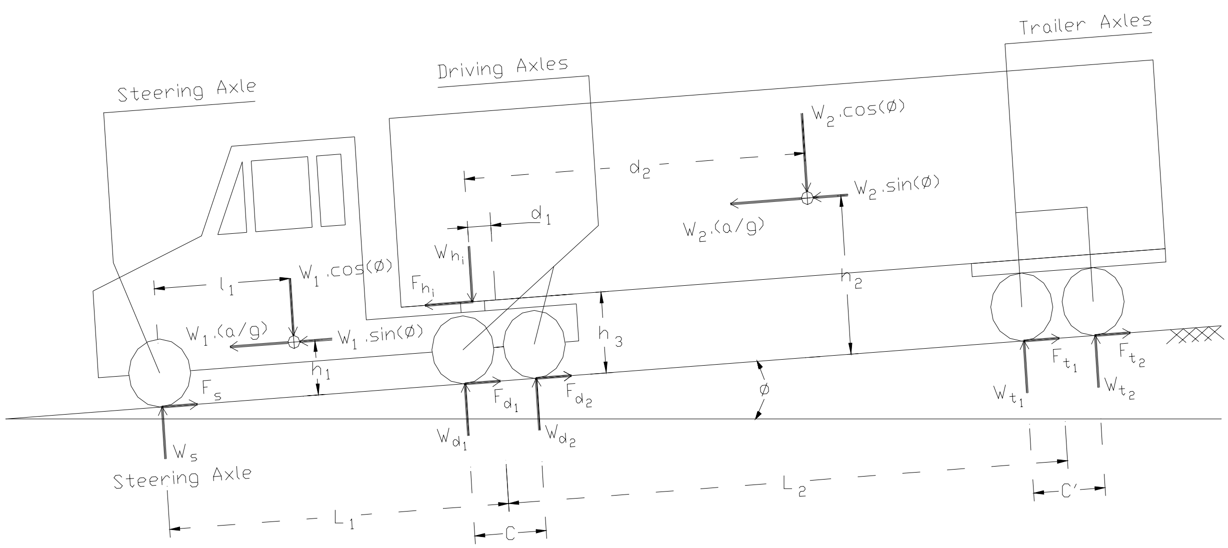


Figure VP3a.1. Forces acting on a tractor-semitrailer during braking.

The UNR team started the work on the 3D-Move model to develop into a menu-driven software. Whenever possible, a structure similar to that of the new AASHTO Mechanistic Empirical Pavement Design Guide (MEPDG) software is followed. Figure VP3a.2 shows the anticipated start-up menu for the 3D-Move overall model. Additionally, the researchers worked on developing a subroutine to calculate the dynamic modulus (|E*|) and the damping ratio from the input of the |E*| laboratory test results. Figure VP3a.3 shows the format of the input required for viscoelastic materials.

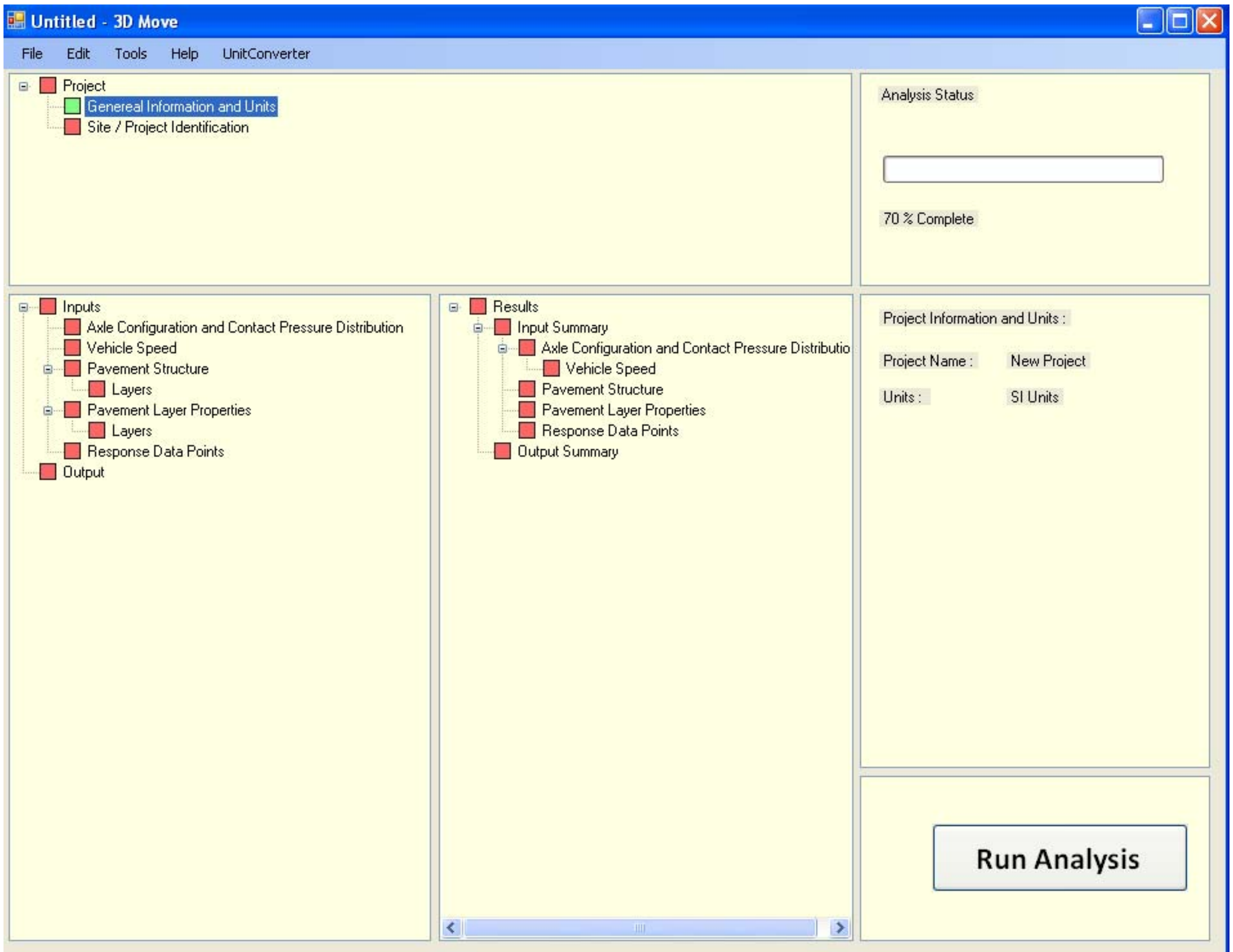
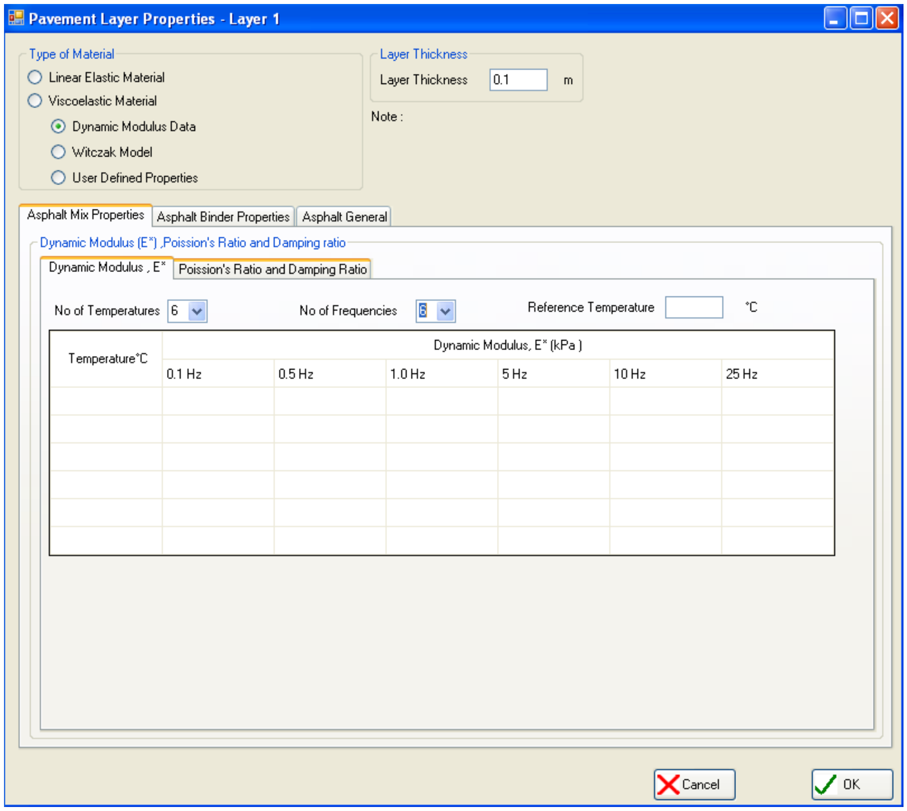


Figure VP3a.2. 3D-Move overall model start-up menu.



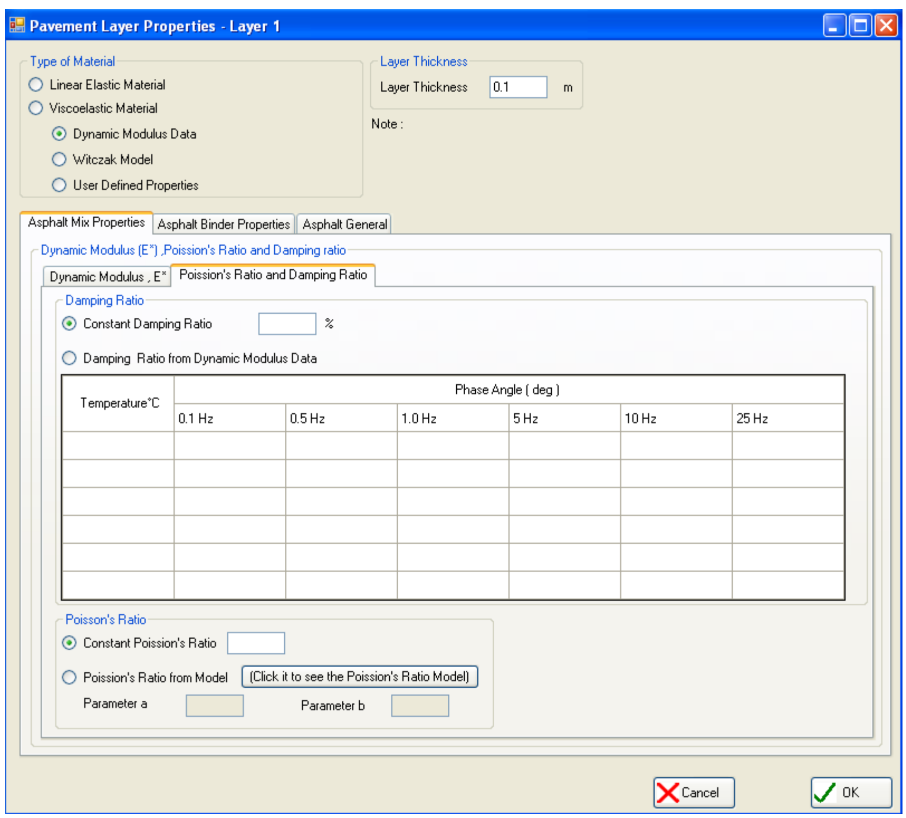


Figure VP3a.3. 3D-Move input for viscoelastic material.

A non-uniform tire-pavement contact pressure distribution measurements were collected from the Nevada Automotive Test Center (NATC). Two main sets of data were provided depending on the measurement system device used. The first set of the data was measured using the South African measurement system called Vehicle-Road Surface Pressure Transducer Array (VRSPTA) that was installed at the University of California, Berkeley. The VRSPTA is capable of measuring the vertical, longitudinal, and lateral stresses at varying speeds, loads and inflation pressures. The second set of data was measured using the Kistler MODULAS Quartz Sensor Array device. The Kistler MODULAS device can measure vertical stresses at varying loads and inflation pressures and at speeds ranging from creep to highway speed. Data were available for single tires, wide base tires, single out dual tires, and dual tires. Table VP3a.1 shows an example of the type of information and number of tests available from the Kistler device.

Table VP3a.1. Summary of the Kistler MODULAS device data for the evaluated tires.

<table>
<tr><th>Tire Type</th><th>Load, kN</th><th>Pressure, kPa</th><th>Measuring Tire Speed</th></tr>
<tr><td rowspan="4">GOODYEAR 295/75 R22.5 (Dual Configuration) (64 Tests)</td><td>4.45</td><td>420; 517; 690; 827</td><td rowspan="12">All tests were performed at the speeds of 2, 20, 30, and 40 mph</td></tr>
<tr><td>25</td><td>420; 517; 690; 827</td></tr>
<tr><td>31</td><td>420; 517; 690; 827</td></tr>
<tr><td>36</td><td>420; 517; 690; 827</td></tr>
<tr><td rowspan="4">GOODYEAR 295/75 R22.5 (Singled Out Dual) (64 Tests)</td><td>8</td><td>420; 517; 690; 827</td></tr>
<tr><td>26</td><td>420; 517; 690; 827</td></tr>
<tr><td>31</td><td>420; 517; 690; 827</td></tr>
<tr><td>36</td><td>420; 517; 690; 827</td></tr>
<tr><td rowspan="4">GOODYEAR 425/65R22.5 WIDE BASE TIRE (Single) (64 Tests)</td><td>8.6</td><td>482; 690; 896; 1000</td></tr>
<tr><td>44</td><td>482; 690; 896; 1000</td></tr>
<tr><td>50</td><td>482; 690; 896; 1000</td></tr>
<tr><td>62</td><td>482; 690; 896; 1000</td></tr>
</table>

Year 3 Work Plan

Subtask VP3a-1: Dynamic Loads

Work for Year 3 will consist of a review of the factors that affect the dynamic loads at the tire-pavement interface and include the information into the 3D-Move model.

Subtask VP3a- 2: Stress Distribution at the Tire-Pavement Interface

Work for Year 3 will consist of continuing the work on defining the distribution of normal and shear stresses at the tire-pavement interface and start building the database of available information on stress distributions. In addition, the UNR researchers will work with FHWA researchers to analyze the pavement response data that were collected at the Ohio test track.

Subtask VP3a-3: Pavement Response Model

Work for Year 3 will consist of continuing the work on the 3D-Move model to develop a menu-driven software.

Subtask VP3a-4: Overall Model

Work for Year 3 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.

Table for Decision Points & Deliverables

Work Element	Date	Deliverable	Description
VP2a	7/31/09	Journal paper	The paper topic will be the use of impedance tubes and sand patch to estimate safety and friction of asphalt mixtures.
VP2a	9/30/09	Preliminary models	Correlate the various parameters (texture, skid resistance, noise).
VP2a	3/31/10	Database	Comprehensive laboratory and testing database.
VP2a	3/31/10	Interim report	Document all research activities and findings.
VP3a	12/31/09	Software	A trial version of the menu-driven version of the 3D-Move pavement response model.

Budget

Work Element	Year 1	Year 2	Year 3	Year 4	Year 5
VP1a: Workshop	50,000				
VP2a: Mix Design for safety and Noise	75,000	100,000	100,000	50,000	
VP3a: Pavement Model		75,000	125,000	150,000	75,000
Total	125,000	175,000	225,000	200,000	75,000
	800,000				

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		P													
VP2a-4: Run parametric studies on tire-pavement noise and skid response			JP			JP, M&A		D									
VP2a-5: Establish collaboration with established national laboratories specialized in transportation noise measurements. Gather expertise on measurements and analysis																	
VP2a-6: Model and correlate acoustic response of tested tire-pavement systems										JP	D	F					
VP2a-7: Proposed optimal guideline for design to include noise reduction, durability, safety and costs											D	P, F					
(3) Pavement Response Model Based on Dynamic Analyses																	
VP3a: Pavement Response Model to Dynamic Loads																	UNR
VP3a-1: Dynamic Loads			JP							D, F	JP						
VP3a- 2: Stress Distribution at the Tire-Pavement Interface										D, F	JP						
VP3a-3: Pavement Response Model						SW, v. β							SW, JP				
VP3a-4: Overall Model													D	F			

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

Work planned
Work completed
Parallel topic

Vehicle-Pavement Interaction Year 3	Year 3 (4/2009-3/2010)												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		M&A						D	
VP2a-5: Establish collaboration with established national laboratories specialized in transportation noise measurements. Gather expertise on measurements and analysis													
VP2a-6: Model and correlate acoustic response of tested tire-pavement systems													
VP2a-7: Proposed optimal guideline for design to include noise reduction, durability, safety and costs													
(3) Pavement Response Model Based on Dynamic Analyses													
VP3a: Pavement Response Model to Dynamic Loads													UNR
VP3a-1: Dynamic Loads													
VP3a-2: Stress Distribution at the Tire-Pavement Interface													
VP3a-3: Pavement Response Model						SW, v. β							
VP3a-4: Overall Model													

Deliverable codes	**Deliverable Description**
D: Draft Report	Report delivered to FHWA for 3 week review period.
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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. 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 3 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. Annual monitoring of the sections will occur around September 2009.

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. There are also ongoing discussions with the province of Manitoba, Canada where there are also LTPP sections going out of service.

Construction of comparative performance sections including RAP have been discussed with the DOT personnel in Texas and California.

Year 3 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.

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 the need for accelerated performance testing in order 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 3 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

<u>Major Findings and Status</u>

Year 2 work included evaluation of progress in specifications for high, intermediate and low-temperature binder testing and specification procedures. The main findings are as follow:

For the high-temperature repeated creep testing following the Multiple Stress Creep and Recovery (MSCR) procedure, results indicate that a critical evaluation of the stress levels proposed (100 Pa and 3200 Pa) needs to be conducted. It was found that for many binders, significant change in creep rate occurs at higher stress levels, in the range of 10,000 to 20,000 Pa. In addition, the number of cycles proposed (10 cycles at each stress level) needs to be re-evaluated. The results collected in Work Element E1b-1 clearly show that the total loading time (number of cycles) is very important and that tertiary flow of binders is possible, particularly for some nonreactive, polymer-modified asphalts. Results of the MSCR test also showed that the cone-and-plate geometry gives different and possibly better results than the parallel-plate geometry currently used. The issue of the testing geometry and its effect on results and ranking of binders must be addressed.

The importance of percent recovery calculated from the MSCR test and its relationship to the results of elastic recovery measured using the ASTM/AASHTO procedure in the ductility test was evaluated. Although there are some correlations, the MSCR procedure appears to be a more scientific method in measuring the presence of elastomeric polymers in binders. The relationship between percent recovery and performance of binders under field conditions remains unclear.

Significant progress was made in Year 2 on binder fatigue criterion. Both the Binder Yield Energy Test (BYET) using the Dynamic Shear Rheometer (DSR) and initial ideas for including such a simple test in specifications have been proposed. The testing protocol has been shared with several laboratories and has been tried with binders and mastics to find its limitations. The repeatability of the results after reaching the maximum point is a concern. Also, there are questions about to which value the analysis of the stress-strain curve should be extended after reaching the yield point.

For the low-temperature cracking properties of binders, the Single-Edge Notched Beam (SENB) test is still under development. The research team has completed a round robin testing experiment using the Asphalt Binder Cracking Device (ABCD). Data are still under analysis but the device is found to be easy to use and can provide repeatable measurements.

There is no information about the final recommendations from the NCHRP project on the new binder aging procedure. Therefore, no work was conducted to evaluate a new binder aging procedure.

Year 3 Work Plan

Subtask V3a-1: Evaluation of the PG-Plus practices and the motivations for selecting the "plus" tests

The research team has already set up an elastic recovery test device (ASTM/AASHTO) using the ductility bath. Direct comparisons of elastic recovery and MSCR results for various modified asphalts will be conducted 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

Interviews of U.S. Department of Transportation personnel and industry representatives will be conducted in Year 3 to understand the benefits and costs associated with changing from the current empirical PG-Plus tests to tests such as the MSCR and BYET.

Subtask V3a-3: Development of protocols for new binder tests and database for properties measured

The research team will start collecting data for various modified binders used around the country to facilitate development of specification limits. This activity will be coordinated with the Binder ETG.

Subtask V3a-4: Development of specification criteria for new tests based on field evaluation of construction and performance

Binders collected from the material library associated with LTPP sections will be tested using the BYET and the SENB. Results will be organized and compared to field performance recorded in the LTPP database.

Subtask V3a-5: Interviews and surveys for soliciting feedback on binder tests and specifications

No activity is planned for Year 3 for this subtask.

Table for Decision Points and Deliverables

Date	Deliverable	Description
6/30/09	Draft Report	Report on testing conditions of the MSCR test and recommendations to the Binder ETG.
8/01/09	Journal Paper	Paper on MSCR analysis and its relationship to the current ductility elastic recovery.
9/30/09	Draft Report	Report on the BYET procedure and its value as a specification procedure.
Jan.-March 2010	Presentation	Presentation at the Binder ETG on the SENB and the ABCD test as a replacement of the Direct Tension Test procedure.

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

During year 2, the UNR researchers designed one MEPDG section for the regional transportation commission of northern Nevada and one MEPDG section for the Wisconsin DOT. The Nevada section was constructed in the summer 2008 and the Wisconsin section will be constructed in summer 2009.

The UWM research team identified the test sections to be investigated for fatigue cracking investigation (table V3b-3.1) as well as candidates for the block cracking investigation (table V3b-3.2).

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

The ARC researchers are still facing strong hesitation from the DOTs to built MEPDG test sections.

Table V3b-3.1. Binders received for fatigue cracking study.

Agency	Exp. No.	SHRP ID	Climate Zone	Fatigue Cracking (m^2)	Sample Location	Sample Type
CT	9A	90902	WF	0		AC PG 64-28
MT	9	300903	DF	0		64-22
NC	9A	370901	WN	0	BC01A01	AC-20
NC	9A	370902	WN	0	BC01A02	64-22
NC	9A	370903	WN	0	BC01A03	70-22
NC	9A	370962	WN	0	BC01A62	PG76-22
WI	9	550903	WF	0		58-72
CT	9A	90960	WF	0.8		AC-10
CT	9A	90961	WF	2.1		PG 58-34
FL	9A	120902	WN	2.2		AC PG 64-16
NC	9A	370961	WN	3.7	BC01A61	PG76-22
CT	9A	90962	WF	4.3		AC PG 58-28
CT	9A	90903	WF	5		PC PG 64-22
PQ	A9	89A902	WN	6.7		52-40
PQ	A9	89A901	WN	8.8		52-34
NJ	9A	340902	WF	11.4	BC01A02	58-28
NC	9A	370963	WN	12.7	BC01A63	AC20
NM	9	350903	DN	15.7		58-22
NC	9A	370965	WN	17.7	BC01A65	PG16-23
NM	9	350902	DN	32		64-22
MO	9A	290963	WF	37.9	BC02A63	64-16
NJ	9A	340901	WF	49.5	BC01A01	64-22
NC	9A	370964	WN	51.1	BC01A64	PG76-22
MO	9A	290901	WF	51.6	BC02A01	64-28
NE	9	310902	DF	65.5		AC
NC	9A	370960	WN	73.1	BC01A60	PG76-22
MT	9	300902	DF	76.2		64-34
NE	9	310903	DF	175.5		AC
NJ	9A	340961	WF	178.8	BC01A61	78-28
AZ	9A	04B901	DN	328		AC BINDER
AZ	9A	04B903	DN	337.9		AC-40, PG 70-10

Table V3b-3.2. Candidates for block cracking study.

SHRP_ID	Sample Type	Sampled Date	GridCoord	Agency
10600	AC LOWER BINDER 67-22 W/O POLYMER	05/12/98	E6-05-01	AL
10600	PG 76-22 UPPER BINDER MIX	05/14/98	E6-05-01	AL
40500	AC-20 BINDER		E3-05-02	AZ
40500	AC-40 BINDER		E3-05-02	AZ
60500	AC FOR RUBBERIZED MIX		E3-06-01	CA
60600	AR-4000 BINDER	08/11/92	E5-02-01	CA
80500	AC-20 BINDER		E2-04-03	CO
170600	AC BINDER		E5-01-01	IL
180600	BINDER (OPENED)		E4-04-02	IN
190100	BC-17, PLANT BINDER	11/11/92	E2-04-03	IA
190600	LIQUID ASPHALT BINDER		E3-01-02	IA
230500	AC BINDER	06/20/95	E6-04-02	ME
280500	BINDER		E2-04-03	MS
290500	OIL FOR VIRGIN IC	08/27/98	E6-04-01	MO
290500	OIL FOR RECYCLE IB MIX	09/02/98	E6-04-01	MO
290600	AC BINDER		E5-03-02	MO
300500	85/100, AC		E3-01-02	MT
300800	A/C		E3-05-02	MT
340500	AC-10 FOR RECYCLED, BINDER		E4-02-02	NJ
340500	AC-20 FOR VIRGIN MIX, BINDER		E4-02-02	NJ
350500	AC CEMENT FOR RAP	09/07/96	E6-01-02	NM
360800	BINDER	08/16/94	B1-02-03	NY
390100	AC-20 BINDER	07/01/94	E3-06-01	OH
400600	AC-20 BINDER		E5-01-01	OK
480500	AC 10 W/3% LATEX	10/16/91	E3-01-01	TX
480500	AC 5 RAP SURFACE BINDER		E3-02-01	TX
480500	AC-10 ASPHALT W/3% LATEX, BINDER	10/16/91	E4-02-02	TX
480800	AC-20 BINDER	07/17/96	E2-04-03	TX
490800	PG 58-34 BINDER	10/17/97	E3-06-01	UT
530800	AR 4000 ASPHALT BINDER	10/26/95	E6-02-02	WA
550903	AR PG 58-72		E2-03-03	WI
810500	150/200 AC BINDER	10/03/90	E2-04-03	AB
810500	200/300 ASPHALT BINDER	10/10/90	E2-04-03	AB

Year Three Work Plan

Subtask V3b-1: Design and Build Sections

The UNR researchers will work with the South Dakota DOT to design and construct 2 MEPDG sections.

Subtask V3b-2: Additional Testing

No work is planned for year 3.

Subtask V3b-3: Select LTPP Sites to Validate New Binder Testing Procedures

The research team will continue to sample the asphalt binders for the fatigue study in accordance with the procedure outlined in the ARC July–September 2008 report. The proposed testing matrix remains unchanged from the Year 2 work plan.

A new testing matrix to evaluate binders from the block cracking test sections will be developed based on discussion with other ARC partners working on aging of asphalts and with reviewers who requested consideration of block cracking in this work plan.

Subtask V3b-4: Testing of Extracted Binders from LTPP Sections

No work is planned.

Subtask V3b-5: Review and Revisions of Materials Models

No work is planned for year 3.

Subtask V3b-6: Evaluate the Impact of Moisture and Aging on Material Properties in MEPDG

No work is planned for year 3.

Budget

		Year 1	Year 2	Year 3	Year 4	Year 5
Category V1 & V2: Field & Accelerated Pavement Testing						
V1a & b V2a & b	Construction and Monitoring of Field Sites Accelerated Pavement Testing	220,000	405,000	810,000	985,000	1,103,000
Category V3: R&D Validation						
V3a	Continual Assessment of Specification	100,000	100,000	75,000	75,000	45,000
V3b	Validation of the MEPDG Asphalt Materials Models and Early Verification of Technologies Developed by ARC using new MEPDG Sites and Selected LTPP Sites.	90,000	175,000	250,000	200,000	150,000
TOTAL		410,000	680,000	1,135,000	1,260,000	1,298,000
		4,783,000				

Validation Year 3

	Year 3 (4/2009-3/2010)												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			D										
V3a-3: Development of protocols for new binder tests and database for properties measured					JP								
V3a-4: Development of specification criteria for new tests based on field evaluation of construction and performance						D					P		
V3a-5: Interviews and surveys for soliciting feedback on binder tests and specifications													
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									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													

Deliverable codes	**Deliverable Description**
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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									D, F								
V3b-2: Additional Testing (if needed)																	
V3b-3: Select LTPP Sites to Validate New Binder Testing Procedures					DP			P		JP		P			D	F	
V3b-4: Testing of Extracted Binders from LTPP Sections																	
V3b-5: Review and Revisions of Materials Models																D, F	
V3b-6: Evaluate the Impact of Moisture and Aging																D, F	

Deliverable codes	Deliverable Description
D: Draft Report	Report delivered to FHWA for 3 week review period.
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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
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DP: Decision Point	Time to make a decision on two parallel paths as to which is most promising to follow througjh

Work planned
Work completed
Parallel topic

PROGRAM AREA: 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 analysis of continuum damage fatigue data. Two new and very useful concepts were included in the improved method. The first is the concept of reduced loading cycles. Reduced loading cycles can be used as 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 improved continuum damage fatigue analysis has been developed. Work was initiated on a draft standard test method for the improved continuum damage fatigue analysis. The draft standard test method is approximately 75 percent complete.

Year Three Work Plan

The draft standard test method will be completed early in Year 3. The Interlaken Asphalt Mixture Performance Tester that is owned by the National Cooperative Highway Research Program (NCHRP) will be modified to perform continuum damage testing. 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 Asphalt Mixture Performance Tester. 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 Asphalt Mixture Performance Tester 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 Three Work Plan

It is planned to continually review research progress to identify potential products.

Work Element TD4: Develop Mid-Term and Long-Term Products

No work is planned in year 3.

Budget

The budget for Technology Development is estimated at $1,000,000 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 2 of the Consortium. The final copies of the year 1 and year 2 work plans all the quarterly progress reports, the ARC newsletters, and any other technical reports have been uploaded to the website.

Year Three Work Plan

The Consortium Website will continue to be maintained and appropriate documents will be uploaded.

Table for Decision Points & Deliverables

Date	Deliverable	Description
07/31/09	Final Report	Upload quarterly progress report and newsletter
10/31/09	Final Report	Upload quarterly progress report
11/30/09	Final Report	Upload newsletter
01/31/10	Final Report	Upload quarterly progress report
03/31/10	Final Report	Upload newsletter
04/30/10	Final Report	Upload quarterly progress report

Work element TT1b: Communications

Major Findings & Status

Three newsletters were published in year 2 of the Consortium. The newsletters were electronically distributed to the industry and were published on the Consortium Website.

Year Three Work Plan

Three ARC newsletters will be published.

Table for Decision Points & Deliverables

Date	Deliverable	Description
07/31/09	Final Report	Newsletter will be published
11/30/09	Final Report	Newsletter will be published
03/31/10	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 Three 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 2, the work element TT1d was revised to include information on the core and no-core materials. Figure TT1d.1 summarizes the differences in the management and use of core vs. non-core materials. Additionally a labeling and tracking system was identified.

A central database of materials was defined and will be designed and used by ARC members (core and non-core). The proposed database consists of four components namely, the Material Database files (MDF), Data Access, Data Utility, and a User Interface as shown in figure TT1d.2.

Material Database Files (MDF): the MDF will house the following information (figure TT1d.3).

- MDF-1: List of all core and non-core constitutive materials used in the ARC research including, aggregates, binders (neat and modified by supplier), fillers, antistrip agents, polymers for lab modification, chemical additives for lab modification, warm mix additives, and emulsifiers. The materials will follow the proposed labeling format.
- MDF-2: List of validation sites/sections with labeling following the proposed format.
- MDF-3: List of all composite materials that are produced from at least one of the constitutive materials listed in MDF-1or MDF-2. The composite materials categories

include, binders, mastic, fine aggregate matrix (FAM), laboratory produced mixes, validation site mixes, and validation sites cores and slabs.

- MDF-4: List of material properties including binder properties, mastic properties, fine aggregate matrix properties, and mixture properties that will be measured as a part of various work elements.
- MDF-5: Database of measured composite materials properties including binders (unmodified, modified by supplier, and modified in the lab), mastics, fine aggregate matrix, and mixtures.

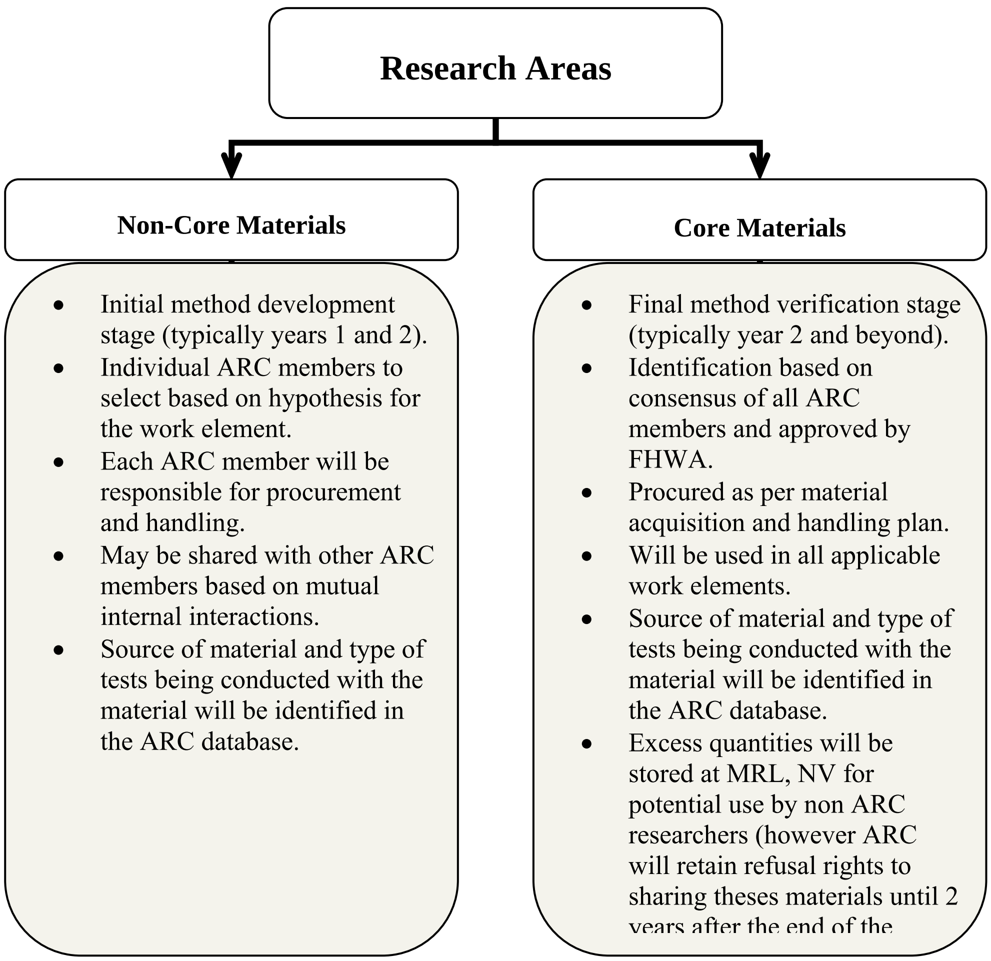
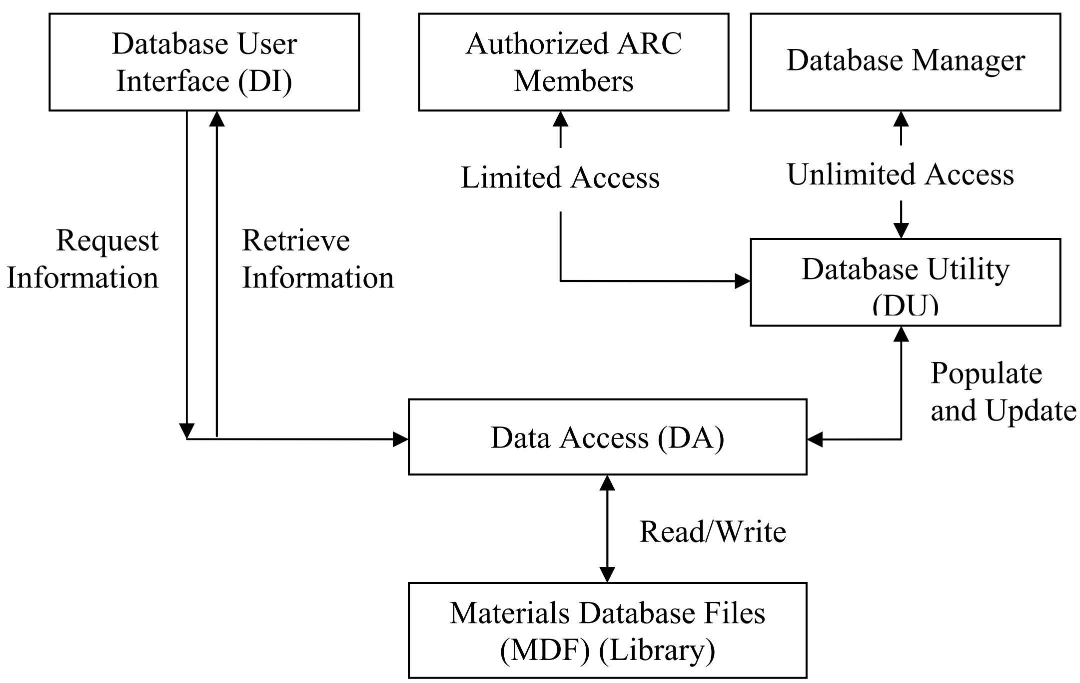


Figure TT1d.1. Core vs. non-core materials.

Data access (DA): This is a dynamic link library containing procedures that a program can call upon to retrieve data from the database using specialized procedures. It provides users with the ability to retrieve as well as update the data and at the same time preserve the data integrity. It contains all queries needed to retrieve information from the database.

Database Utility (DU): Using this utility, a Database Manager can directly work with the data stored in the *Material Database Files*. It allows the manager to find, update, add and delete records as well as display database information. The database will be initially uploaded with the information lists on materials and made available to all ARC members for updating with other area specific information and material properties. Consequently, it is anticipated that the database manager will create and generate the lists in MDF-1, MDF-2, MDF-3, and MDF-4 upon a request submitted electronically by other authorized ARC research members. This component also includes facilities to allow authorized users from ARC members to connect to the database to populate and update the database information in MDF-5. Additionally, the DU encompasses data management capabilities such as data cleaning, quality checks and formatting.

Database User Interface (DI): It allows a user to retrieve information from the database. It allows the user to see, print information retrieved from the database. The user will identify the information needed from the database. The input focuses the search on locating specific materials corresponding to the information entered by the user.



FigureTT1d.2. Materials database structure.

The work started on developing the Microsoft Access database tables according to the entity relationships diagrams (ERD). Additionally, the work started on converting the ARC website from a static to a dynamic web site using the Microsoft Active Server Pages (ASP.NET) web application.

Both the ASP.NET web application and the database site were created and the work started on the development of the prototype pages which will allow for imputing the materials' data. Additionally, an authentication scheme is created to allow three levels of users:

1. Administrative users (UNR) will have full access to the ARC materials database.
2. Consortium users will have the ability to post materials test results and perform other tasks as defined by the Work Element Lead.
3. A third category of user will have read-only access to data as determined by the Work Element Lead. Access will be restricted both at the database-level and at the Web page level.

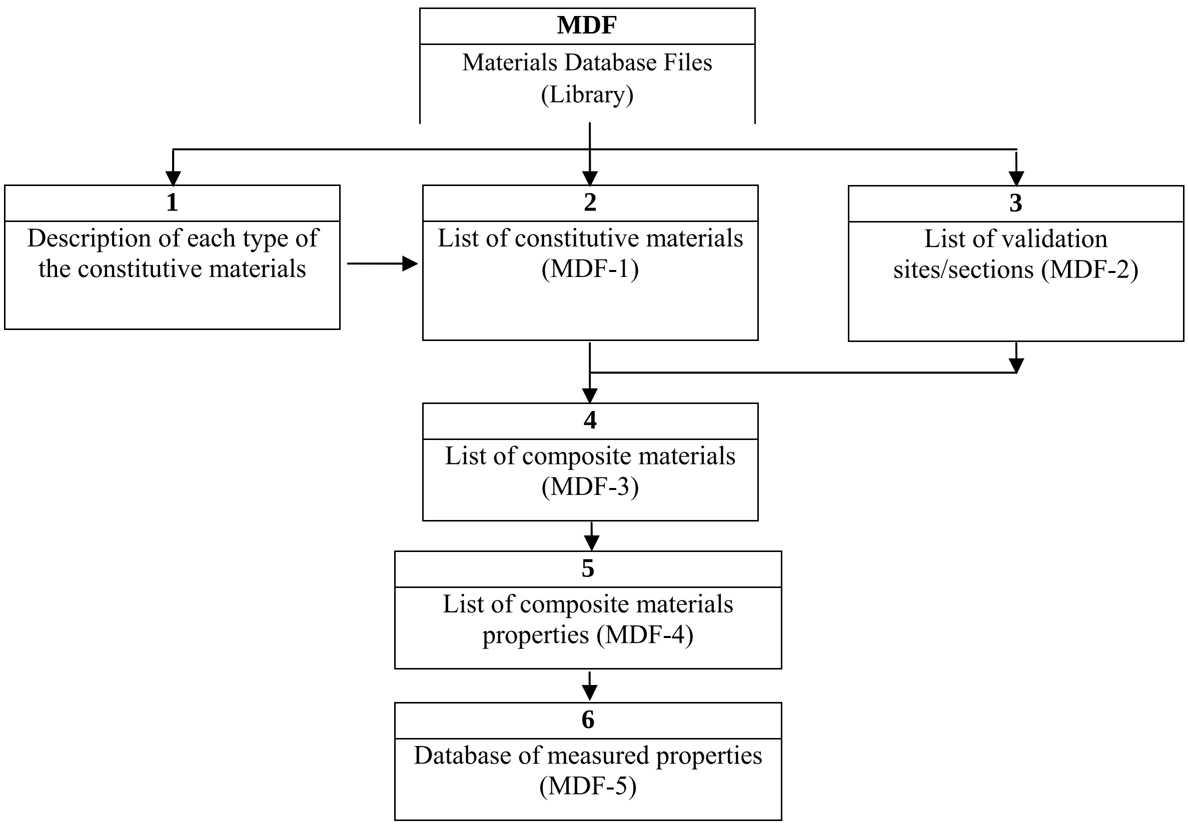


Figure TT1d.3. Flow chart for materials database files showing different information blocks.

Year 3 Work Plan

Work for Year 3 will consist of completing and implementing the database.

Table for Decision Points & Deliverables

Date	Deliverable	Description
8/30/09	Populate Database	Implement essential pages for ARC members to enter validation sites, print material label, and other high-priority pages
12/31/09	Populate Database	Finalize the implementation of the materials database

Work element TT1e: Development of Research Database

Major Findings & Status

The final version of the year 2 work plan, the quarterly progress reports and several ETG presentations 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 is 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 Three 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

The ARC did not hold any workshops and training activities during year 2.

Year Three 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.

Table for Decision Points & Deliverables

Work Element	Date	Deliverable	Description
TT1a	07/31/09	Final Report	Upload quarterly progress report and newsletter
TT1a	10/31/09	Final Report	Upload quarterly progress report
TT1a	11/30/09	Final Report	Upload newsletter
TT1a	01/31/10	Final Report	Upload quarterly progress report
TT1a	03/31/10	Final Report	Upload newsletter
TT1a	04/30/10	Final Report	Upload quarterly progress report
TT1b	07/31/09	Final Report	Newsletter will be published
TT1b	11/30/09	Final Report	Newsletter will be published
TT1b	03/31/10	Final Report	Newsletter will be published
TT1d	8/30/09	Populate Database	Implement essential pages for ARC members to enter validation sites, print material label, and other high-priority pages
TT1d	12/31/09	Populate Database	Finalize the implementation of the materials database

Budget

Work Element	Year 1	Year 2	Year 3	Year 4	Year 5
TT1a: Website	84,500	142,500	107,000	80,000	70,000
TT1b: Communications	5,000	7,000	10,000	10,000	10,000
TT1c: Presentations and Publications	30,000	40,000	40,000	40,000	40,000
TT1d: Materials Database	10,000	25,000	35,000	35,000	20,000
TT1e: Research Database	3,000	5,000	5,000	5,000	5,000
TT1f: Workshops and Training				200,000	200,000
Total	132,500	219,500	197,000	370,000	345,000
	1,264,000				

Technology Transfer Year 3	Year 3 (4/2009-3/2010)												Team
	4	5	6	7	8	9	10	11	12	1	2	3	
(1) Outreach and Databases													
TT1a: Development and Maintenance of Consortium Website													UNR
TT1b: Communications													UNR
TT1c: Prepare presentations and publications													UNR
TT1d: Development of Materials Database													UNR
TT1d-1: Identify the overall Features of the Web Application													
TT1d-2: Identify Materials Properties to Include in the Materials Database													
TT1d-3: Define the Structure of the Database													
TT1d-4: Create and Populate the Database								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

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)			
	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																
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TT1e: Development of Research Database																
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																

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