Western Research INSTITUTE

Asphalt Research Consortium

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By
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TABLE OF CONTENTS

INTRODUCTION

This document is the Quarterly Report for the period of October 1 to December 31, 2008 for 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 Quarterly Report is grouped into seven areas, Moisture Damage, Fatigue, Engineered Paving Materials, Vehicle-Pavement Interaction, Validation, Technology Development, and Technology Transfer. The format of the report is based upon the Research Work Plan that is grouped by Work Element and Subtask.

This Quarterly Report summarizes the work accomplishments, data, and analysis for the various Work Elements and Subtasks. This report is being presented in a summary form in response to a request from the FHWA Agreement Officer's Technical Representatives (AOTR's) Dr. Jack Youtcheff and Mr. Eric Weaver. Reviewers may want to reference the Revised Year 2 Work Plan in order to obtain background information on specific areas of research. The more detailed information about the research such as approaches to test method development, data collection, and analysis will be reported in research publications as part of the deliverables. The Revised Year 2 Work Plan is posted on the ARC website, www.ARC.unr.edu.

The previous quarterly reports, Year 1, Revised Year 2, and Year 3 Work Plans, and other related documents and information about the Asphalt Research Consortium can be found at the ARC website, www.ARC.unr.edu.

SUPPORT OF FHWA AND DOT STRATEGIC GOALS

The Asphalt Research Consortium research is responsive to the needs of asphalt engineers and technologists, state DOT's, and supports the FHWA Strategic Goals and the Asphalt Pavement Road Map. More specifically, the research reported here supports the Strategic Goals of safety, mobility, and environmental stewardship. By addressing the causes of pavement failure and thus determining methods to improve asphalt pavement durability and longevity, this research will provide the motoring public with increased safety and mobility. The research directed at improved use of recycled asphalt pavement (RAP), warm mix asphalt, and cold mix asphalt supports the Strategic Goal of environmental stewardship.

GENERAL CONSORTIUM ACTIVITIES

PROGRESS THIS QUARTER

Consortium members, Dr. Peter Sebaaly, Dr. Hussain Bahia, and Mr. Michael Harnsberger attended the RAP ETG meeting in Phoenix on October 28 and 29, 2008. Following the RAP ETG, the Consortium members, Dr. Peter Sebaaly, Dr. Hussain Bahia, Dr. Dallas Little, and Mr. Michael Harnsberger met with Co-AOTR's Dr. Jack Youtcheff and Mr. Eric Weaver to discuss preparation of the Year 3 Work Plan and associated documents. A brief Consortium Advisory Board meeting was also held to discuss Consortium research, resources, budgets, and other matters.

WORK PLANNED FOR NEXT QUARTER

Many Consortium members and their staff planned to attend the 88th Annual Meeting of TRB where several members/staff have presentations, and/or are members of TRB committees. During the week of TRB, a Consortium Advisory Board meeting is planned to discuss the progress on the Year 3 Work Plan preparation and other business.

All Consortium members and staff will complete the preparation of the Annual Work Plan for Year 3 and deliver the plan to FHWA in January 2009. In addition, a Quarterly Report on the Consortium activities for the period October 1, 2008 to December 31, 2008 will be prepared and delivered.

Consortium members are also expecting to attend the February 2009 Binder, Mix and Construction, and Fundamental Properties and Advanced Models ETG meetings in Irvine, California. It is anticipated that a substantial portion of the Fundamental Properties and Advanced Models ETG meeting will focus on the modeling activities in the Consortium. It is also expected that presentations may be made at the Binder and the Mix and Construction ETG meetings.

PROGRAM AREA: MOISTURE DAMAGE

CATEGORY M1: ADHESION

Work Element M1a: Affinity of Asphalt to Aggregate (UWM)

Work Done This Quarter

The material used for testing during this quarter was mainly CRM, a PG 58-28 neat binder with a low content of asphaltenes (9.06% as determined per ASTM D4124-01).

Granite rock disks were prepared and used for Dynamic Shear Rheometer (DSR) testing. Modified binders were prepared using the above binder as base. Moisture-damage tests were conducted following the previously approved testing matrix. The focus was to continue work from the previous quarter and finish comparisons between two rock disks and one rock disk and one plate. The research team also continued evaluating whether a metal cone can be used with a rock disk in a cone-and-plate geometry while ensuring uniformity of stress distribution in a sample.

Significant Results

From the previous quarter, it was seen that the results were more repeatable by using only one disk instead of two for dry conditions on granite. To finally evaluate whether one disk is better than two disks, water conditioning tests were conducted.

Figure M1a.1 and figure M1a.2 show a comparison between tests conducted on an asphalt sample between two granite rock disks versus one granite disk and one steel plate for two different binders (neat in figure M1a.1 and modified in figure M1a.2). The geometry for the wet condition moisture tests is a 25 mm parallel plate with a 1 mm gap. It is clearly shown that results are repeatable. For water-conditioned samples, tests using one rock disk yield more repeatable results than tests performed using two rock disks.

The research team recommends using one disk instead of two based on previously reported results. This will allow running twice the number of tests using the same number of rock disks. In addition, one rock disk is used for comparison between cone-and-plate and parallel-plate, and for comparison between DSR test with modified Pneumatic Adhesion Tensile Testing Instrument (PATTI) test results and the DSR-run tack test.

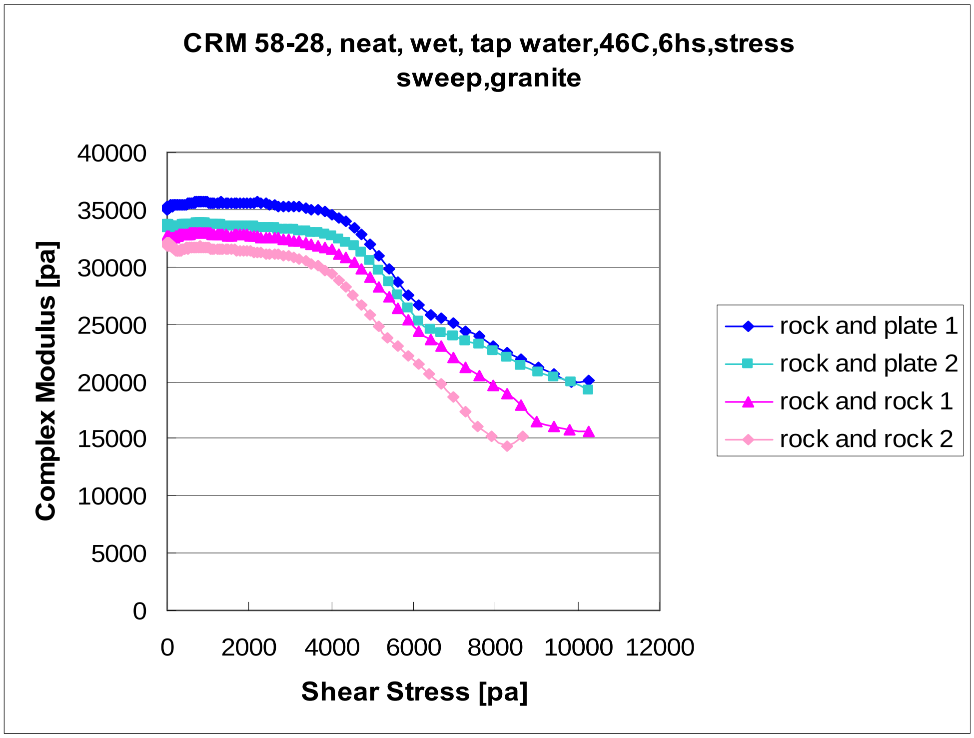

Figure M1a.1. Graph. Stress sweep testing results at 46 ºC for the CRM neat binder in wet conditions, on granite after 6 hours conditioning in tap water.

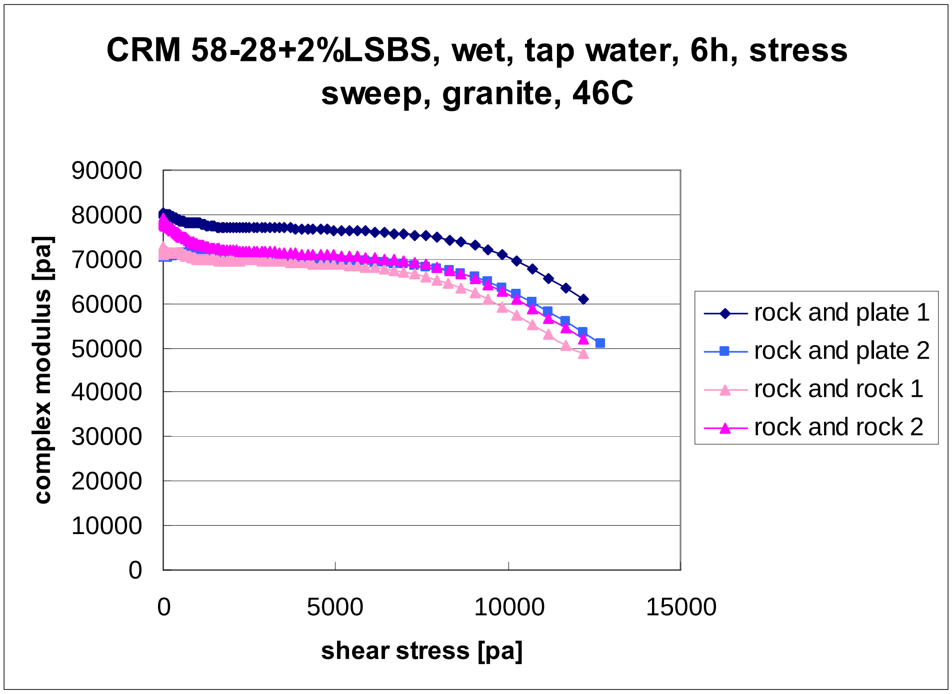

Figure M1a.2. Graph. Stress sweep testing results at 46 ºC for the CRM modified with 2% wt linear styrene-butadiene-styrene (LSBS) binder in wet conditions, after 6 hours conditioning in tap water, with granite rock disks.

Comparison between cone-and-plate and parallel-plate

All tests for comparison between cone-and-plate and parallel-plate are performed using one rock disk and one steel plate. Cone-and-plate and parallel-plate geometries are used. The cone-and-plate geometry is a 25 mm plate with a 0.998º angle cone and a truncation of 0.049 mm. Due to sample size differences between the parallel-plate and the cone-and-plate geometries, the failure of the tested sample shows a different trend. By finding an appropriate testing gap so that both geometries have similar sample volumes, parallel-plate and cone-and-plate tests show similar failure trends in the binder.

As shown in testing results for neat binder (figure M1a.3) and modified binder (figure M1a.4), cone-and-plate and parallel-plate have results of the same original complex modulus. By testing different film thicknesses in the parallel-plate, the exact gap is found for which there is both the same sample volume and failure trend as the cone-and-plate geometry. That test gap was 0.37 mm.

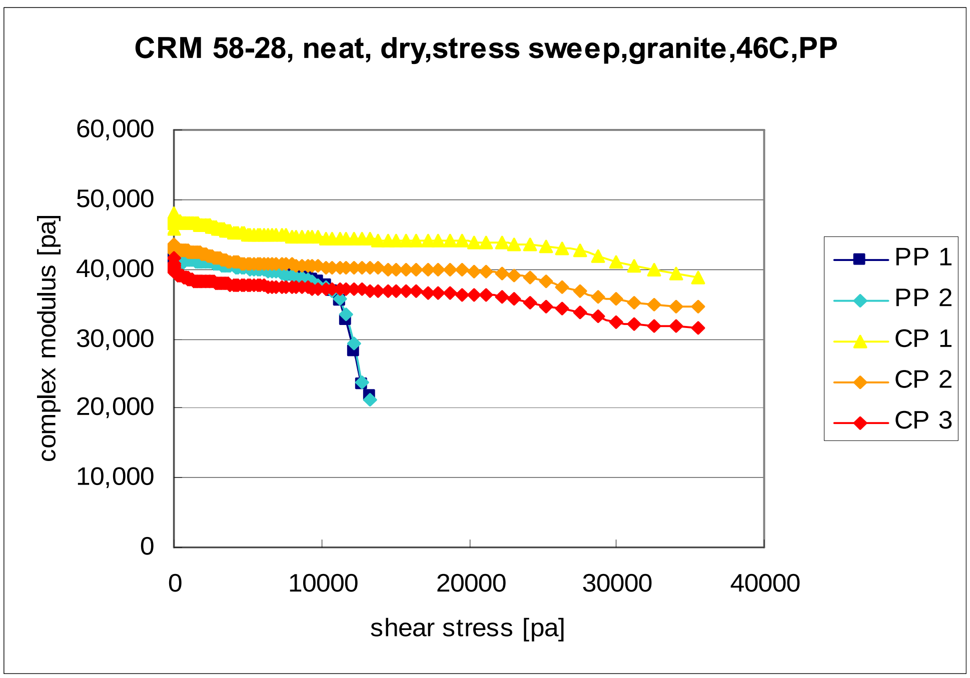

Figure M1a.3. Graph. Stress sweep testing results at 46 ºC for the CRM neat binder in dry conditions, with granite and with cone-and-plate and parallel-plate.
(CP = cone-and-plate, PP = parallel-plate)

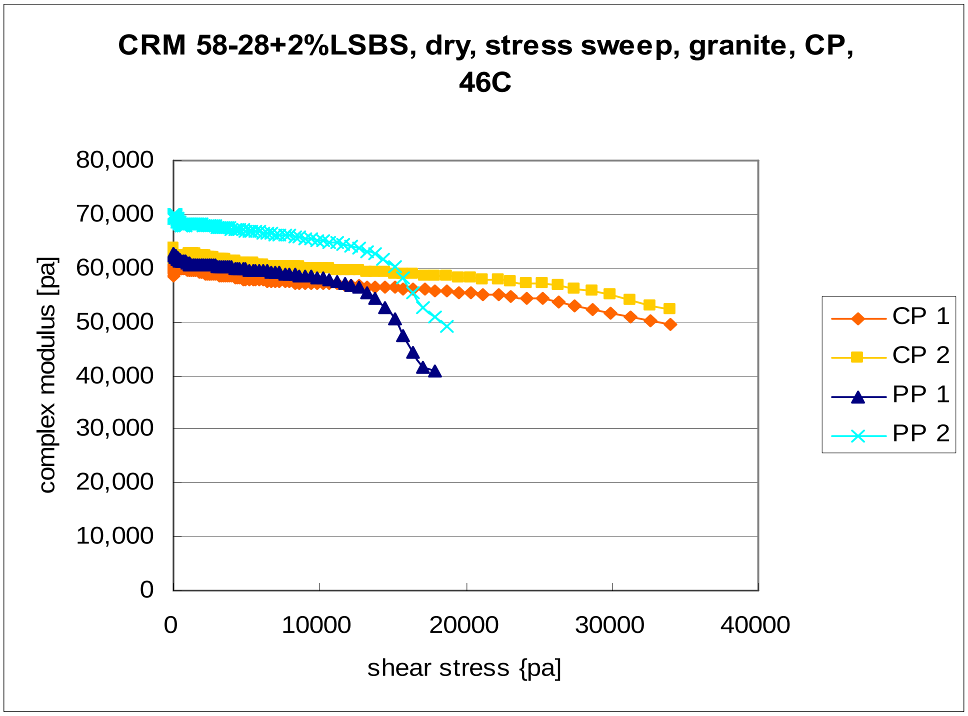

Figure M1a.4. Graph. Stress sweep testing results at 46 ºC for the CRM modified with 2% wt LSBS binder in dry conditions, with granite and with cone-and-plate and parallel-plate. (CP = cone-and-plate, PP = parallel-plate)

Work Planned Next Quarter

Next quarter the research team will continue running tests using the modified DSR procedure. The team will also continue working on evaluating the moisture damage of asphalt mixtures as described in the work plan, and it will work on correlating DSR results to PATTI results as well as the binder test results with the results obtained on mixtures.

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 (TAMU)

Work Done This Quarter

No activity was planned for this quarter.

Work Planned Next Quarter

The need for a subtask on the use of the micro-calorimeter to measure the total energy of adhesion will be developed in the next quarter. The assessment will be made based on the findings from studies that have been conducted using the micro-calorimeter outside of the ARC.

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

Work Done This Quarter

The primary objective of this subtask is to determine the entropic contribution to the surface free energy of adhesion for asphalt thin films. The subtask involves the study of wetting kinetics and frictional adhesion hysteresis with respect to the influence of these properties on adhesive quality. From these measurements a more fundamental thermodynamic model of asphalt-aggregate bond strength will be developed. Work related to this subtask is based on the use of atomic force microscopy to make precision force measurements at nano-scale, and the use of spin casting techniques to prepare thin asphalt films of controlled thickness.

Pursuant to the need to make precision quantitative AFM measurements, repeated preliminary tests were conducted using known samples to assess the relative precision of the AFM measurements. These preliminary tests revealed problems with the AFM metrology hardware. Attempts were made to recalibrate the metrology scan-head, and the head was returned to the manufacturer for repair. Problems with the system persisted in spite of several attempts at repair. Ultimately the equipment manufacturer agreed to replace the metrology system, and this was accomplished near the end of the quarter. Testing of the new system (including new operating software) is currently underway.

Preliminary force curve measurements have been conducted on clean bare glass using a contact-mode AFM cantilever with a glass micro-bead tip. At the time of this writing the results of this preliminary testing have not been completely analyzed. However, it appears that the metrology system is currently working correctly and delivering results with the expected level of precision.

A robotic arm was fitted to WRI's spin casting system to improve the quality and consistency of prepared thin film samples. The robotic arm provides for a controlled volumetric sample delivery rate as well as controlled radial movement of the confined droplet. Preliminary testing of the robotic spin-casting system was conducted this quarter. Results of this testing indicate improved consistency and control of film thickness. The robotic system also eliminates the need for a specifically skilled technician for sample preparation. Final adjustments are being made with respect to the geometry between the sample applicator tip and the substrate.

Significant Results

The functionality and precision of equipment that will be used for experimental work under this subtask has been assessed. A major piece of equipment was replaced. Preliminary testing related to equipment evaluation and method development has been successfully completed.

Significant Problems, Issues and Potential Impact on Progress

Persistent problem with the AFM metrology hardware have delayed progress on this subtask. These problems have been resolved, and no further impact on progress of this subtask is anticipated.

Work Planned Next Quarter

In the next quarter work will commence on items as specified in the detailed Year 2 Work Plan. A sample set consisting of neat asphalts that vary in compatibility and wax content will be assembled. A second sample set will be prepared from the same asphalts after RTFO-PAV aging. Preliminary contact mechanics measurements will begin next quarter. A literature search relevant to this subject will continue.

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

Work Done This Quarter

This subtask is investigating the mechanisms responsible for adhesion and debonding of model organic compounds (representing functional groups in asphalt binder) to minerals and representative aggregates. We are measuring the heat of reactions of the chemical mechanisms using a dual-mode flow adsorption calorimeter. Differences in molar heats of reaction of different organics bonding to the same absorbent are indicative of differences in the bonding strength of each absorbate with the absorbent of interest.

Work during this quarter focused on continued development of the instrument. In particular, we integrated an ultraviolet-visible spectrophotometer with the dual-mode flow adsorption calorimeter to provide continuous monitoring of the solution concentration of the organics compounds.

In addition, we established the reproducibility and accuracy of the calorimeter by repeated measurements of the molar heats of reactions of benzoic acid adsorption and desorption to silica at pH 3 during flow-through experiments.

Work Planned Next Quarter

We plan on initiating flow through experiments to measure the molar heat of reaction of the adhesion of model organic compounds that represent asphalt to minerals and aggregates, as well as the molar heats of reactions of water adsorption to organic-coated minerals and aggregates.

Adhesion will be modeled in the flow-through calorimeter by organic sorption from nonaqueous phase solvents. Experimental variables include the chemistry of the model organic, single versus mixtures of model organics, ionic salt content of the nonaqueous phase solvent, and the surface chemistry of the mineral or aggregate.

Competition of water and the model organics for the mineral or aggregate surfaces will be characterized through flow-through experiments that introduce small amounts of water to the systems created during the adhesion studies above.

Work Element M1c: Quantifying Moisture Damage Using DMA (TAMU)

Work Done This Quarter

No activity was planned for this quarter.

Work Planned Next Quarter

Work on this task will start in year 3 of the project.

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 (TAMU)

Work Done This Quarter

No activity was planned for this quarter.

Work Planned Next Quarter

Work on this task is anticipated to start in year 4 of the project.

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

Work Done This Quarter

The primary objective of this subtask is to determine the surface entropy of asphalts and to relate this property to moisture susceptibility through interfacial thermodynamic theories. Preliminary work related to equipment evaluation and verification of precision conducted under subtask M1b-2 is also directly relevant to this subtask.

Significant Results

AFM hardware problems were resolved as a result of work conducted this quarter.

Significant Problems, Issues and Potential Impact on Progress

Persistent problem with the AFM metrology hardware have delayed progress on this task. These problems have been resolved, and no further impact on progress of this subtask is anticipated.

Work Planned Next Quarter

In the next quarter work will commence on items as specified in the detailed Year 2 Work Plan. A sample set consisting of eight asphalts and four representative aggregate materials will be assembled. Surface energy will be measured for the asphalt sample set as a function of temperature. Phase transition temperatures from the surface tension data will be compared with physical performance data and correlation or lack of correlation will be noted. Preparation will begin for water soaking experiments to be conducted in the second quarter of year two work. A literature search relevant to this subject will continue.

Work Element M2b: Impact of Moisture Diffusion in Asphalt Mixtures

Subtask M2b-1: Measurements of Diffusion in Asphalt Mixtures (TAMU)

Work Done This Quarter

The main effort in the last quarter was to establish a procedure that allows testing of more than one sample simultaneously in order to obtain multiple test results in a given span of time. During these tests, the FTIR cell (along with the binder coating and water retaining cell) was removed from the spectrometer after the spectra was recorded to allow the measurement of the other specimens. Based on preliminary tests it was found that: (i) it is important to ensure that all the samples remained horizontal and minimal disturbance while the cell was removed and replaced back in the FTIR between two measurements, and (ii) if a different accessory was used for another experiment with the FTIR in between two measurements, the ATR accessory must be kept in place in the FTIR for at least 12 hours before the next reading to stabilize the interferogram. Following this precaution and procedure it was possible to test several cells simultaneously using the spectrometer. At this time, two specimens of three different asphalt binders are being tested.

Another important issue addressed in the past quarter was the procedure for the measurement of the asphalt binder film thickness and refractive index using the ellipsometer. A spectroscopic/nulling ellipsometer was used in this study. Typically, the term "spectroscopic" refers to the ability of changing the wavelength of measurements. Nulling is a condition that it creates with the angles of the analyzer and compensator (optics in the arms) so that the polarization of the incident and reflected light cancel each other out. Establishing the nulling condition makes calculations much simpler when modeling. The choice for a dispersion function for modeling the data from a specimen depends on how the specimen interacts with light. There are different types of dispersion functions based on the type of material under consideration. We chose the Cauchy function since it represents the behavior of light in a transparent polymer (or other organic molecule).

Researchers are still working on the procedure to determine the influence of hysteresis in moisture gradient on the diffusivity through binder films. In the preliminary procedure, the binder film was exposed to moisture for a 15 day period. The water in the cell was removed and the exposed film surface was left at room temperature until the asphalt spectra stabilized. The rate at which moisture diffuses out from the binder was also determined using the spectral measurements. After drying the film for certain duration, the film surface was again exposed to moisture and the rate of diffusion was determined as before. This test is currently in progress and researchers are interested in comparing the rate of moisture diffusion through the original film and through the same film after it has been exposed to one wet-dry cycle.

Significant Results

Figure M2b.1 illustrates the results from tests on five specimens being conducted simultaneously. The figure also illustrates the differences in the diffusivity of the three different asphalt binders as well as the good repeatability of the test protocol that was developed.

Work Planned Next Quarter

Measurements using the FTIR to determine the diffusivity of water through asphalt binders will be continued through the next quarter. Emphasis in the next quarter will be to, establish the repeatability of the test method; evaluate sensitivity of the test method to changes in film thickness and type of binder; complete the method described above to test multiple specimens at the same time using a single FTIR; and conduct preliminary analysis of the data.

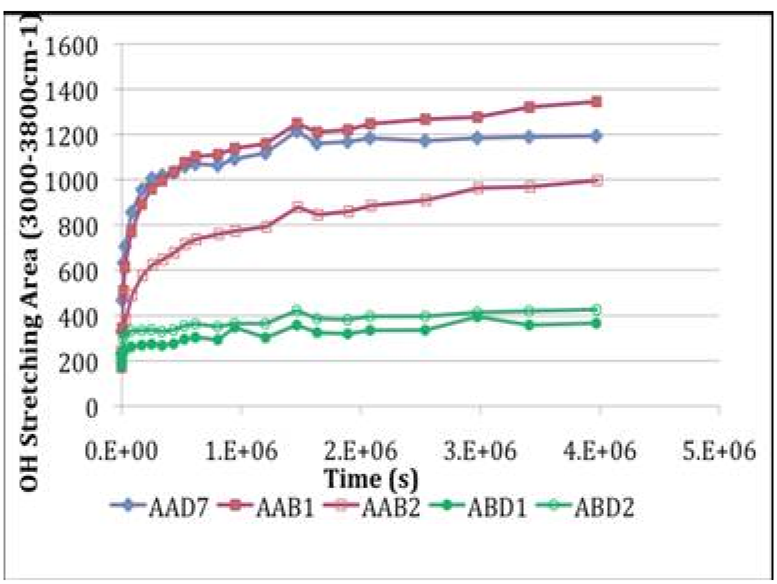

Figure M2b.1. Typical results for moisture diffusion through thin films of asphalt binders as recorded using the FTIR

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

Work Done This Quarter

Most of the work accomplished under subtask M2b-1 also directly relates to this subtask. The most significant difference in this subtask is that a portion of the binder-ATR window interface will be purposefully exposed to be in direct contact with the water. This will allow the water to diffuse through the film as well as propagate along the binder-ATR window interface.

Work Planned Next Quarter

Researchers plan to continue work with emphasis on M2b-1 before addressing the specifics of this subtask.

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

Work Done This Quarter

The team continued to evaluate the Pneumatic Adhesion Tensile Testing Instrument (PATTI) device and modify the PATTI test procedure. Significant advances were made in redefining LabVIEW algorithms to accurately capture the stub pullout rate. The new algorithm calculates the slope between 30% and 70% of the maximum amplitude of the pullout tension.

The team redesigned PATTI stubs to ensure a constant film thickness of 0.4 mm. This result was achieved by integrating supports into the stub design, which elevated the stub head by the film thickness without significantly increasing the area of the stub head. Modified stubs are pictured in figure M2c.1. This idea was first used by a group at the University of Ancona in Italy. The research group there, led by professors Santagata and Canestrari, is sharing data and ideas with the consortium members.

Figure M2c.1. Photographs. New stub design.

Significant Results

- Plots of pullout tension over time for modified PATTI stubs show an uncharacteristic double peak. This result may be due to the fact that there is additional adhesion on the stub legs. The smaller peak does not seem to reduce the ultimate pullout tension.
- The results show sensitivity to pressure increase rate; a device for better control of the pressure rate is needed.
- The modified stub show acceptable and repeatable results for measuring adhesion.
- The device was also used for investigation of the adhesive behavior of emulsions. Results reveal that adhesive failure tension increases with curing time, ultimately converging toward the pullout tension of the neat binder.

Work Planned Next Quarter

The team will continue to work on developing test methods and procedures while producing repeatable data using the PATTI device. It will also be investigated as a surrogate method for conducting the Dynamic Shear Rheometer (DSR) tack test. While the response variables differ for each method, results may be correlated using the tack factor. In January 2009, the team will begin a full experiment to evaluate four aggregate surfaces (diabase, granite and two kinds of limestone); curing conditions; environmental conditions; and water/no-water conditioning. Collaboration with the University of Stellenbosch on cost-share basis has started, and a student at that university will be conducted parallel testing and providing data to the project.

CATEGORY M3: AGGREGATE SURFACE

Work Element M3a: Aggregate Surface Characterization (TAMU))

Work Done This Quarter

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.

Tasks completed this quarter include additional chemical and mineralogical analysis for the following aggregates: Lithonia granite (RA), basalt (RK), and Gulf Coast Gravel (RL). In addition, mineralogical samples were obtained for kaolinite, montmorillonite and chlorite. Specific accomplishments are highlighted in the tables below.

Surface energy measurements for quartz, microcline, calcite, labradorite, biotite, and olivine have been collected using the universal sorption device. The components of surface energy were calculated on replicates of the samples.

Sample preparation and aggregate surface characterization tasks completed this quarter are shown in the table below.

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

SHRP	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

Sample preparation and mineral surface characterization tasks completed this quarter are shown in the tables below.

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 (continued). 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
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

Table M3a.2 (continued). 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**
Muscovite	Mica	1	(1) > 65 grams acquired (G&G collection, Room 008) (2) Polished mount to be prepared	Preliminary quantitative chemical analysis acquired.
		2	In progress	In progress
Biotite	Mica	1	(1) > 175 grams acquired (G&G collection, B0857) (2) Polished mount to be prepared	In progress
		2	In progress	In progress
Biotite	Mica	1	(1) > 150 grams acquired (G&G collection, Room 008) (2) Polished mount to be prepared	Preliminary quantitative chemical analysis acquired.
		2	In progress	In progress
Calcite	Carbonate	1	(1) > 100 grams acquired (Mexico; RNG specimen) (2) Polished mount to be prepared	In progress
		2	In progress	In progress
Dolomite	Carbonate	1	Samples to be acquired	NA
		2	NA	NA

Table M3a.2 (continued). 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
Hematite	Iron Oxide	1	Samples to be acquired	NA
		2	NA	NA
Magnetite	Iron Oxide	1	Samples to be acquired	NA
		2	NA	NA
Ilmenite	Iron Titatium Oxide	3	> 100 g sample (Ontario; RNG specimen)	NA
Goethite	Iron Oxyhydroxide	1	Samples to be acquired	NA
		2	NA	NA
Kaolinite (KGA-1B)	Clay Mineral	3	Samples acquired	NA
		2	Samples acquired	In progress
Kaolinite	Clay Mineral	3	Samples acquired	NA
		2	Samples acquired	In progress
Montmorillonite (SAz-2)	Clay Mineral	3	Samples acquired	NA
		2	Samples acquired	In progress
Chlorite	Clay Mineral	3	Samples acquired; ~25 g Calumet and New Melones (RNG)	NA
		2	Samples acquired	In progress

Significant Results

Establishing a Surface Energy Predictive Model

One of the first goals will be to establish a model for predicting aggregate bulk surface energies based on mineralogical composition. Improved prediction of aggregate bulk properties pertinent to moisture damage susceptibility can lead to better methods to measure material properties and moisture damage susceptibility of asphalt/aggregate mixes. Development of a simple visual field test of aggregate surface energy properties will aid in on-site evaluation of aggregate moisture damage susceptibility.

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.

Methods – A Universal Sorption Device can be used to measure pure phase mineral surface energies by calculating the amount of a reference gas (water, hexane, and methylpropyl ketone in this case) sorbed to the mineral surface at various pressures. The adsorption isotherm for each reference gas is used to calculate equilibrium spreading pressure for each of the vapors along with the specific surface area (SSA) using the BET Equation. 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. The validity of the model will be tested by using the same Universal Sorption Device technique on the aggregate samples. A statistical analysis will be performed on the observed measurements versus predicted values.

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. Pure phase minerals are being collected by Dr. Ray Guillemette based on the findings of the SHRP. These minerals are the dominant constituents in all major aggregates of the study. The chosen minerals are listed in table 1.

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^{o} 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^{o} C for future analysis.

After each of the pure phase mineral surface energies have been quantified the SHRP aggregate samples themselves will be crushed and analyzed on the Universal Sorption Device to statistically determine the linear additive model's validity.

Data- The data gained from this experiment will be in $erg / (cm)^2$ for each pure phase mineral and SHRP aggregate. In order to calculate mineral surface energy the isotherm for each reference gas must be calculated. To obtain a full isotherm, the aggregate is exposed to ten equal increments of partial probe vapor pressure from vacuum to saturated vapor pressure. At each stage the adsorbed mass is recorded after it reaches equilibrium. The adsorbed mass of each stage is then used to plot the isotherm. The measured isotherm for hexane is then used to calculate the specific surface area (SSA) using the Branauer, Emmett, and Teller BET equation:

$$A = \left(\frac{N_m N_0}{M}\right)\alpha$$

where N_0=Avogadro's number; M=molecular weight of the probe vapor; α = projected area of a single molecule; and N_m=monolayer capacity of the aggregate surface. The specific surface area and each adsorption isotherm 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 γ^{Total} = total surface energy of the material; γ^{lw} = Lifhsitz–van der Waals or dispersive component; γ^{AB} = acid-base component; γ^{+} = Lewis acid component, and γ^{-} = Lewis base component.

Current Results

In order to use the Universal Sorption Device as an appropriate measuring device for surface energy the reproducibility must first be known. In order to test the reproducibility one of the SHRP aggregates was chosen at random and the surface energy was measured on the sorption device. The aggregate was RD-7, a shaly limestone composed primarily of calcite. Hexane and methylpropyl ketone were run in triplicate and water vapor was tested four times. The results indicated that there was a good deal of internal consistency between the test runs, and the overall surface energy calculation was within a 95 percent confidence interval to previous study of the aggregate over two years ago. In total 8 minerals are currently at various stages of testing. All minerals will be tested in triplicate for each vapor. The results to date are included in the following chart.

Mineral Surface Energy					
		Energy Components (ergs/cm^2)			
Mineral	SSA	LW	Acid	Base	Total
RD-7	0.23	48.97	0.52	467.57	80.27
Quartz	0.08	51.42	0.00	399.59	52.05
Microcline	0.07	61.63	1.04	194.15	90.09
Calcite	0.09	41.68	0.09	153.69	49.11
Biotite	0.05	52.51	0.07	809.98	67.41
Labradorite	0.08	39.72	0.03	1062.49	51.29
Andesine	0.07	40.64	0.40	4953.91	129.89
Albite	0.05	51.58	0.22	501.70	72.78
Siderite	0.02	NA	NA	NA	NA

Work Planned Next Quarter

Work planned in the next quarter includes continued analysis of the aggregates and minerals, with specific reference to surface energies.

CATEGORY M4: MODELING

Work Element M4a: Micromechanics Model (TAMU)

<u>Work Done This Quarter</u>

Lattice Micromechanical Model

The multi-scale virtual fabrication and lattice modeling (MS-VFLM) software is made computationally more efficient by rewriting the lattice modeling engine. The past version is based on general purpose finite element code and has significant overhead associated with the generality of the finite element code. The new engine is completely focused on lattice modeling and is substantially more efficient. The incorporation of special down-dating algorithm is near completion. In its final form, the new code is expected to be an order of magnitude more efficient than the existing MS-VFLM software. Separate from lattice modeling, with respect to linking continuum damage to fracture, the literature review is continuing with respect to proper micromechanical understanding of damage.

Cohesive Zone Micromechanical Model

The researchers at TAMU used the numerical micromechanical coupled model developed during the previous quarter to analyze the response of a two-dimensional sample of a real asphalt mixture that was subjected to the combined effects of moisture vapor diffusion and mechanical loading. The sample was composed by two real-shape aggregates embedded in a mastic matrix (figure M4a.1.). The model was implemented in the finite element software Abaqus® using the sequentially coupled moisture-mechanical scheme described in the previous 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.

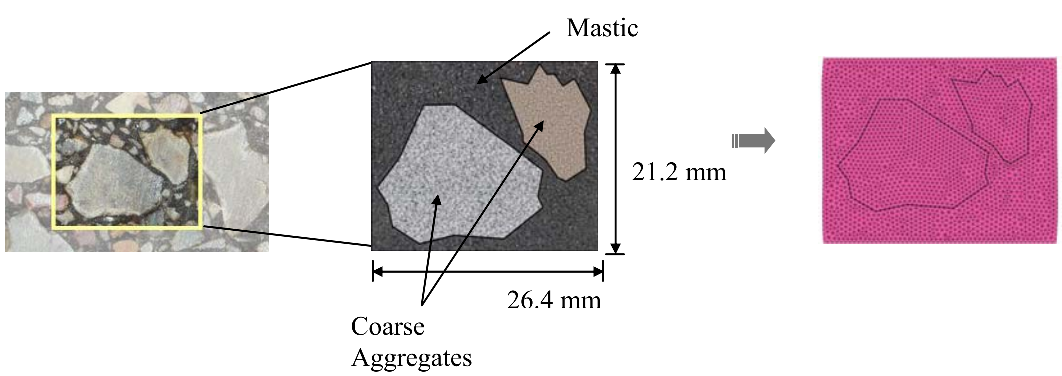

Figure M4a.1. Geometry and finite element implementation of a micromechanical model from a real asphalt mixture.

The simulations conducted were useful to:

- corroborate the coupling abilities of the model,

- analyze 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.2.),
- 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.

Recently, a comprehensive sensitivity analysis was initiated. A sample of a real asphalt mixture containing more aggregates (31 aggregates of different shape) and more complex geometry was designed to analyze the impact of different material properties, environmental conditions and loading conditions (type, magnitude and rates of loading) on the development of moisture damage.

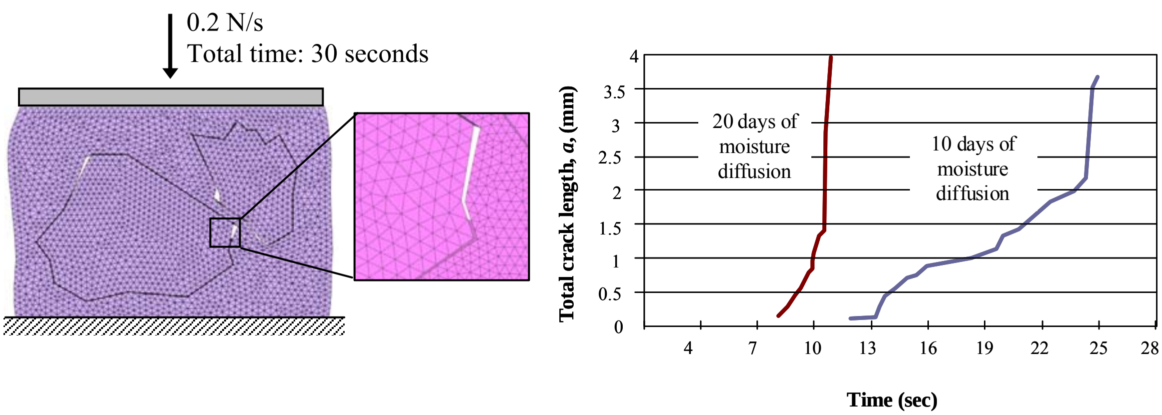

Figure M4a.2. Crack length at the interface vs. time during the mechanical test conducted on a sample subjected to 20 days of moisture diffusion and a sample subjected to 10 days of moisture diffusion (same boundary conditions).

Significant Results

Cohesive Zone Micromechanical Model

The model has proven to be successful in simulating the coupled moisture-mechanical damage occurring at the microscale level in asphalt mixtures. The simulations conducted during this quarter overcame one of the main challenges previously reported in relation to the incorporation of realistic microstructure geometry and realistic physical and mechanical material properties for the mastic and the aggregates. As a result of the work conducted during this quarter a technical paper titled "A Coupled Micromechanical Model of Moisture Damage in Asphalt Mixtures" was submitted for evaluation to the Journal of Materials in Civil Engineering, ASCE (November 2008).

Significant Problems, Issues and Potential Impact on Progress

Cohesive Zone Micromechanical Model

The incorporation of actual material properties for the aggregate-mastic interfaces (also called *adhesive zones*) continues being a challenge, although the advancements in the experimental work on adhesive fracture properties are expected to provide this information in the near future.

Work Planned Next Quarter

Lattice Micromechanical Model

The implementation and testing of the new MS-VFLM will be completed. Work will initiate on investigating the current limitations of lattice modeling in scaling up from binder to smallest scale mastic. With respect to linking continuum damage to fracture, literature review will continue on micromechanical description of damage as well as nonlocal damage mechanics.

Cohesive Zone Micromechanical Model

The research will focus on the sensitivity analysis initiated during this quarter. The main objective is to identify the relevance and impact of the geometrical, physical and mechanical parameters involved in the development of moisture-induced damage. In addition, it is expected to use the model to determine the effect of the internal void structure of asphalt mixtures (air voids sizes and distribution) in the development of moisture damage.

Work Element M4b: Analytical Fatigue Model for Mixture Design

See the progress reported under subtask F3b-1.

Work Element M4c: Unified Continuum Model

Work Done This Quarter

Work element F3c presents the development of the mechanical damage formulation as part of the TAMU continuum model. We have worked in the past 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; (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 jetting water flow imposed by passing traffic. 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.

Work Planned Next Quarter

The work will be on including the moisture damage formulation as part of the main formulation of TAMU continuum model. We will also conduct parametric analysis of the continuum model with different parameters in the moisture damage model. The parametric analysis results will be useful to verify that the model is capturing the main effects of moisture on the response of asphalt mixtures. We will compare the model results with limited data of the response of asphalt mixtures subjected to cyclic loading at different moisture conditions.

CATEGORY M5: MOISTURE DAMAGE PREDICTION SYSTEM

This area is planned to start later in the project.

Moisture Damage Year 2

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

LEGEND

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

Work planned

Work completed

Parallel topic

	Moisture Damage Year 2 - 5	Year 2 (4/08-3/09)				Year 3 (4/09-3/10)				Year 4 (04/10-03/11)				Year 5 (04/11-03/12)			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Adhesion																	
M1a	**Affinity of Asphalt to Aggregate - Mechanical Tests**																
M1a-1	Select Materials		DP														
M1a-2	Conduct modified DSR tests		P		P												
M1a-3	Evaluate the moisture damage of asphalt mixtures				DP		P			P							
M1a-4	Correlate moisture damage between DSR and mix tests						P		P								
M1a-5	Propose a Novel Testing Protocol				P				P				JP, F				
M1b	**Work of Adhesion**																
M1b-1	Adhesion using Micro calorimeter and SFE						JP				JP,F						
M1b-2	Evaluating adhesion at nano scale using AFM							JP					JP				JP, F
M1b-3	Mechanisms of water-organic molecule competition				JP						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	**Development of Model**																
M4a-1	Micromechanics model development				JP				JP				M&A	D	DP	F, SW	
M4a-2	Analytical fatigue model for use during mixture design															M&A,D	F
M4a-3	Unified continuum model								JP				M&A	D	DP	F, SW	

LEGEND

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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
[x]	Indicates completion of deliverable x

Work planned

Work completed

Parallel topic

PROGRAM AREA: FATIGUE

CATEGORY F1: MATERIAL AND MIXTURE PROPERTIES

Work Element F1a: Cohesive and Adhesive Properties

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

Work Done This Quarter

The work on improving the white paper relating the ideal work of fracture to the practical work of fracture was continued.

Work Planned Next Quarter

Improvements to this white paper will be made continually based on literature review. In addition, researchers plan to validate the findings from this paper in the context of bituminous materials by accomplishing the various subtasks in this work element.

Subtask F1a-2: Develop Experiment Design (TAMU)

Work Done This Quarter

The experiment design was completed and reported previously.

Work Planned Next Quarter

At this time, researchers do not anticipate any changes to this experiment design. However, as the work progresses in this subtask and in the area of modeling, some refinement to the proposed experiment design may be required in future.

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

Work Done This Quarter

The objective of this subtask is to provide the surface free energy of asphalt binders that will be used in other subtasks as a material property input or for the comparison with results from other test methods. Based on the requirements from other tasks, tests under this subtask will be ongoing through the remainder of this project.

Work Planned Next Quarter

Based on the requirements from other tasks, tests under this subtask will be ongoing through the remainder of this project.

Subtask F1a-4: Mechanical Work of Adhesion and Cohesion

Work Done This Quarter

The sample preparation and testing protocol were refined this quarter. Many of the problems encountered last quarter were overcome. Three asphalt binders from the AASHTO Material Reference Library, AAB, AAD, and ABD, were chosen for use in this study. They were chosen due to their wide range of surface free energy values. Based on fracture theory, AAD had the lowest surface free energy, ABD had the highest surface free energy, and AAB was in between. All three asphalt binders were initially tested using a film thickness of 15-µm. In addition, a film thickness sweep was run on all asphalt binders to determine where the transition thickness between cohesive and adhesive failure was.

The main problem encountered this quarter was variability in the results. There were two causes for this variability. Both were the result of problems in the sample preparation. The first came from thermal expansion of the sample holders and subsequent preparation fixture. An AR 2000 Rheometer from TA Instruments was used for the sample preparation because of its fine gap resolution. Around 5 inches of metal was heated to 150^0C. Even though the software is supposed to auto correct for this, the initial gap setting was off by 300-µm after heating of the sample holders. To adjust for this the sample holders would have to be incrementally lowered as they cooled. This process; however, was very time consuming and did not guarantee the correct gap was reached due to inequalities in the starting and ending temperatures of the preparation fixtures. Due to this, a new preparation procedure was developed to be more efficient and eliminate errors. In brief: a propane torch is used to heat only the testing surface of the top and bottom sample holders. This step was performed to remove water vapor and organic matter from the surface and achieve better adhesion of the asphalt binder to the metal substrate. The environmental chamber on the rheometer is not used. The second was from the alignment of the sample faces. It was assumed that the sample faces were parallel after insertion into preparation fixture. It was found later that there were small misalignments between the sample faces that were increasing the variability of the results. Once these were discovered, they were adjusted for and practically eliminated. The new results are currently being measured and have not been analyzed.

Significant Problems, Issues and Potential Impact on Progress

The results based on the new protocol described above need to be analyzed. It is anticipated that this would remedy the problems associated with high variability that has caused some delay in this subtask.

Work Planned Next Quarter

Researchers will finish executing the tests as per the experiment design developed in Subtask F1a-4 and reported in the previous quarterly report.

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

Work Done This Quarter

No activity was planned for this quarter.

Work Planned Next Quarter

Work on this subtask is planned in year 4 of this project.

Work Element F1b: Viscoelastic Properties (Year 1 start)

Subtask F1b-1: Separation of Nonlinear Viscoelastic Deformation from Fracture Energy under Cyclic Loading (TAMU)

Work Done This Quarter

The main objective of this task was to develop an approach to determine the following three main aspects of material response during cyclic loading:

i) identify the limiting stress or strain amplitude that results in a nonlinear viscoelastic response without causing damage,

ii) model and monitor the change in the nonlinear viscoelastic parameters with increasing number of load cycles, and

iii) model and monitor the change in the nonlinear viscoelastic parameters within each cycle.

Researchers have made significant progress to achieve the first two steps. The third step is currently in progress. The literature on different constitutive equation and models for modeling nonlinear viscoelastic behavior of material showed that Schapery's single integral is very capable and also the simplest tool to deal with nonlinear viscoelastic behavior. This model contains four viscoelastic parameters for functions. All of these functions are equal to one at low stress or strain level, linear region. These parameters can be defined as a function of stress or strain depending on the approach. Schapery's non-linear viscoelastic model has been extensively applied for isotropic and anisotropic materials. Numerical integration methods for non-linear viscoelastic constitutive models, within a finite element (FE) formulation, have been explored for both isotropic and anisotropic materials. Recursive numerical integration algorithm, as reported in subtask F1b-2, is an example of one of these methods. The objective of this task is to develop a simpler analytical expression for the response of a non-linear material subjected to cyclic loading. The ultimate goal of this analytical tool is to accurately characterize fatigue cracking resistance of materials.

The first step towards developing an analytical solution to characterize the response of non-linear viscoelastic materials subjected to dynamic loading is 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 is being carried out using available creep-recovery data for a non-linear viscoelastic adhesive material (figure F1b.1). 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.2.)

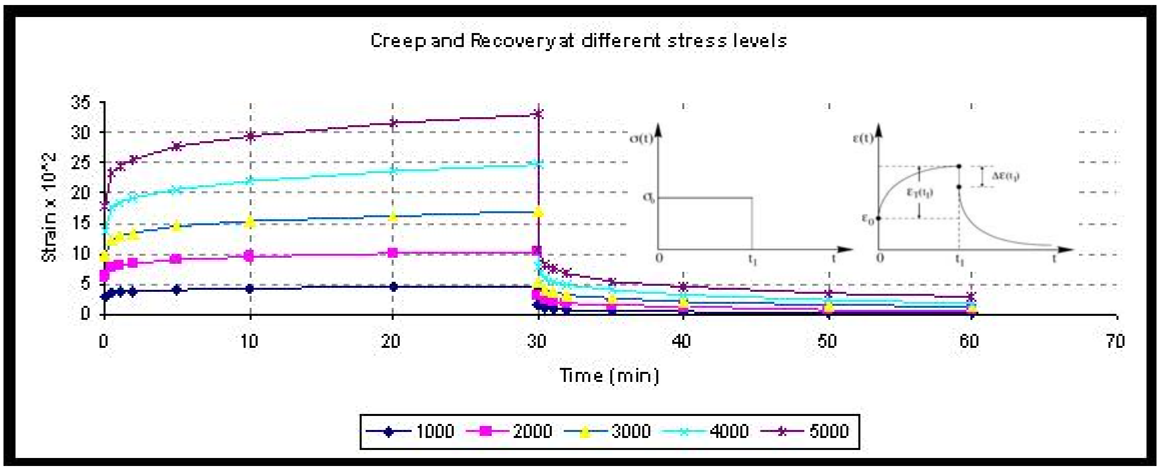


Figure F1b.1. Sample creep-recovery data used to obtain the four non-linear parameters following the approach developed by Schapery.

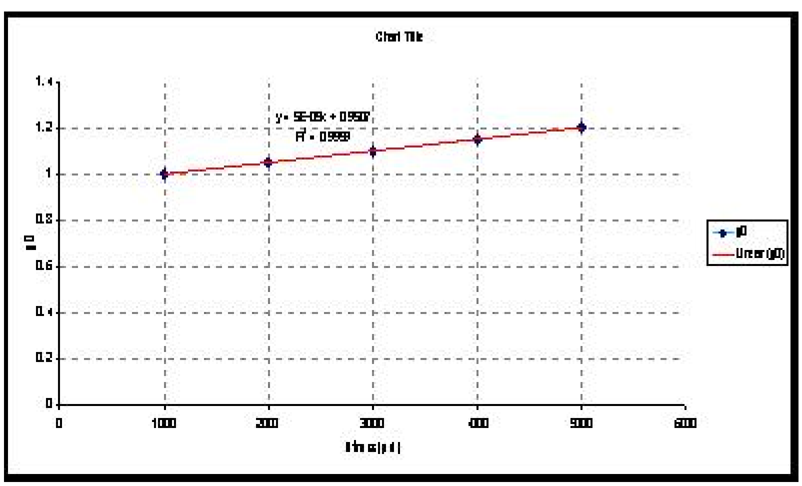


Figure F1b.2(a). g_0 as a bilinear function of stress.

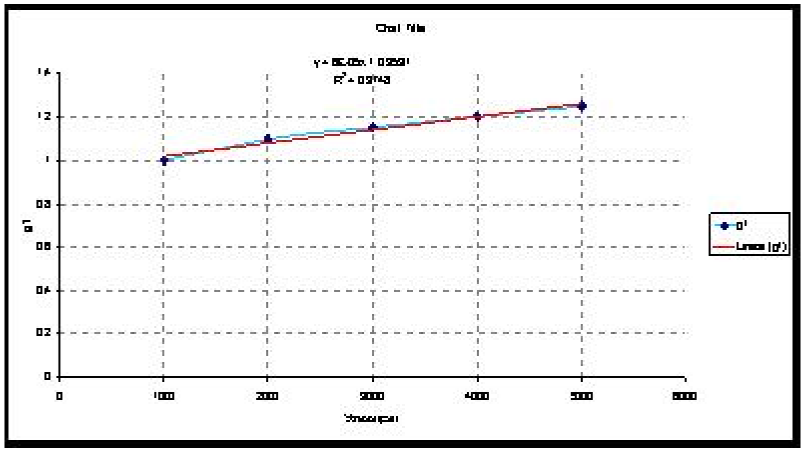


Figure F1b.2(b). g_1 as a bilinear function of stress.

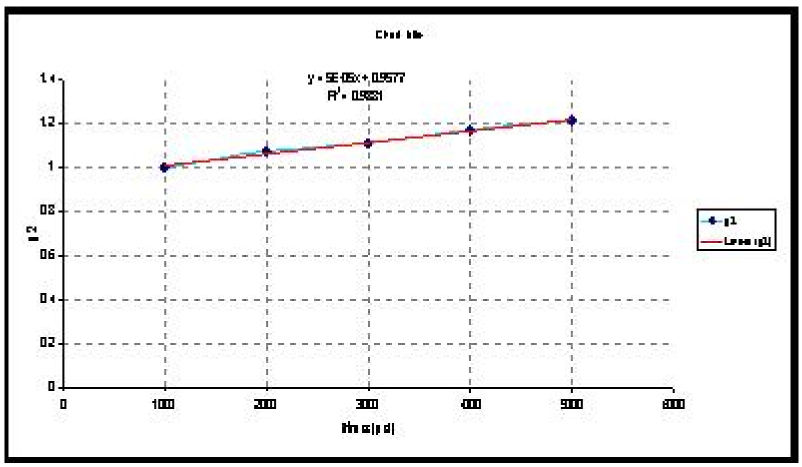


Figure F1b.2(c). g_2 as a bilinear function of stress.

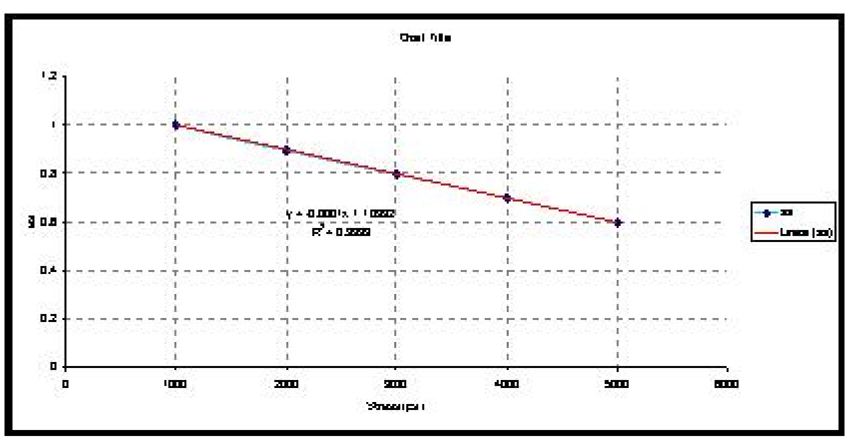


Figure F1b.2(d). a_σ as a bilinear function of stress.

Work Planned Next Quarter

The parameters determined above will be used in the modified form of the convolution integral to predict response of the material under dynamic loading. Also, tests will be conducted on typical asphalt binders to determine the non-linear parameters. The model will then be used to predict the response of the same material subjected to dynamic loading.

Subtask F1b-2: Separation of Nonlinear Viscoelastic Deformation from Fracture Energy under Repeated and Monotonic Loading

Work Done This Quarter

No work was conducted in this subtask.

Work Planned Next Quarter

The analysis approach developed under subtask F1b-1 will be applied to monotonic data.

Work Element F1c: Aging

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

Work Done This Quarter

There is no literature review work this quarter.

Work Planned Next Quarter

Review of previous work is an ongoing effort.

Subtask F1c-2: Develop Experimental Design (TAMU)

In this quarter, a draft detailed experimental design was completed and submitted to FHWA. The work plan objectives are:

(1) to determine fundamental mixture parameters that control the decline of mixture fatigue resistance with aging (Subtask F1c-4 including polymer modified asphalt materials in Subtask F1c-5) by using enhanced mixture testing protocols developed in Work Element F2c

(2) to validate transport model of binder oxidation (Subtask F1c-3 including polymer modified asphalt materials in Subtask F1c-5)

Table F1c-2.1 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, critical information, together with the binder oxidation model of subtask F1c-3, for modeling mixture performance in pavements over its service life.

Table F1c-2.1. 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 $\pm$ 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-2.2 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-2.2. Summary of testing input and output 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

Significant Results

The pilot experiment design was completed, and specimen fabrication (Subtask F1c-4) continued in preparation for beginning work on the planed experiments in the next quarter.

Significant Problems, Issues and Potential Impact on Progress

Further review of the core materials for use in the expanded experiment and of additional field sites for validation is needed.

Work Planned Next Quarter

Conducting the laboratory experiments of the experimental design that use the improved testing protocol (work element F2c) will begin in the next quarter. Also, additional field sites for use in validation of the transport oxidation model and for evaluating the impact of binder oxidation on fatigue will be considered.

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

Work Done This Quarter

Work this quarter combined the pavement temperature and binder oxidation models. This integrated model now can be used to calculate binder oxidation rates in a pavement for a specific asphalt binder, air void characteristic and pavement location (where site-specific model parameters for the temperature prediction model are available).

Key parameters for the pavement binder oxidation model are the binder reaction kinetics properties and air void characteristics of the pavement. These key parameters will need to be estimated if they are not otherwise available. To demonstrate this capability, work this quarter used a least squares parameter estimation procedure to estimate unknown parameters by comparing aging rates obtained for compacted mixtures aged in a 60 C Environmental Room (ER) to those calculated by the integrated model. The parameters that have been estimated are the binder reaction kinetics parameters (frequency (pre-exponential) factor (A) and the activation energy (E_a)) and mixture properties (the asphalt volume fraction (ε), tortuosity (τ), and binder film thickness). After the parameters were estimated, they were used in the pavement binder oxidation model integrated with the pavement temperature prediction model to calculate a pavement aging rate under the actual varying pavement temperature conditions.

As an initial trial of the procedure, the pavement temperature profiles estimated by the temperature model at different depths of State Highway 21 in Bryan, Texas during the year of 1994 were used as reaction temperatures in the calculations. The oxidation rates of asphalt binder (Exxon AC-20) obtained from the model compared quite well to the aging rates measured from the SH-21 field cores for 1994 and reported by Glover et al. (2005).

Significant Results

Significant progress on model parameter estimation has considerably increased the applicability of the integrated pavement oxidation model. The pavement binder oxidation model is an important capability for predicting the asphalt binder physical properties in pavements.

Significant Problems, Issues and Potential Impact on Progress

Further binder oxidation model validation is needed. More actual pavement aging rates need to be compared to model calculations. Also, air void characteristic data for the corresponding pavements should be obtained or measured. Higher resolution X-ray CT scans are being evaluated for their ability to provide these air void data. If these air void characteristic data are not available, then parameter estimation method will be employed.

Work Planned Next Quarter

As the pavement temperature prediction model is further developed, the temperature calculations would tremendously benefit the pavement research that is thermally related. The coordination with the research groups that require accurate temperature prediction model to study the thermal cracking in pavement, for example, the inter-mountain region research group, will be initiated.

Pavement oxidation simulations of more climate regions throughout the country will be conducted to investigate the effect of asphalt binder oxidation under those specified weather conditions.

Cited Reference

Glover, C. J., R. R. Davison, C. H. Domke, Y. Ruan, P. Juristyarini, D. B. Knorr, and S. H. Jung, "Development of a new method for assessing asphalt binder durability with field validation," Report FHWA/TX-03/1872-2, 2005, Texas Transportation Institute, College Station, TX.

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

Work Done This Quarter

In this quarter, specimen fabrication for the pilot experiment (Subtask F1c-2) continued. Additionally, further development of the testing protocol proceeded under work element F2c.

Significant Problems, Issues and Potential Impact on Progress

Resolution of problems with the MTS equipment used for direct tension continued this quarter. In addition, upgrading the existing TTI MTS system and the purchase of a second MTS system for mixture testing by TTI has proceeded and we are awaiting these equipment installations.

Work Planned Next Quarter

Mixture testing utilizing the enhanced CMSE* testing protocol (Work Element F2c) will commence for the pilot experiment specimens. Beginning this testing has been delayed due to equipment issues (above). At the end of the protocol, binder extraction, recovery, and property measurements will also commence. Also, AV characterization (total air voids and water accessible air voids) through determination of specific gravities and X-ray CT and image analysis will commence.

Binders from field samples obtained from selected sites will be extracted and recovered for binder physical property measurements. These results together with the specific information on type of binder, type of mixture and climatic data will be used to conduct the pavement binder oxidation model validation process.

Subtask F1c-5: Polymer Modified Asphalt Materials (TAMU)

<u>Work Done This Quarter</u>

No activity this quarter.

<u>Work Planned Next Quarter</u>

No work planned.

Work Element F1d: Healing

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

<u>Work Done This Quarter</u>

The literature review was continued in this quarter.

<u>Work Planned Next Quarter</u>

This is an ongoing subtask that will be continued through this project.

Subtask F1d-2: Select Materials with Targeted Properties (TAMU)

<u>Work Done This Quarter</u>

The work on comparison of molecular morphology to healing rates was continued this quarter. A paper relating the intrinsic healing properties to the molecular morphology was submitted to ASCE for consideration. The findings from this paper were based on molecular dynamics simulations and were consistent with healing hypothesis and experimental work done by Kim, Little and co-workers earlier.

<u>Work Planned Next Quarter</u>

In the next quarter we will determine the morphological properties such as MMHC ratio for the six asphalt binders using the FTIR and compare these properties to the long term intrinsic healing characteristics of the asphalt binders measured using the DSR. We will also try to include the core materials subject to availability.

Subtask F1d-3: Develop Experiment Design (TAMU)

Work Done This Quarter

A preliminary experiment design was developed and discussed with other consortium members to ensure that there was no duplication of effort.

Work Planned Next Quarter

A detailed experiment design to validate the healing model and properties will be developed after making significant progress in subtasks F1d-2 and F1d-4. The information from these tasks is necessary in order to develop an efficient experimental design. We anticipate that the experiment design will be developed in the last quarter of this project year or early in the next project year (late spring).

Subtask F1d-4&5: Investigate Test Methods to Determine Material Properties Relevant to Asphalt Binder Healing (TAMU)

Work Done This Quarter

One of the material properties related to the self-healing in asphalt binders is the self-diffusivity of bitumen molecules. Molecular modeling work from subtask F1d-2 demonstrates that MMHC ratio can be related to the self-diffusivity and consequently to the long term healing rate of asphalt binders. Researchers have done some preliminary work to determine the MMHC ratio for the selected asphalt binders.

Work Planned Next Quarter

Complete measuring the MMHC ratio for the same set of five asphalt binders that were used with the DSR to determine the intrinsic healing function.

Subtask F1d-5: Testing of Materials <u>for model validation</u>* (TAMU)

*Note: Title of the subtask was changed to clarify that the testing in this subtask is not to obtain material properties but to validate the model. The former is accomplished in subtask F1d-4.

Work Done This Quarter

No work planned.

Work Planned Next Quarter

Work in this subtask is planned for later after completion of Subtask F1d-3.

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

Work Done This Quarter

This quarter, the research team continued to develop protocols for determining the healing of fatigue damage in asphalt binder. The focus has been primarily on applying the index methods described in the Year 2 work plan for repeated cyclic loading with rest periods. The team has applied the methods of Texas A&M University (healing potential index, or HPI) used for mastics and the University of Genoa (healing index, or HI) used for binder. Results of this analysis were mixed, as variability still appears to be an issue in some cases. However, issues regarding the variability of time sweep fatigue testing appear to be under control.

Significant Results

Researchers applied two methods of measuring the healing properties of fatigue damage to two binders: PG 58-28 and PG 64-22. The procedures for the three types of tests (Time Sweep, Time Sweep with 1 Rest Period and Time Sweep with 10 Rest Periods) are described in detail in the ARC Q3 2007 report. The calculations for the index parameters are described below.

Texas A&M University, HPI:

$$HPI = \frac{A - B}{A},$$

where A and B are the absolute value of the slope of the normalized modulus versus the number of cycles plot (representing microcracking speed) with and without rest periods, respectively.

University of Genoa, HI:

$$HI = \left| \frac{W_{Reload} - W_{Load}}{W_{Load}} \right|,$$

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

HPI and HI results are given in table F1d-6.1, along with the original time sweep number of cycles to 50% $|G^*|$ for comparison. The normalized modulus versus number of cycles plots are also shown in figures F1d-6.1 and F1d-6.2.

Table F1d-6.1. Results from healing of fatigue damage index measurements.

Binder	Test Method	Replicate	No. of Cycles to 50% |G*|	HPI (TAMU)	HI (Genoa)
PG 64-22	Time Sweep (TS)	1	40,050		
		2	41,019		
		3	41,999		
	TS - 1 Rest Period	1			0.357
		2			0.519
		3			0.485
	TS - 10 Rest Periods	1	65,747	0.394	
		2	49,476	-0.007	
PG 58-28	TS	1	32,284		
		2	30,585		
	TS - 1 Rest Period	1			0.291
		2			0.305
	TS - 10 Rest Periods	1	39,767	0.211	
		2	37,585	0.088	

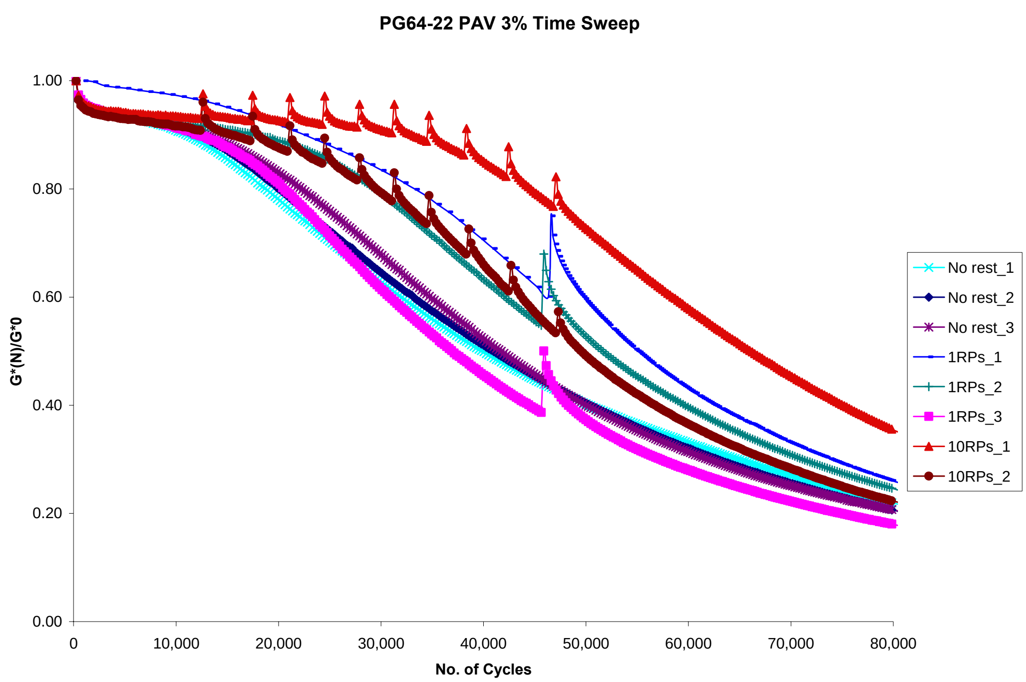


Figure F1d-6.1. Graph. Fatigue damage plots for PG 64-22.

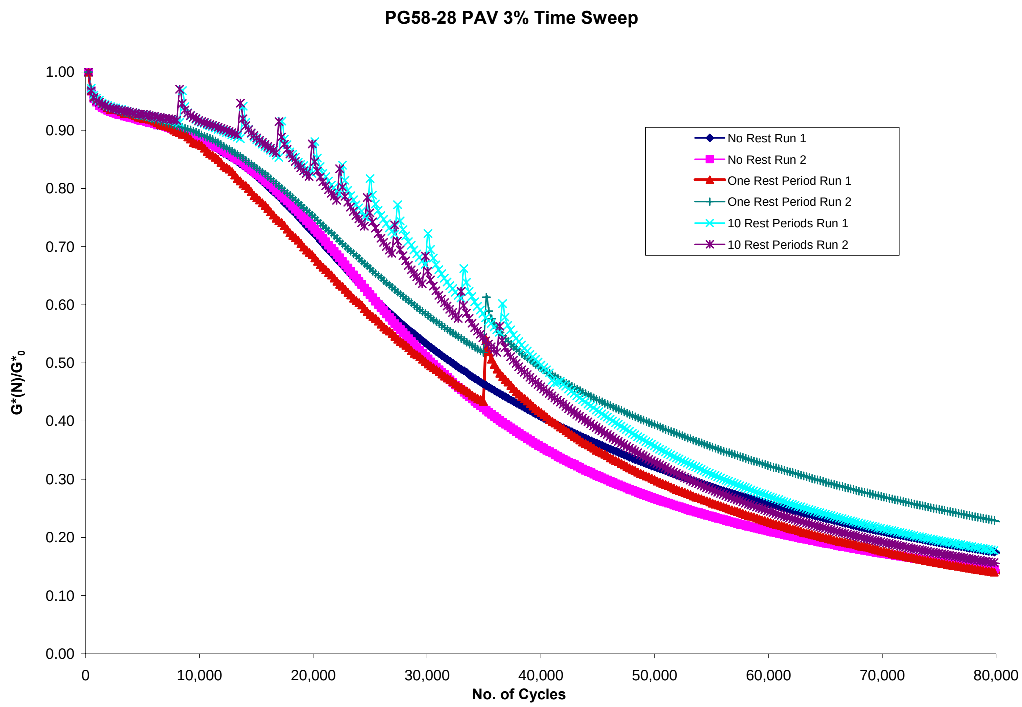


Figure F1d-6.2. Graph. Fatigue damage plots for PG 58-28.

Table F1d-6.1 shows that with carefully controlled specimen preparation, the time sweep number of cycles to 50% $|G^*|$ appears to yield consistent results. Further, the University of Genoa HI values appear to be reasonably consistent, although the fatigue damage plots do not appear to be as consistent. HPI values have significant variability, but it is apparent from the fatigue damage plots that the tests were not repeatable, and further work on the test protocol may be necessary to properly evaluate the HPI of these materials.

Significant Problems, Issues and Potential Impact on Progress

Variability with the Multiple Rest Period Cyclic Test procedure has led to inconsistent results. The team will examine this procedure to determine what actions (if any) are necessary to reduce variability. If this issue remains unresolved, the multiple Rest Period Cyclic Test procedure will be eliminated from the testing matrix.

Work Planned Next Quarter

Work will continue in accordance with the testing matrix described in the Year 2 work plan, with additional work being performed to further develop the proposed Damage-Healing Test described in the ARC Q3 2008 report. The team plans to finalize a procedure for the Damage-Healing Test next quarter and perform further investigation into the aforementioned repeatability issues.

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

Work Done This Quarter

In this quarter, data analysis of a backlog of experimental results to determine physico-chemical properties of the various asphalt systems including chemical potentials and phase separation phenomena continued. The data obtained from these analyses are used for the asphalt microstructure model discussed in the Year 2 Work Plan for Work Element F3a. The data generated from these analyses will then be incorporated into the chemo-mechanical models of asphalt and asphalt mastic structures.

Work Planned Next Quarter

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).

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

Work Done This Quarter

No work planned for this quarter.

Work Planned Next Quarter

Work on this subtask is scheduled for later years of this research.

CATEGORY F2: TEST METHOD DEVELOPMENT

Work Element F2a: Binder Tests and Effect of Composition (UWM)

Work Done This Quarter

In this quarter, the research team continued analyzing data obtained in Q3 2008 using the following tests: the Binder Yield Energy Test (BYET), the stress sweep test and the frequency sweep test.

Significant Results

Tables F2a.1 and F2a.2 show that as the polymer concentration is increased, the Binder Yield Energy (BYE) increases. At 2% wt linear styrene-butadiene-styrene (LSBS), BYE does not increase significantly compared with the unmodified binder. Heavily modified binders dramatically increase the BYE. Elvaloy® (ELV)-modified binders give a BYE higher than LSBS-modified binders by one order of magnitude.

Table F2a.1. BYET results (kPa) for FH-modified binder.

	Run 1	Run 2	Average	Standard Deviation	Coefficient of variation, %
FH NEAT PAV	305.16	339.19	322.17	24.06	7.47
FH 2LSBS PAV	439.61	391.15	415.38	34.27	8.25
FH 0.7ELV PAV	1896.19	2116.14	2006.17	155.53	7.75
FH 4LSBS	353361.54	448251.03	400806.28	67097.00	16.74
FH 1.5 ELV	2947941.34	3130905.32	3039423.33	129375.07	4.26

Table F2a.2. BYE and strain at maximum stress for FH-based binder.

	Run 1	Run 2	Average	Standard Deviation	Coefficient of variation, %
FH NEAT	1.90	2.20	2.05	0.21	10.35
FH 2LSBS	1.50	1.40	1.45	0.07	4.88
FH 0.7ELV	5.60	6.40	6.00	0.57	9.43
FH 4LSBS	1.13	1.48	1.30	0.25	18.97
FH 1.5 ELV	9.48	8.33	8.90	0.81	9.14

Figure F2a.1 shows the variation of stress versus strain for FH neat and FH modified with 4% LSBS and 1.5% ELV.

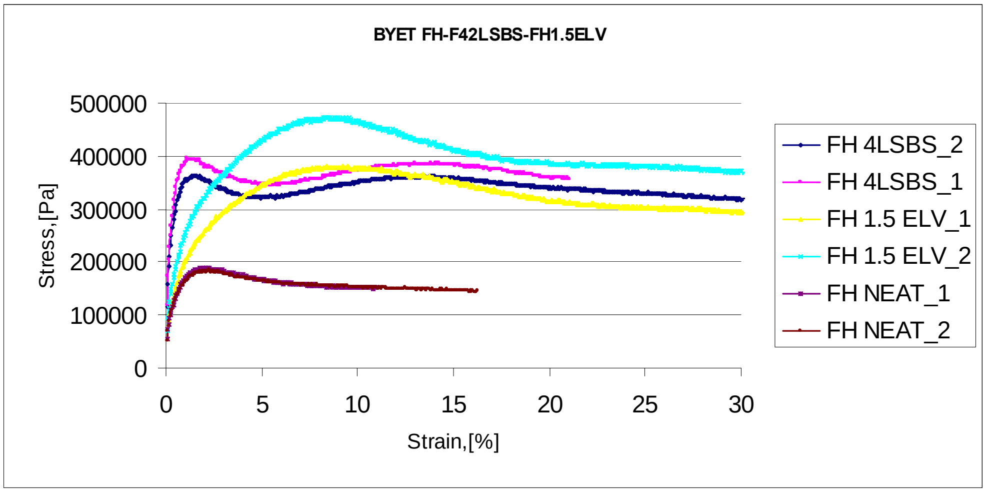


Figure F2a.1. Graph. Stress versus strain for FH-based binder.

A similar trend was observed for the yield energy on CRM-based binder (tables F2a.3 and F2a.4).

Table F2a.3. BYET results (kPa) for CRM-based binder.

	Run 1	Run 2	Average	Standard deviation	Coefficient of variation, %
CRM NEAT	166.95	186.22	176.58	13.62	7.72
CRM 2LSBS	1523.36	1577.98	1550.67	38.62	2.49
CRM 0.7ELV	1492.20	1082.75	1287.47	289.53	22.49
CRM 4LSBS	317315.77	251589.13	284452.45	46475.75	16.34
CRM 1.5 ELV	1748761.26	1674945.44	1711853.35	52195.67	3.05

Table F2a.4. BYE and strain at maximum stress for CRM-based binder.

	Run 1	Run 2	Average	Standard deviation	Coefficient of variation, %
CRM NEAT	2.19	2.44	2.32	0.18	7.64
CRM 2LSBS	11.53	12.04	11.79	0.36	3.06
CRM 0.7ELV	10.59	7.83	9.21	1.95	21.19
CRM 4LSBS	2.49	1.59	2.04	0.64	31.34
CRM 1.5 ELV	10.48	10.59	10.53	0.08	0.75

Table F2a.5 presents the stress value at which the complex modulus is reduced by 50% for FH-based binders.

Table F2a.5. Stress sweep results for FH-based binders.

	50% Complex Modulus, kPa					Stress, kPa				
	Run 1	Run 2	Average	STDEV	Coeff of variation,%	Run 1	Run 2	Average	STDEV	Coeff of variation,%
FH 4LSBS	19550	19350	19450	141.42	0.73	1100	1090	1095	7.07	0.65
FH1.5 ELV	14100	13900	14000	141.42	1.01	930	916	923	9.90	1.04
FH NEAT	14250	16150	15200	1343.5	8.84	942	946	944	2.83	0.30
FH 0.7 ELV	18550	18550	18550	0.00	0.00	1060	1000	1030	42.43	4.12
FH 2LSBS	20950	18600	19775	1661.7	8.40	1140	1090	1115	35.36	3.17

These data show that the stress at which complex modulus is 50% from the initial value does not change by increasing polymer concentration. The same results are plotted as complex modulus versus stress in figure F2a.2.

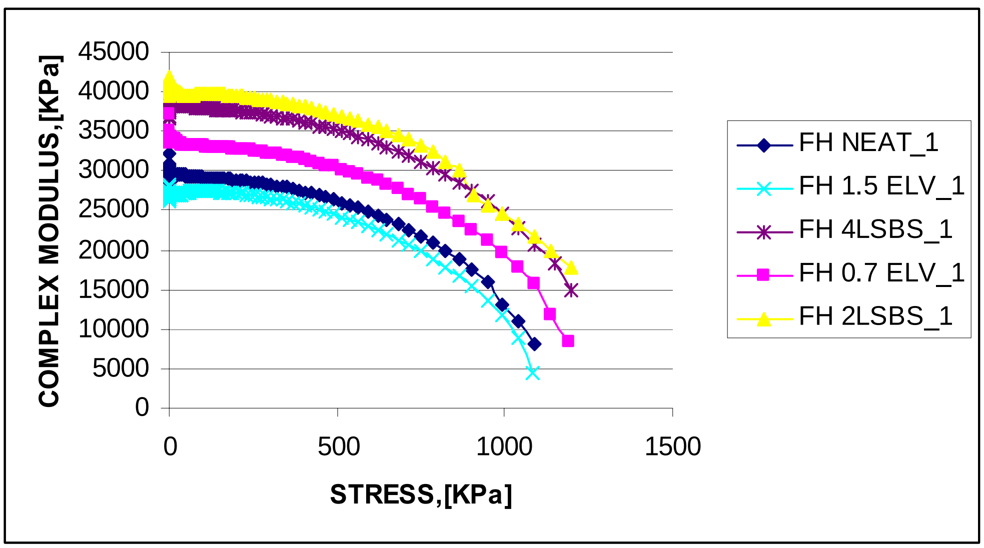


Figure F2a.2. Graph. Complex modulus versus stress for FH-based binder.

Similar results were obtained for CRM-based binder.

Figure F2a.3 shows an example of master curve build for FH un-aged binder:

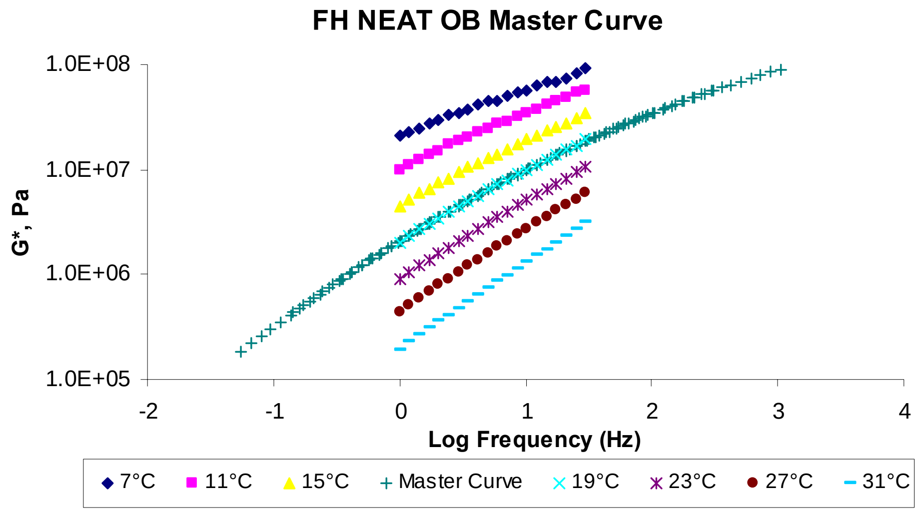


Figure F2a.3. Graph. Master curve FH original binder.

Figure F2a.4 shows the variation of phase angle with frequency for the FH original binder.

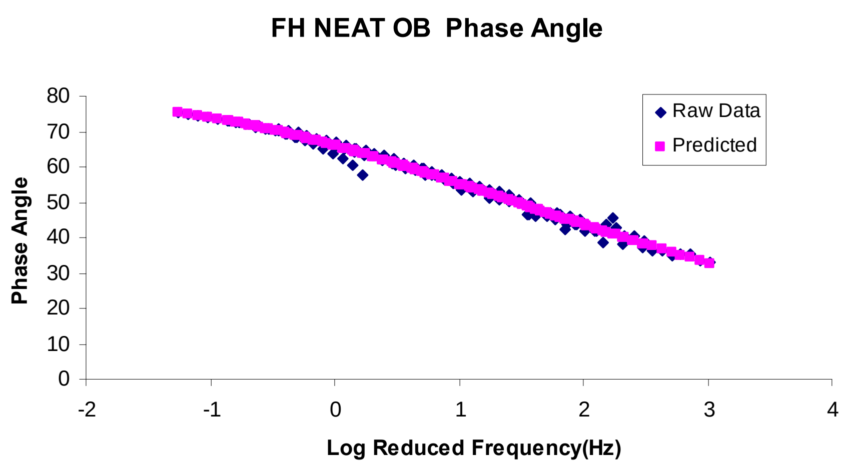


Figure F2a.4. Graph. Phase angle versus frequency FH original binder.

Similar master curves were obtained for all the materials included in the F2a work plan. Multiple Stress Creep and Recovery (MSCR) tests were also performed, but data analysis was not complete by the time this report was finalized.

<u>Work Planned Next Quarter</u>

Next quarter, the team will continue data analysis and start blending the selected binders with the other additives included in the work plan (Elvaloy AM, Radial SBS). The team will also start aging these materials.

Work Element F2b: Mastic Testing Protocol (TAMU)

<u>Work Done This Quarter</u>

Improvements to the test protocol to determine fatigue-cracking resistance of FAM specimens using the DMA were made in Subtask F1b-1. Further work on this subtask will be carried out in coordination with the technology development area. The tentative protocol was presented to the mixture ETG at the semi-annual meeting in Reno, NV.

<u>Work Planned Next Quarter</u>

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

Work Element F2c: Mixture Testing Protocol (TAMU)

<u>Work Done This Quarter</u>

A technical report, entitled *Aging Experiment Design Including Revised CMSE* Testing Protocols and Analysis to Characterize Mixture Fatigue Resistance*, was completed and submitted to the Federal Highway Administration (FHWA). This report has been distributed to the Expert Task Group (ETG) of the FHWA. This report detailed the mixture testing protocols and data analysis methods that were developed in this quarter and previous quarters. These test protocols included tensile strength test, viscoelastic characterization (VEC) test, revised repeated direct tension (RDT) test, and X-Ray Computed Tomography test. These test protocols were able to characterize both undamaged and damaged properties of asphalt mixture specimens.

The VEC test protocol was designed to characterize the undamaged properties of asphalt mixtures under tensile loading. The undamaged properties of asphalt mixtures are the basis of inferring both fracture and plastic damage as well as moisture damage and aging effects using the Dissipated Pseudo-Strain Energy (DPSE) approach. The VEC tensile test protocol was summarized in a technical paper (Luo and Lytton 2008), which was submitted to and is currently under review by the *Journal of Transportation Engineering*, American Society of Civil Engineers. This paper was scheduled to be presented in the Transportation Research Board (TRB) AFK50 (1) Subcommittee Meeting in the 88^{th} TRB Annual Meeting in Washington, D.C., January, 2009.

The revised RDT test protocol was designed to characterize the damaged properties of asphalt mixtures, including both fracture damage and plastic deformation. Figure F2c.1 shows the loading configuration for the revised RDT test. There were nine different rest periods in decreasing order after each 1000-cycle loading interval to allow the asphalt mixture specimen to relax and to evaluate the damage and healing levels. A data analysis approach was developed to quantify the fracture damage and plastic deformation that were produced by the repeated cyclic loading. Hysteresis loops were used to illustrate the relationships between stress and applied strain, and between stress and pseudo strain. The rate of DPSE accumulation was determined as the slope of DPSE (W_{R1}) versus the logarithm of the number of load cycles (Log N) in figure F2c.2. This protocol was also able to characterize the short-term and long-term healing properties using three healing parameters. These parameters were (1) ratio of difference between the modulus of the first load cycle in the first 1000 cycles; (2) ratio of difference between dissipated energy after healing and that before healing with respect to the original dissipated energy in the first 1000 cycles; and (3) difference of dissipated pseudo strain energy before and after healing divided by the dissipated pseudo strain energy in the first 1000 cycles. The revised RDT test protocol and data analysis were drafted in three technical papers (Luo et al. 2009a, 2009b, 2009c) and will be submitted to technical journals.

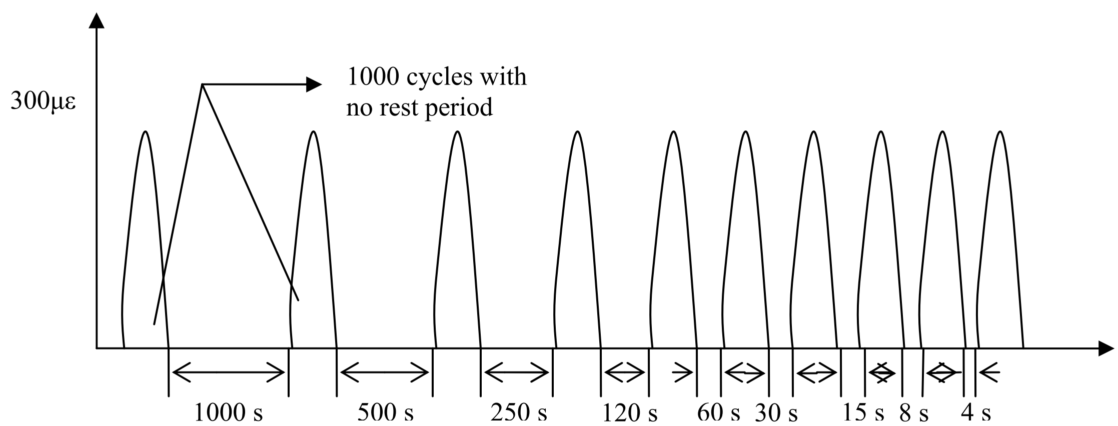


Figure F2c.1 Loading configuration for revised RDT test.

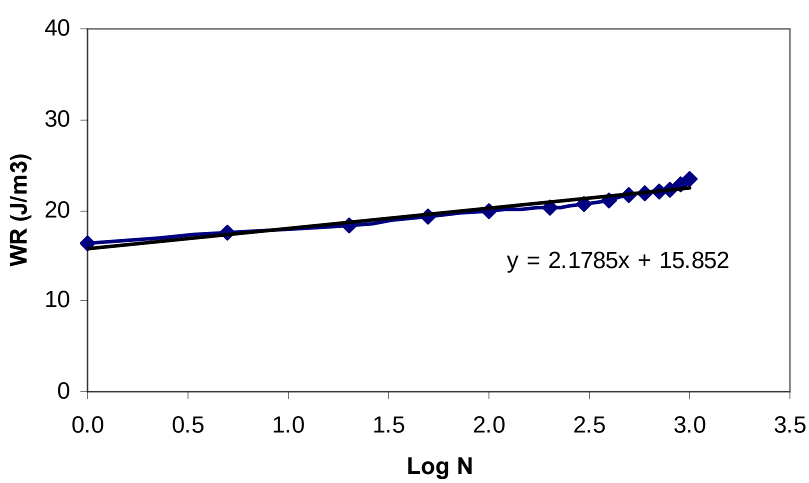


Figure F2c.2 Relationship between DPSE and number of load cycles.

In addition to the test protocols detailed in the aforementioned technical report, a new test protocol was developed to characterize the anisotropic viscoelastic properties of undamaged asphalt mixtures under compressive loading. The Universal Testing Machine (UTM) and the available Rapid Triaxial Test (RaTT) Cell were used to conduct the test on cylindrical asphalt mixture specimens with a diameter of 6 inches and height of 6 inches. Three test scenarios were performed in order to obtain the viscoelastic Poisson's ratios and compliance/modulus in both the vertical (axial) and horizontal (radial) directions. The compliance and modulus were determined as complex functions of frequency, from which the magnitude and phase angle of the compliance/modulus were calculated.

Significant Results

Test protocols were developed to characterize: 1) the undamaged properties of asphalt mixtures under tensile and compressive loading; and 2) damaged properties of asphalt mixtures including fracture damage and plastic deformation. A data analysis approach was developed to determine the DPSE and to separate the energy used for developing cracks from the energy used for developing plastic deformation. The test protocols and data analysis methods were detailed in a technical report that was submitted to the FHWA and was distributed to the FHWA ETG members by the FHWA. Four technical papers on the test protocols were drafted and submitted or will be submitted to technical journals.

Significant Problems, Issues and Potential Impact on Progress

Since the Material Test System (MTS) was not able to control the specimen displacement at a constant level, a new data acquisition system for the MTS was ordered to replace the old one. With the new data acquisition system, it is expected that the MTS equipment will be able to control the Linear Variable Differential Transformers (LVDTs) to obtain reliable data.

The available RaTT Cell was designed to determine the anisotropic viscoelastic properties of asphalt mixtures under compressive loading using a six inch high by six inch diameter specimen. In order to use this size cell, lab-mixed-lab-compacted (LMLC) specimens were not cored to a smaller diameter. However, it was found that their non-uniformly distributed air voids had a significant impact on the test results, which therefore were not reliable. To eliminate this non-uniform aid void distribution, a new RaTT Cell was ordered that was designed to test a specimen with four inch diameter and four or six inch height.

The new data acquisition system of the MTS and the new RaTT Cell will be delivered in January 2009.

Work Planned Next Quarter

The new RaTT Cell will be used to test the undamaged anisotropic viscoelastic properties of the asphalt mixtures with four inch height and four inch diameter. The test will determine the Poisson's ratio, compliance and modulus of the asphalt mixtures under compressive loading in both axial and radial directions. This test protocol will be conducted at three temperatures so that the master curves of the magnitude and phase angle of the complex modulus can be constructed versus reduced frequency.

With the new data acquisition system, the MTS equipment will be used to conduct controlled-stress and controlled-strain tests on asphalt mixture specimens in order to obtain the damaged properties of the specimens. The developed data analysis approach will be used to quantify the fracture damage, plastic deformation and healing parameters of the asphalt mixture specimens induced by the cyclic loading. Several specimens with different air void contents will be used to investigate the effect of air voids on the damaged properties of asphalt mixtures.

Cited References

Luo, R., and R. L. Lytton, 2008, "Characterization of the Tensile Viscoelastic Properties of an Undamaged Asphalt Mixture." Submitted to *Journal of Transportation Engineering,* American Society of Civil Engineers, under review.

Luo, X., R. Luo, R. L. Lytton, and A. Epps Martin, 2009a, "A New Method of Simulating Material Responses and Calculating Dissipated Pseudo-Strain Energy in Repeated Direct Tension Test for Asphalt Mixtures," draft available.

Luo, X., R. Luo, R. L. Lytton, and A. Epps Martin, 2009b, "Evaluation of Fatigue Damage and Permanent Deformation of Asphalt Mixtures Using Dissipated Pseudo-Strain Energy," draft available.

Luo, X., R. Luo, R. L. Lytton, and A. Epps Martin, 2009c, "Application of Bond energy and Dissipated Pseudo-Strain Energy Concept to HMA Mix Fatigue Crack Modeling," draft available.

Work Element F2d: Tomography and Microstructural Characterization (TAMU)

Work Done This Quarter

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.

Significant Results

Figure F2d.1 illustrates the typical creep-recovery data obtained using the AFM tip on the surface of the asphalt binder.

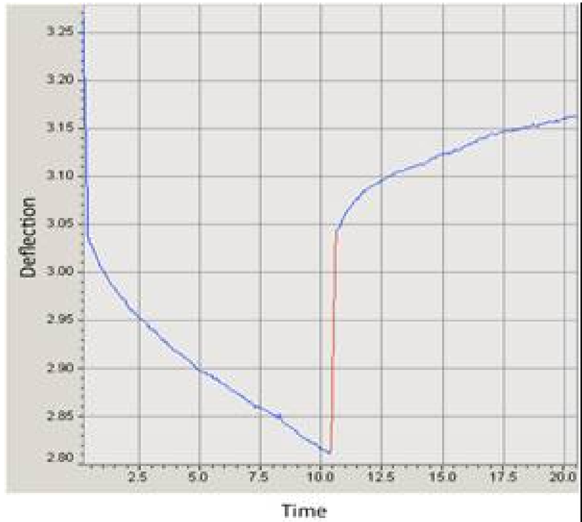


Figure F2d.1. Creep-recovery data obtained by applying a constant force for 10 seconds and removing it thereafter using the AFM tip.

Work Planned Next Quarter

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.

Work Element F2e: Verification of the Relationship between DSR Binder Fatigue Tests and Mixture Fatigue Performance (UWM)

Work Done This Quarter

The research team continued to work on binder evaluation using the Binder Yield Energy Test (BYET) at varying temperatures and rates. The research team has also begun looking into analyzing BYET data past the point of maximum stress because it has been recommended that this softening area may yield additional information on a material's damage resistance. Another accelerated test method, the strain sweep, has been incorporated into the testing plan. This test will be used diagnostically to determine strain levels for controlled-strain time sweep testing. It will then be analyzed on its own using the viscoelastic continuum damage (VECD) framework to determine if it is a suitable surrogate for fatigue testing.

The research team submitted papers on the results of this work both for the TRB annual meeting and for the AAPT annual meeting. Both papers were accepted for presentation and publication at these conferences. The research team received a number of comments from reviewers and has completed revisions of the papers based on these comments. The research team also continued the discussion of the effect of nonlinearity and plasticity on the VECD analysis.

Significant Results

Binder testing continues on one base binder modified with linear styrene-butadiene-styrene (LSBS) and Elvaloy® (ELV). Testing at 25 °C is almost complete, with an example of a complete data set shown in figure F2e.1 for one testing combination at three shear strain rates. In this case, repeatability appears to be good. However, some additional replicates are being run to verify anomalous results for other materials.

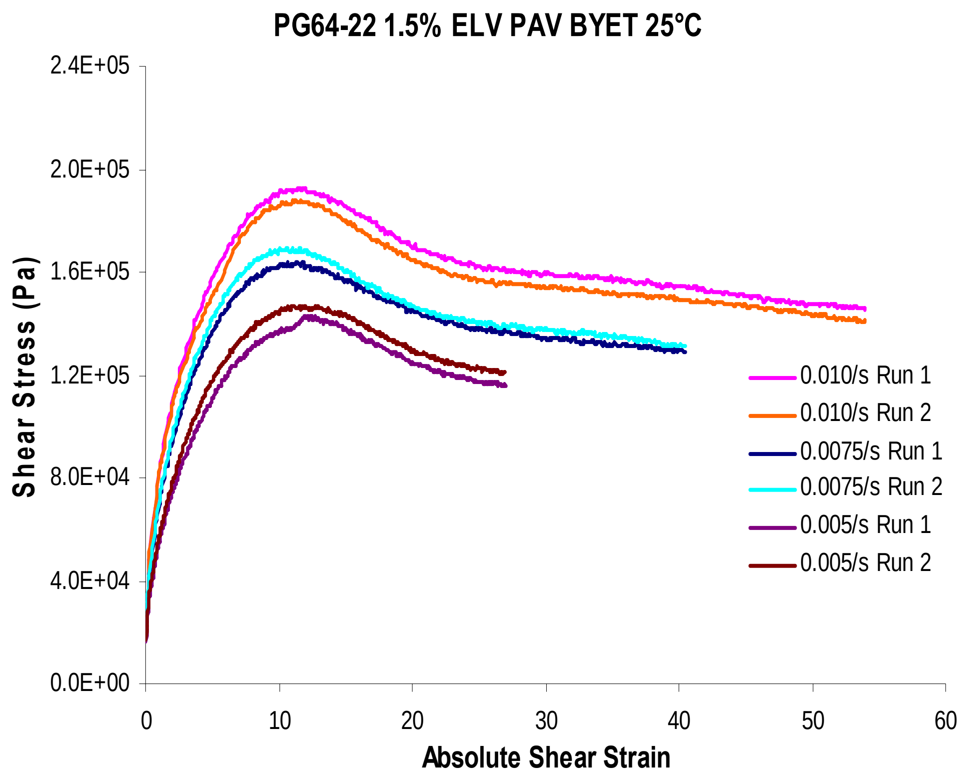


Figure F2e.1. Graph. BYET results for an ELV-modified PG 64-22 base binder at 25 °C.

Strain sweep testing is also complete for 19 °C test conditions. The procedure is currently being run at 10 Hz from 0.1% to 50% shear strain using a linearly increasing step rate. The linear increase is being used as opposed to logarithmic steps to induce a more gradual decrease in $|G^*|$, which will aid in the analysis of the strain sweep as a stand-alone fatigue performance test using VECD. Strain sweep results in figure F2e.2 appear to be able to distinguish different performances for the different types of modification, which is one requirement for the proposed accelerated fatigue tests.

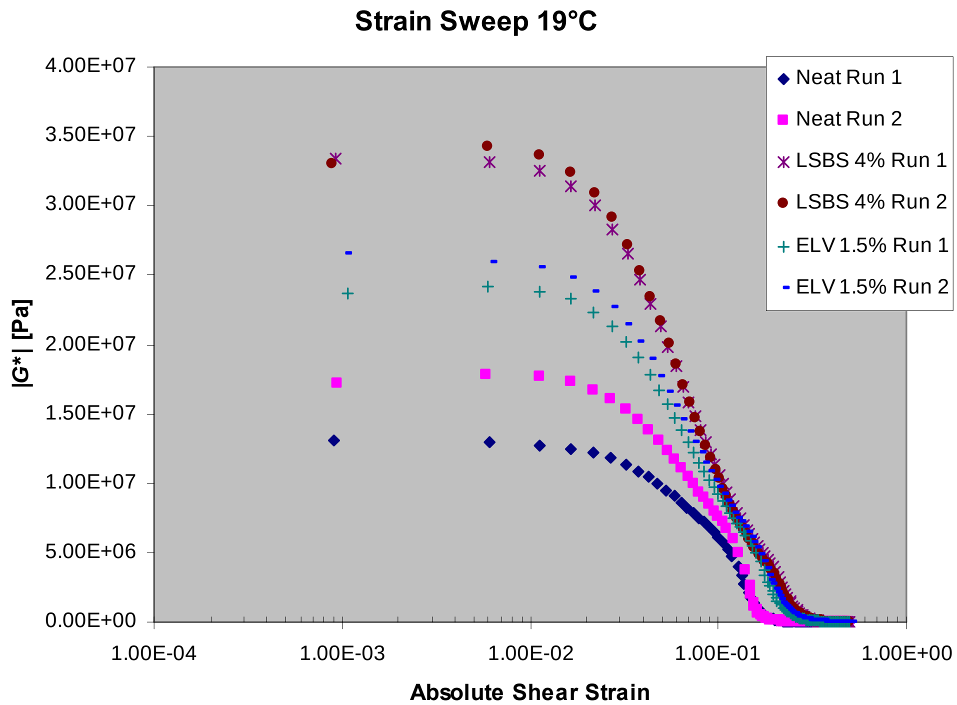


Figure F2e.2. Graph. Strain sweep results for three materials at 19 °C (unmodified base binder, binder modified with 4% LSBS and binder modified with 1.5% ELV).

The research team also met with Professor M. Emin Kutay of Michigan State University to discuss a possible collaboration effort. The team is considering using Professor Kutay's experience in testing the Accelerated Load Facility (ALF) polymer-modified binder mixtures to supplement work already performed at the University of Wisconsin–Madison on fatigue testing of the binders themselves. Professor Kutay also has experience applying the same VECD concepts for fatigue test data as those currently in use at UW–Madison.

Two papers regarding this work have been accepted for publication at the TRB Annual Meeting and the AAPT Annual Meeting, respectively.

<u>Significant Problems, Issues and Potential Impact on Progress</u>

The effect of nonlinearity and visco-plasticity on the VECD analysis has proved to be a significant challenge. It is taking longer time to resolve and could result in changing some of the testing conditions that were originally planned.

<u>Work Planned Next Quarter</u>

The research team will continue to collect BYET data and will begin using Time Sweep analysis on existing data to develop the characteristic damage plots from VECD analysis on both stress and strain sweep data. A work plan for Professor Kutay's involvement in this work element is under development, with work scheduled to start next quarter.

CATEGORY F3: MODELING

Work Element F3a: Asphalt Microstructural Model (WRI)

Work Done This Quarter

A significant amount of time was spent during the quarter in gathering the needed documentation, consisting of detailed work plans, detailed budgets, institutional contracting information, and cost share information from the proposed subcontractors on this work element, the National Institute of Standards and Technology (NIST), Virginia Tech University (VT), and the University of Rhode Island (URI). The subcontractors and their contribution to this effort were described in the Revised Year 2 Work Plan (posted on the ARC website www.ARC.unr.edu). The detailed documentation is necessary in order to establish subcontracts with these organizations that meet FHWA approval.

In the WRI research on this work element, persistent problem with the AFM metrology hardware have delayed progress. Preliminary tests in subtask M1b-2 revealed problems with the AFM metrology hardware. Attempts were made to recalibrate the metrology scan-head, and the head was returned to the manufacturer for repair. Problems with the system persisted in spite of several attempts at repair. Ultimately the equipment manufacturer agreed to replace the metrology system, and this was accomplished near the end of the quarter. Testing of the new system (including new operating software) is currently underway. These problems have been resolved, and no further impact on progress of this subtask is anticipated.

Significant Problems, Issues and Potential Impact on Progress

Problems with the AFM metrology scanner have delayed progress with this work element. The problems have been resolved.

Work Planned Next Quarter

It is planned to establish subcontracts with the National Institute of Standards and Technology (NIST) and Virginia Tech University (VT). Details and required documentation for a subcontract with the University of Rhode Island (URI) will be pursued.

Subsequent to subcontract initiation, the detailed work plan will be started.

Work Element F3b: Micromechanics Model (TAMU)

Subtask F3b-1: Model Development

<u>Work Done This Quarter</u>

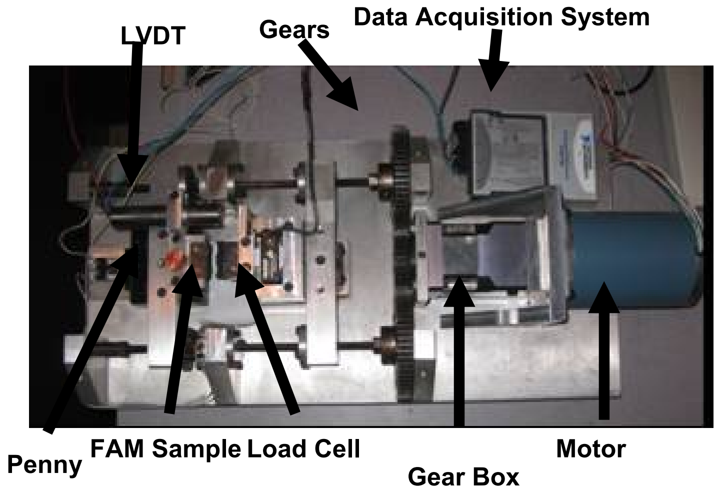
Lattice Micromechanical Model

The multi-scale virtual fabrication and lattice modeling (MS-VFLM) software is made computationally more efficient by rewriting the lattice modeling engine. The past version is based on general purpose finite element code and has significant overhead associated with the generality of the finite element code. The new engine is completely focused on lattice modeling and is substantially more efficient. The incorporation of special down-dating algorithm is near completion. In its final form, the new code is expected to be an order of magnitude more efficient than the existing MS-VFLM software.

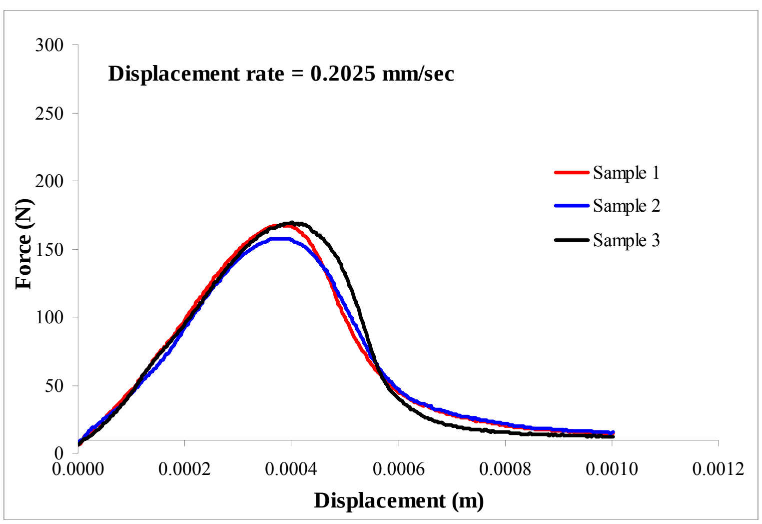
Cohesive Zone Micromechanical Model

<u>Work Done This Quarter</u>

Experimental work during this quarter focused on the development of a fracture testing system (shown in figure 3b.1(a)) and its preliminary testing (figure 3b.1(b)) to obtain cohesive zone (CZ) fracture properties of asphalt matrix phase (referred to as the fine aggregate matrix (FAM) in other ARC tasks related: M1c, F1b, F2b) and the application of the digital image correlation (DIC) technique, as presented in figure 3b.2, to asphalt concrete mixtures in order to determine the proper dimension of the representative volume elements (RVEs) of heterogeneous asphalt concrete mixtures where damage events such as cracking are involved.



(a) Configuration of the fracture testing system



(b) Preliminary test results

Figure F3b-1.1. A revised fracture testing system for the CZ model parameters of FAM phase.

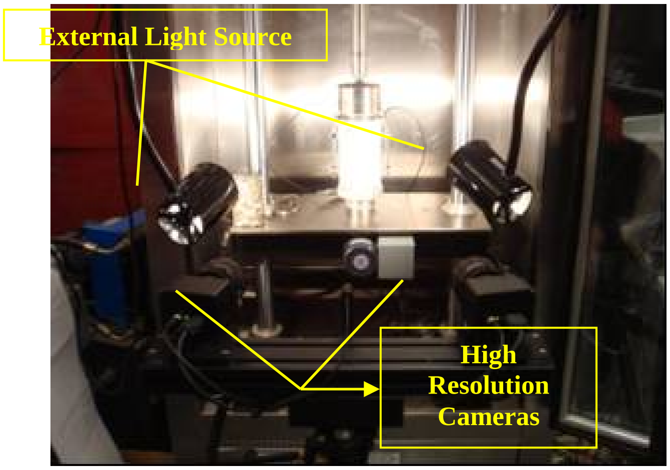
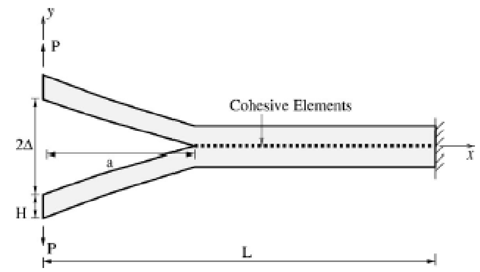
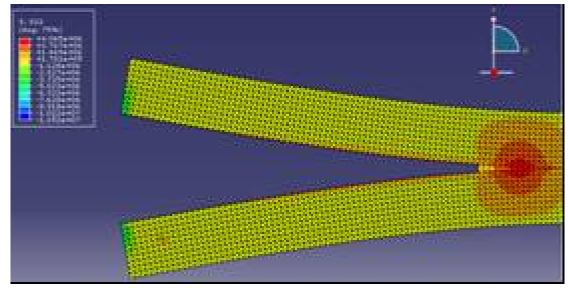


Figure F3b-1.2. DigitaliImage correlation (DIC) testing system and a specimen after testing.

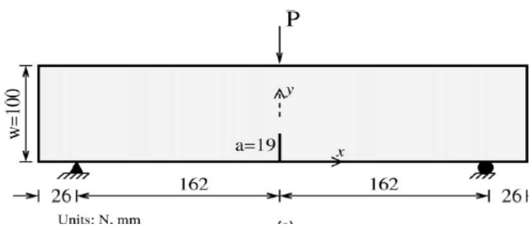
In the computational modeling part, we have investigated various CZ models developed by researchers for a better understanding of their features, characteristics, benefits, and limitations. This is to seek a more appropriate application of CZ models to the modeling of asphalt concrete fracture. Among various different CZ models reviewed, the bilinear CZ model was further investigated during this quarter, since the bilinear CZ model was found to generally match with fracture test results, and the model is a physically sound, intrinsic model used by many researchers (Geubelle and Baylor 1998, Espinosa and Zavattieri 2003, Song et al. 2006a, and many more) for various different materials and their fracture. Furthermore, the model provides computational convenience in describing the fracture process.

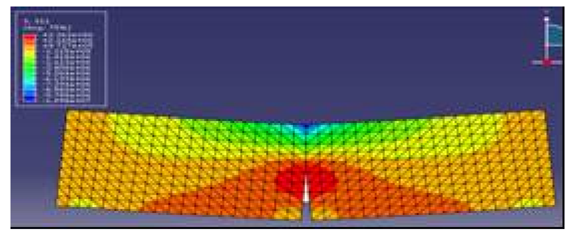
More specifically, for a more efficient investigation of the bilinear CZ model, we have tried to mimic cases presented in literature (Wagoner et al. 2005, Song et al. 2006a, 2006b) published by researchers at the University of Illinois at Urbana-Champaign (UIUC). The UIUC team led by Dr. Glaucio Paulino has worked on fracture-damage-failure modeling of various materials and composites. Figure 3b.3 illustrates cases investigated during this quarter. They are (1) an elastic double cantilever beam (DCB) fracture problem (figure 3b.3(a)) to evaluate numerical solutions via CZ elements by comparing to analytical solutions; (2) a single-edge beam (SE(B)) fracture problem (figure 3b.3(b)) to evaluate the artificial compliance issue due to the use of intrinsic CZ models such as the bilinear CZ model; and (3) a disk-shaped compact tension (DC(T)) fracture problem (figure 3b.3(c)) to investigate the effects of material viscoelasticity on overall fracture behavior of an object. Simulation results indicate that intrinsic cohesive zone models introduce the artificial compliance which should be addressed appropriately 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.



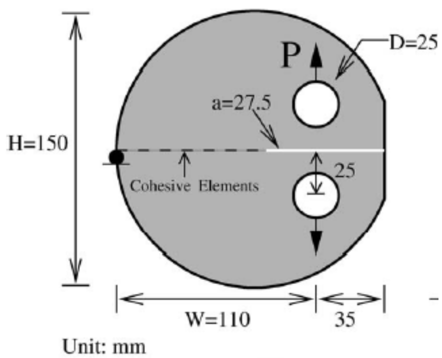


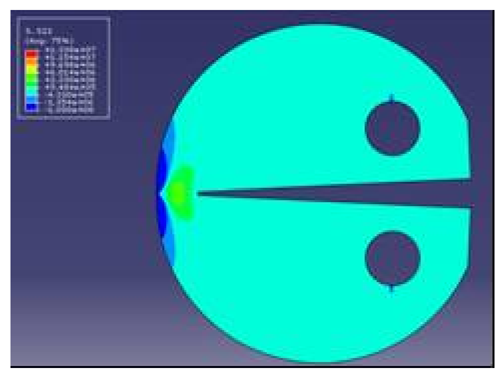
(a) DCB Problem





(b) SE(B) Problem





(C) DC(T) Problem

Figure F3b-1.3. CZ model simulations performed during this quarter.

Significant Results

The following are some of the results from the cohesive zone micromechanical model:

- The revised fracture testing system for FAM mixtures is expected to provide more efficient and accurate results for identifying CZ fracture properties that are implemented into the UNL computational micromechanics model. Fracture properties of FAM mixtures can also be related and compared to strength testing results of thin film binder/mastic samples and to surface energy measurements that are attempted by TAMU and UTA researchers.

- Intrinsic cohesive zone models introduce artificial compliance of bulk mixtures, and this issue should be appropriately handled in modeling of asphalt concrete mixtures.
- The use of a bilinear CZ model with bulk material viscoelasticity considered seems to be a potentially promising way, because it can model rate-dependent fracture behavior of asphalt concrete mixtures with relatively reduced modeling efforts.

Work Planned Next Quarter

Lattice Micromechanical Model

The implementation and testing of the new MS-VFLM will be completed. Work will initiate on investigating the current limitations of lattice modeling in scaling up from binder to smallest scale mastic.

Cohesive Zone Micromechanical Model

The development of fracture testing system and DIC tests including data analyses will be completed in the next quarter. Fracture test results will then be used to determine CZ parameters that are implemented into the UNL micromechanics model. Model simulations of a real asphalt concrete mixture will be performed and compared to bulk sample test results for model verification and calibration. We will also start to evaluate properties of common materials (binders and aggregates) selected by ARC modeling teams (TAMU, NCSU, UTA, and UNL).

Cited References

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.

Geubelle, P. H., and J. Baylor, 1998, The Impact-Induced Delamination of Laminated Composites: A 2D Simulation. *Composites, Part B*, 29B: 589-602.

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

Song, S. H., G. Paulino, and W. G. Buttlar, 2006b, Simulation of Crack Propagation in Asphalt Concrete Using an Intrinsic Cohesive Zone Model. *Journal of Engineering Mechanics*, *ASCE*, 1215-1223.

Wagoner, M. P., W. G. Buttlar, and G. H. Paulino, 2005, Disk-shaped Compact Tension Test for Asphalt Concrete Fracture. *Society for Experimental Mechanics*, 45(3): 270-277.

Subtask F3b-2: Account for Material Microstructure and Fundamental Material Properties

Note: These two subtasks work together until such time as the development progresses. Subtask F3b-2 will begin in the latter part of the Year 2 Work Plan.

<u>Work Done This Quarter</u>

No activity was conducted on this subtask.

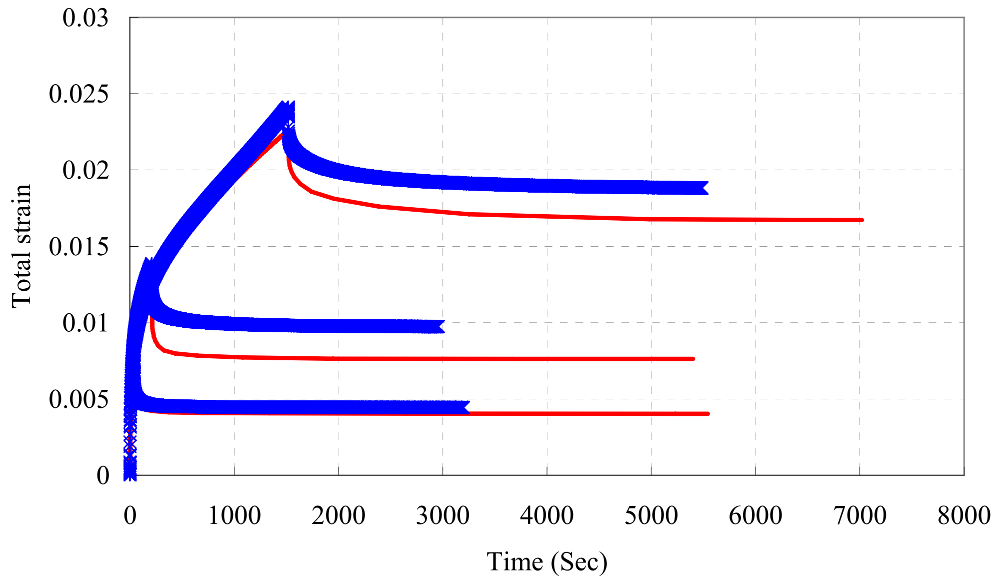
<u>Work Planned Next Quarter</u>

No work planned.

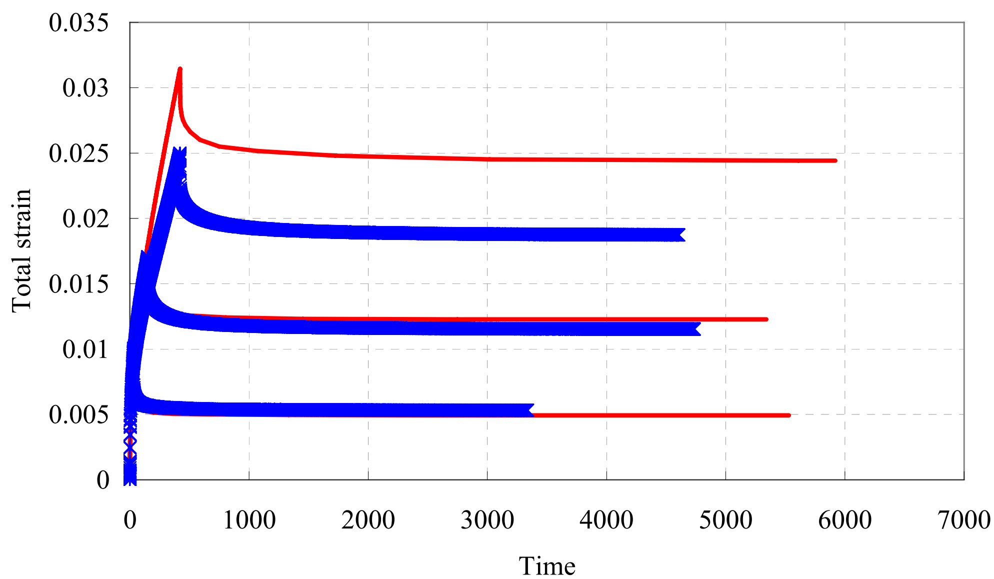
Work Element F3c: Development of Unified Continuum Model (TAMU)

<u>Work Done This Quarter</u>

The TAMU continuum model's results were verified using laboratory experiments from the Nottingham database. The experimental measurements used in the verification were from creep-recovery tests at different temperatures and stress levels. Examples of the comparison between the model and some of the experimental measurements are shown in figure F3c.1. The method developed for the separation of the nonlinear viscoelastic response from the viscoplastic response was applied to the Nottingham experimental measurements. Finite element analyses of pavement structures have demonstrated that the pavement performance is related directly to the material characteristics and model parameters.



(a) Stress Level=1000kPa



(b) Stress Level=1500kPa

Figure F3c.1 Comparison between total strain measurements and finite element results.

Significant Results

The analysis showed that the model is capable of describing the recovered and permanent responses of asphalt mixtures at different temperatures and stress levels.

Significant Problems, Issues and Potential Impact on Progress

None

Work Planned Next Quarter

The verification of the model will continue during the coming quarter using the Nottingham database. In addition, the ALF database from NCSU will be organized in order to start the model verification using this comprehensive database.

Work Element F3d: Calibration and Validation

This work element is planned to start later in the project.

	Fatigue Year 2	Year 2 (4/08-3/09)											
		4	5	6	7	8	9	10	11	12	1	2	3
Material Properties													
F1a	**Cohesive and Adhesive Properties**												
F1a-1	Critical review of literature					JP(1)							
F1a-2	Develop experiment design												
F1a-3	Thermodynamic work of adhesion and cohesion												
F1a-4	Mechanical work of adhesion and cohesion												
F1a-5	Evaluate acid-base scale for surface energy calculations												
F1b	**Viscoelastic Properties**												
F1b-1	Separation of nonlinear viscoelastic deformation from fracture energy under cyclic loading									D, JP			F
F1b-2	Separation of nonlinear viscoelastic deformation from fracture energy under monotonic loading									D, JP			F
F1c	**Aging**												
F1c-1	Critical review of binder oxidative aging and its impact on mixtures												
F1c-2	Develop experiment design					D(3)	F(3)						
F1c-3	Develop transport model for binder oxidation in pavements				P(4)						P		JP
F1c-4	Effect of binder aging on properties and performance						JP(2)						P
F1c-5	Polymer modified asphalt materials												
F1d	**Healing**												
F1d-1	Critical review of literature												
F1d-2	Select materials with targeted properties												
F1d-3	Develop experiment design												
F1d-4	Test methods to determine properties relevant to healing							JP					
F1d-5	Testing of materials												
F1d-6	Evaluate relationship between healing and endurance limit of asphalt binders										P		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						DP						
F2a-2	Select Virgin Binders and Modifiers and Prepare Modified Binder						DP						
F2a-3	Laboratory Aging Procedures												
F2a-4	Collect Fatigue Test Data				P						JP		
F2a-5	Analyze data and propose mechanisms												P
F2b	**Mastic testing protocol**												
F2b-1	Develop specimen preparation procedures						D(5)						
F2b-2	Document test and analysis procedures in AASHTO format						D(5)						
F2c	**Mixture testing protocol**					D, JP	F						
F2d	**Tomography and microstructural characterization**												
F2d-1	Micro scale physicochemical and morphological changes in asphalt binders												
F2e	**Verify relationship between DSR binder fatigue tests and mixture fatigue performance**												
F2e-1	Evaluate Binder Fatigue Correlation to Mixture Fatigue Data												
F2e-2	Selection of Testing Protocols				D, JP					DP,F			
F2e-3	Binder and Mixture Fatigue Testing												
F2e-4	Verification of Surrogate Fatigue Test										P		
F2e-5	Interpretation and Modeling of Data				JP						P		
F2e-6	Recommendations for Use in Unified Fatigue Damage Model												
Models													
F3a	**Asphalt microstructural model**												
F3b	**Micromechanics model**												
F3b-1	Model development									JP			
F3b-2	Account for material microstructure and fundamental material properties												
F3c	**Develop unified continuum model**												
F3c-1	Analytical fatigue model for mixture design												
F3c-2	Unified continuum model						JP						
F3c-3	Multi-scale modeling												

LEGEND

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

Work planned

Work completed

Parallel topic

	Fatigue Year 2 - 5	Year 2 (4/08-3/09)				Year 3 (4/09-3/10)				Year 4 (04/10-03/11)				Year 5 (04/11-03/12)			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Material Properties																	
F1a	**Cohesive and Adhesive Properties**																
F1a-1	Critical review of literature			JP													
F1a-2	Develop experiment design																
F1a-3	Thermodynamic work of adhesion and cohesion																
F1a-4	Mechanical work of adhesion and cohesion						JP	D	F								
F1a-5	Evaluate acid-base scale for surface energy calculations														JP		
F1b	**Viscoelastic Properties**																
F1b-1	Separation of nonlinear viscoelastic deformation from fracture energy under cyclic loading			D,JP	M&A, F				JP		JP		P		JP,M&A,D		F
F1b-2	Separation of nonlinear viscoelastic deformation from fracture energy under monotonic loading			D,JP	M&A, F				JP		JP		P		JP,M&A,D		F
F1c	**Aging**																
F1c-1	Critical review of binder oxidative aging and its impact on mixtures																
F1c-2	Develop experiment design			D		F											
F1c-3	Develop transport model for binder oxidation in pavements		P		P, JP		P		P, JP		P		P, JP			D, M&A	F
F1c-4	Effect of binder aging on properties and performance				JP, P		JP	D	F						JP	D	F
F1c-5	Polymer modified asphalt materials						P				P					D	F
F1d	**Healing**																
F1d-1	Critical review of literature																
F1d-2	Select materials with targeted properties																
F1d-3	Develop experiment design																
F1d-4	Test methods to determine properties relevant to healing			JP					JP	D	F						
F1d-5	Testing of materials						JP				JP			M&A,D	JP, F		
F1d-6	Evaluate relationship between healing and endurance limit of asphalt binders	DP			P	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

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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
[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 (TAMU)

Work Done This Quarter

A technical paper (Luo and Lytton, 2008) was written to detail the new test and data analysis protocol that was developed to characterize the viscoelastic properties of the undamaged asphalt mixtures under tensile loading. Tests made at three temperatures provided sufficient data to construct master curves for both the magnitude and phase angle of the complex modulus and the time-temperature shift functions for both. The Poisson's ratio was found to depend upon temperature only. This paper was submitted to and is currently under review by the Journal of Transportation Engineering, American Society of Civil Engineers (ASCE). This paper was scheduled to be presented in the Transportation Research Board (TRB) AFK50(1) Subcommittee Meeting in the 88th TRB Annual Meeting in Washington, D.C., January 2009.

In addition to the test protocol of characterizing tensile properties of asphalt mixtures, a new test and data analysis protocol was developed to obtain the anisotropic viscoelastic compressive properties of the undamaged asphalt mixtures. When an asphalt mixture is under compression, the aggregate plays a more important role. Because the aggregates tend to lie with their long dimension horizontal after compaction, the asphalt mixture has strong anisotropic properties under compressive loading. The compressive viscoelastic properties of the asphalt mixtures should be characterized in the vertical plane and horizontal plane separately. It is crucial to properly characterize the undamaged properties of an asphalt mixture in both tension and compression because they are the basis of inferring both fracture and plastic damage as well as moisture damage and aging effects using the Dissipated Pseudo-Strain Energy approach.

In the new test protocol, the anisotropic viscoelastic properties of lab-mixed-lab-compacted (LMLC) asphalt mixture specimens were characterized using the Universal Testing Machine (UTM) and the Rapid Triaxial Test (RaTT) Cell. Because of the geometry of the available RaTT Cell, the asphalt mixture specimens used in the protocol were cylindrical with a diameter of 6 inches and height of 6 inches. The protocol included three scenarios:

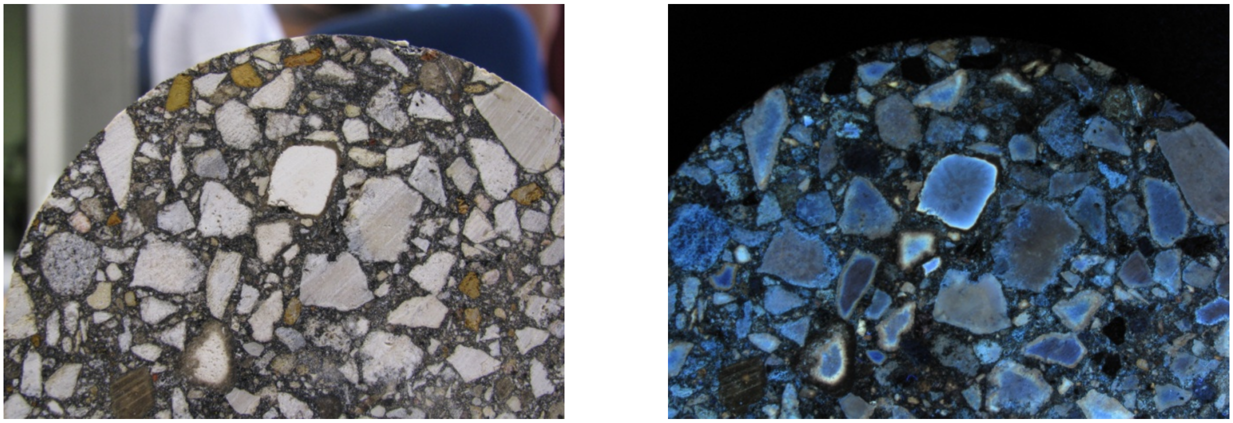
- Apply a constant axial load only to the specimen, and measure the axial and radial deformations with time;
- Apply a constant radial confinement pressure to the specimen without loading the specimen in the axial direction, and record the axial and radial deformations with time;
- Apply a constant axial load and radial confinement pressure simultaneously to the specimen, and measure the axial and radial deformations with time.

Both axial load and radial confinement pressure were controlled to keep the axial and radial deformations of the specimen within the linear range. Therefore, the specimens were not damaged during the compressive test and were saved for subsequent tests characterizing the damaged properties of the specimens.

The test data from all three scenarios were analyzed using a newly developed viscoelastic formulation for transversely isotropic materials. In the first two test scenarios, the viscoelastic formulation took as input the axial strain function and radial strain function, both of which were functions of time, to determine the viscoelastic Poisson's ratios in the axial direction and radial direction, respectively. Together with the determined Poisson's ratios, the test data from the third test scenario were used to obtain the viscoelastic compliance/modulus as a complex function of frequency in both the axial direction and radial direction. Based on the complex function of compliance/modulus, the magnitude and phase angle of the compliance/modulus were calculated.

Since the test specimens were not cored from the original LMLC specimens due to the limitation of available RaTT Cell, the air voids were not uniformly distributed in the specimen. It was found from the test results that the non-uniformly distributed air voids had a significant impact on the measurements. In order to reduce the effect of non-uniform air void distribution, a new RaTT Cell was ordered, which would be able to test a specimen with 4 inch diameter and 4 or 6 inch height. Therefore, the LMLC asphalt mixture specimens will be cored and cut to 4 inch in diameter by 4 inch in height, in which the air voids are expected to be much more uniformly distributed. The new RaTT Cell will be delivered in January 2009.

The tensile and compressive properties of undamaged asphalt mixtures were taken as input parameters for the inverse and forward self-consistent micromechanics models that were developed and programmed in the previous quarters. According to the calculation of the inverse model, the aggregate exhibited viscoelastic properties instead of elastic. The bulk modulus and shear modulus of aggregates were found to increase as the frequency increased. This finding indicated that the inverse micromechanics model was able to characterize the viscoelastic properties of aggregates, which agreed with what was reported in the literature (Cristescu 1989; Lakes 1999). In addition, ultraviolet light test showed that the porous aggregates and fines selectively absorbed certain asphalt components, which increased the viscoelasticity of the aggregates. With aging, the degree of viscoelasticity of these aggregates diminished. Figure E1a.1 shows the asphalt mixture specimen under natural light and under ultraviolet light. It is clear from this figure that some asphalt molecules traveled inside the aggregates through the pores.



(a) Asphalt Mixture under Natural Light (b) Asphalt Mixture under Ultraviolet Light

Figure E1a.1 Asphalt mixture under natural light and ultraviolet light.

Significant Results

The test and data analysis protocols for tensile properties of an undamaged asphalt mixture were documented in a technical paper, which was submitted to *Journal of Transportation Engineering,* ASCE.

A new test protocol was developed to characterize the anisotropic viscoelastic properties of asphalt mixtures under compressive loading. The test data were analyzed using a recently developed viscoelastic formulation for transversely isotropic materials including asphalt mixtures under compressive loading. This formulation was able to determine the viscoelastic Poisson's ratios, compliance and modulus, as complex functions of frequency in both the axial (vertical) direction and the radial (horizontal) direction.

The inverse model was found to be able to capture the viscoelastic properties of aggregates, which was also reported in the literature. Ultraviolet light test was conducted on a number of asphalt mixture specimens. It was found that the porous rocks and fines in the asphalt mixture selectively absorbed certain asphalt components that made the aggregate more viscoelastic. As the asphalt mixture aged, the degree of viscoelasticity of the aggregates diminished.

Significant Problems, Issues and Potential Impact on Progress

The available RaTT Cell was designed to test a specimen with 6 inch height and 6 inch diameter. Therefore, the LMLC specimens were not cored in order to make use of the available RaTT Cell. Since the air voids were not uniformly distributed in the 6 inch height by 6 inch diameter specimen, the test results were significantly affected by the air void distribution, which introduced non-negligible errors. In order avoid the effect of nonuniform air void distribution, a new RaTT Cell was ordered that was designed to test a specimen with 4 inch diameter and 4 or 6 inch height. The new RaTT Cell will be delivered in January 2009.

Work Planned Next Quarter

The LMLC specimens will be cored and cut to 4 inch height and 4 inch diameter in order to achieve approximately uniform air void distribution in the specimens. Since the new RaTT Cell will be delivered at the beginning of next quarter, it will be used to test the 4-inch-high and 4-inch-diameter cylindrical specimens. The test will determine the Poisson's ratio, compliance and modulus of the asphalt mixture specimen in both axial and radial directions. With tests run at three different temperatures, the master curves of the anisotropic viscoelastic properties of the asphalt mixture specimens will be characterized under compressive loading.

Test data on binders and mastics are expected to be delivered in January 2009 by University of Wisconsin at Madison, a team member of the Asphalt Research Consortium (ARC). The forward and inverse self-consistent micromechanics models will be applied to the mastic, which is a composite material of asphalt binder, fillers that can pass No. 200 sieve, and air. The properties of the fillers will be determined by the inverse model. One question to be answered with these test results is what level of viscoelasticity is imposed on these fillers by the asphalt binder that they absorb.

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Work element E1b: Binder Damage Resistance Characterization (DRC) (UWM)

Subtask E1b-1: Rutting of Asphalt Binders

Work Done This Quarter

In this quarter, materials selection and work plan development were finalized on time. These tasks were part of activity (ii) in the Year 2 work plan. The work plan includes three separate plans, namely, an asphalt binder testing plan, an asphalt mastic testing plan and an asphalt mixture testing plan. Laboratory testing continued following these testing plans. The binder testing under way has generated data from frequency sweep (FS) and Multiple Stress Creep and Recovery (MSCR) tests. Mastic testing will generate initial MSCR results with the DSR. Planned mixture testing includes repeated load in uniaxial compression (flow number, or FN) and dynamic modulus for permanent deformation (E*) tests.

Preparation of the testing is under way following related specifications (AASHTO TP 62-07 and ASTM D3497-79(2003)) and reports of NCHRP 09-19 and 09-29 projects (Bonaquist 2008, Bonaquist et al. 2004, Christensen and Bonaquist 2004, Witczak 2005 (1), Witczak 2005 (2), Witczak et al. 2002). In addition, one of the papers prepared in the previous quarter was presented at the Canadian Technical Asphalt Association (CTAA) 53rd annual conference and will be published in the proceedings.

Significant Results

The CTAA paper is entitled "Effects of Increased Loading Level and Time on Rutting Resistance of Modified Asphalt Binders and Mixtures." The results presented in the paper show that the testing geometry in the DSR (parallel-plate versus cone-and-plate) 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 are highly dependent on modification type and aggregate gradation. A discussion of the need for considering and modeling stress dependency of permanent deformation is presented. The results point out the need to simulate actual loading ranges in testing of paving materials, and the errors that could result from underestimating loads or using linear viscoelastic properties to characterize asphalt binders and mixtures.

Based on the analysis presented in the CTAA paper and on the recommendations received by reviewers from the ETGs on the Year 2 work plan, the experimental plan for this work element was finalized. Nine asphalt binders, three asphalt fillers and two mineral aggregates were selected as constituent materials to be included in the testing plans. The following lists include materials selected and planned testing conditions:

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.

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

- Temperatures: high grade temperature (HT), 58 °C and 46 °C (also 34 °C for 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): 0.1 to 30 Hz, 10 data points per logarithm decade, at a constant strain of 3%.
- MSCR test and RCR Test (AASHTO TP 70-07):
    - Loading pattern: 1 s loading + 9 s unloading.
    - Stress levels: 100, 3000, 10000, and 30000 Pa.
    - Number of cycles: 300 or that at which the specimen fails.

Asphalt Mastic Testing Conditions: The variables in the 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, and 1.4.
- Temperatures: same as in binder testing.
- Equipment: same as in binder testing.
- FS test (AASHTO T 315-06): 0.1 to 30 Hz, 10 data points per logarithm decade, at strains that range between 0.1 and 0.3% .
- MSCR test and RCR (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 the mastic is the actual binder in the asphalt mixture holding the aggregate particles.

Asphalt Mixture Testing Conditions: The 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).
  - Dust To Binder Ratio: 1.0.
- Basic testing 1: Repeated load in uniaxial compression (FN) test (NCHRP 465 [Witczak et al. 2002] Appendix B).
  - Temperature: 46 °C.
  - Load magnitudes: 22, 100 and 200 psi.
  - Confining pressure: 0.
- Basic testing 2: E* test (AASHTO TP 62-07, also NCHRP Report 465 [Witczak et al. 2002] Appendix A, and NCHRP Report 547 [Witczak 2005 (1)]).
  - Temperatures: 14, 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.

Asphalt mastic testing will begin next quarter. Initial test data will include MSCR test results with the DSR.

<u>Significant Problems, Issues and Potential Impact on Progress</u>

Preliminary results indicate that asphalt mastic testing with DSR is more difficult than binder testing. While MSCR testing is successful, RCR and FS tests have not generated reasonable results. This mastic testing problem is not expected to have significant impact on the progress. Trial mastic testing will continue next quarter. More care will be taken in preparing test specimens; both controlled stress and controlled strain modes will be compared; and appropriate stress or strain levels will be selected for meaningful test results.

Work Planned Next Quarter

In the next quarter, 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 on an ongoing basis as data are analyzed and interpreted.

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Christensen, D. W., and R. F. Bonaquist, 2004, Evaluation of Indirect Tensile Test (IDT) Procedures for Low-Temperature Performance of Hot Mix Asphalt. NCHRP Report 530, National Cooperative Highway Research Program, Transportation Research Board, National Research Council.

Witczak, M. W., 2005, Simple Performance Tests: Summary of Recommended Methods and Database. NCHRP Report 547, National Cooperative Highway Research Program, Transportation Research Board, National Research Council.

Witczak, M. W., 2005, Specification Criteria for Simple Performance Tests for Rutting, Volume I: Dynamic Modulus (E*), Volume II: Flow Number and Flow Time. NCHRP Report 580, National Cooperative Highway Research Program, Transportation Research Board, National Research Council.

Witczak, M. W., K. Kaloush, T. Pellinen, M. El-Basyouny, and H. Von Quintus, 2002, Simple Performance Test for Superpave Mix Design. NCHRP Report 465, National Cooperative Highway Research Program, Transportation Research Board, National Research Council.

Subtask E1b-2: Feasibility of Determining Rheological and Fracture Properties of Thin Films of Asphalt Binders and Mastics using Nano-indentation (UWM)

Work Done This Quarter

A collaborative effort is being coordinated with the University of Minnesota for this project. This quarter the research team discussed the feasibility of continuing this subtask and reviewed the problems encountered in getting access to the necessary testing devices at the University of

Wisconsin–Madison and the University of Minnesota. It is clear that the manufacturer of the device that provided initial data does not expect a simple solution to the problem of stickiness of probes to the samples. In addition, the possibility of purchasing a temperature-controlled chamber for the existing devices is unlikely for this exploratory work.

The research team is considering changing the focus of this task and has started review of the work done in the experimental field of viscoelasticity regarding the use of small scale (0.1 to 25 mm) indenters to measure response at various temperatures. The theoretical background of using a hemispherical indenter in a standard penetration device was pursued last quarter. Preliminary testing of binders and mastics was set up using a resilience test with a ball penetration tool (ASTM standard 5329). It was determined that the standard ball is too heavy for binder and mastic testing at the performance grade high temperature (PG-HT). A lighter hemispherical shape was machined and testing has begun in order to determine the feasibility of the test and the relationship to $G^*/\sin(\delta)$ values. The results and the initial literature review are expected to lead to a new work plan for this task.

Significant Problems, Issues and Potential Impact on Progress

The challenges found in using standard nanoindentation devices and the problems with stickiness of probes to the surface of asphalts have delayed this task. A rethinking of the work plan to focus on larger indenters and more practical equipment is under way.

Work Planned Next Quarter

A new work plan focused on small-scale indenters will be formulated next quarter. Preliminary testing using a hemispherical indenter and a conventional binder penetration device will further explore the possibilities. The indenter shape and theoretical analysis of the stress/strain field of such devices will be further investigated. It is expected that a new work plan for Year 3 will be proposed next quarter.

Work Element E1c: Warm and Cold Mixes

Subtask E1c-1: Warm Mixtures

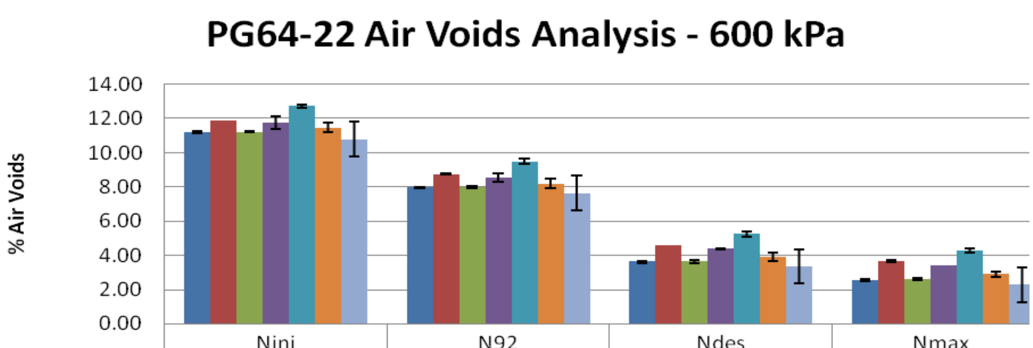
Work Done This Quarter

The research team conducted a thorough analysis of the existing laboratory compaction data for both control specimens and specimens containing a mineral-based additive. Team members accomplished this task using an air voids analysis as well as force index data collected using the pressure distribution analyzer (PDA). They also performed a laboratory compaction on a loose mix that was sampled from a field project in which a surfactant-based warm mix additive was being evaluated with varying proportions of recycled asphalt pavement (RAP). The team has started preliminary work for evaluating the same surfactant-based additive using the experimental conditions set up for the mineral-based additive. Preparation of aggregate blends for coarse gradation mixtures continued this quarter. Analysis of images for mixtures compacted at various combinations of temperature and pressure has started in order to evaluate the effect of reducing compaction temperatures on aggregate structure. A meeting with Dr. Emin Kutay of Michigan State University took place in Madison to discuss a joint effort to develop a standard software to evaluate aggregate orientation and contact points. It is expected that this software will help determine the effect of reducing temperature on details of aggregate structure as defined by orientation and contact points. This could lead to a better understanding of possible effects of reduced temperatures during compaction, with and without use of warm mix additives, on the performance of mixtures.

Significant Results

Evaluation of the effects of warm mix additives on workability and stability of mixes

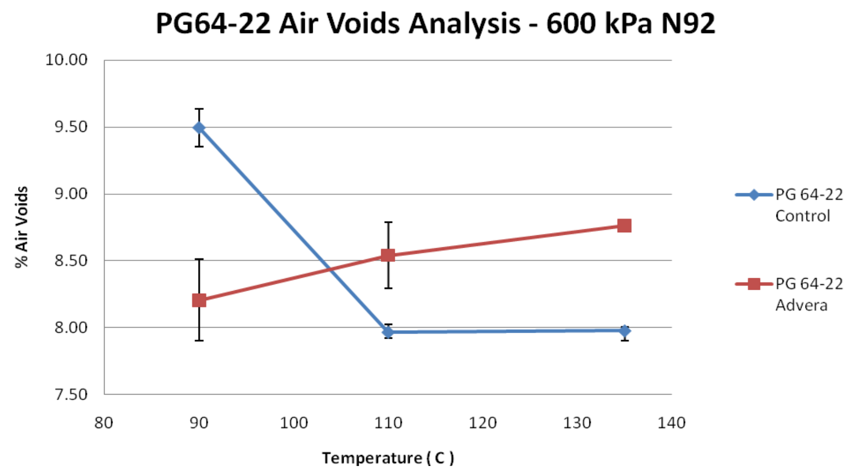
Analysis of the compaction data has focused on looking at three standard air void levels for numbers of gyrations: N_{ini}, N_{des} and N_{max}. The team has added a fourth level—N92—to examine the air voids at the number of gyrations needed to achieve 92% G_{mm} in the control mix at 135 °C. As can be seen in figure E1c-1.1, the control mix at 135 °C has an air void content of 7.97% at N92, which corresponds in this case to 21 gyrations. To determine relative ease of compaction, the team compared other test combinations at the same number of gyrations, used as a benchmark. The plot in figure E1c-1.1 shows that the PG 64-22 mixtures containing the mineral-based warm mix additive Advera did not achieve the same level of density at N92, but it should be noted that at 90 °C, the Advera mixture did reach 91.8% G_{mm}. It should also be noted that the team has begun to evaluate the surfactant-based additive Revix, shown in the bottom row of the table in figure E1c-1.1.



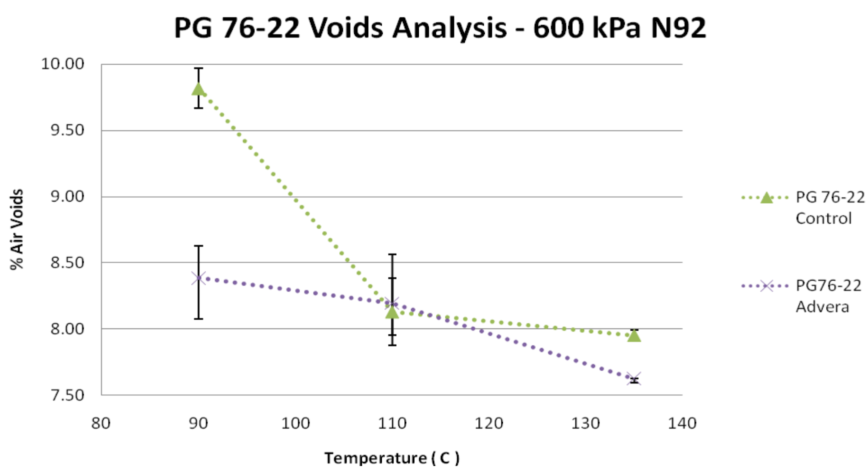
	Nini	N92	Ndes	Nmax
Control_135	11.21	7.97	3.63	2.54
Advera_135	11.88	8.76	4.61	3.67
Control_110	11.23	7.96	3.63	2.63
Advera_110	11.75	8.54	4.37	3.39
Control_90	12.73	9.49	5.25	4.27
Advera_90	11.47	8.20	3.91	2.91
Revix 110	10.81	7.64	3.34	2.26

Figure E1c-1.1. Graph. Plot of air voids analysis for mixtures using PG 64-22 binder at 600 kPa compaction pressure.

Further, the Advera mixtures appear to have a reduced sensitivity to temperature in comparison to control mixes for both PG 64-22 and PG 76-22 mixtures, as shown in the plots in figure E1c-1.2.



(a)



(b)

Figure E1c-1.2. Graphs. Plots of percent air voids versus compaction temperature for (a) PG 64-22 and (b) PG 76-22 mixtures.

Field project selection and coordination

Loose mixture sampled from the field demonstration attended by the research team in September (detailed in ARC Q3 2008 report) has been subjected to similar testing combinations as the laboratory mixture study described above. Testing is under way using two compaction pressures (600 kPa and 300 kPa) and three temperatures (135 °C, 110 °C and 90 °C). Additionally, specimens are being prepared for $|E^*|$ and FN (flow number) testing to develop the organization and data analysis methodology for the mechanical testing of the laboratory-prepared mixtures.

Work Planned Next Quarter

Investigation of effects of warm mix additives on the rheological properties of binders

- Begin testing binders containing the surfactant-based additive.
- Develop an experimental plan for rheological evaluation of foamed asphalts.

Evaluation of the effects of warm mix additives on workability and stability of mixes

- Continue with the compaction of the mixtures using the surfactant-based additive.
- Select either the Nynas workability tester or the University of Massachusetts, Dartmouth torque tester to measure mixture workability, and begin testing.

Mixture performance testing

- Control specimens will be compacted and sent to the University of Nevada, Reno for mechanical evaluation.

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

Work Done This Quarter

Efforts this quarter were related to evaluating emulsions in the laboratory, developing experimental designs to support the Year 3 work plan and quantifying energy consumption used in the application of emulsion technologies relative to conventional HMA.

Evaluation of Emulsions

Evaluation of emulsions focused on two separate tasks: addressing comments received from the Project Advisory Group related to the paper titled "Rheological Characterization of Emulsion Residues Using a Newly Developed Residue Recovery Technique," presented during a poster session at TRB; and continuing to develop tests and experimental plans related to construction properties of emulsions (curing time and development of adhesion).

Preliminary results of both efforts were presented to the Emulsion Task Force (ETF) December 15, 2008, at the Asphalt Institute. Other presentations to and discussions with the ETF confirmed the decision point presented in the ARC Q3 2008 report to move forward with using the ASTM evaporative recovery procedure referenced in the paper submitted to TRB by the University of Wisconsin–Madison. The ETF concluded that the recovery method results in some aging of the residue; however, it provides emulsion that properly displays the effects of emulsification. These conclusions are consistent with the findings provided in the revised version of the TRB paper. Specific results are reported in the "Significant Findings" section of this report.

Testing methods were refined and experimental plans developed related to the evaluation of the construction properties of emulsions. Efforts continued to be focused on evaluation of curing as it relates to the performance properties of resistance to raveling and flushing. These performance parameters were simulated in the Dynamic Shear Rheometer (DSR) using the strain sweep and Multiple Stress Creep and Recovery (MSCR) testing procedures. The details of the procedures were defined in the paper submitted to TRB in 2009. Significant refinement to the equipment and procedures using the Pneumatic Adhesion Tensile Testing Instrument (PATTI) test to evaluate development of adhesion were made to address comments provided by the Project Advisory Group and increase the repeatability of the test. Specific results will be presented in subsequent sections of the quarterly report. Measurement of adhesion and the rheological parameters obtained from the DSR tests will be related to performance using the sweep test. The current ASTM D7000 method and ongoing research efforts related to chip seal performance are under review for potential modification to ensure that adequate ranges in performance are obtained.

Experimental plans were developed for evaluation of the construction properties of emulsions applied to chip seals and how they are affected by variations in environmental conditions, emulsion type and aggregate properties. Specifically, the effects of temperature and humidity will be investigated through curing in different controlled environments. Furthermore, emulsions of different setting rates and modification types as well as aggregates of different mineralogies and porosities will be evaluated. A full experimental matrix is provided in the ARC Year 3 work plan. Emulsions will be supplied by HG Meigs, from Portage, Wisconsin, and SemMaterials. A letter of commitment was signed by HG Meigs this quarter to provide local materials and cooperation in constructing field sections.

Energy Analysis

A literature review of current energy analysis frameworks and definition of ranges in energy consumption suitable for practice in the United States has been completed. The research team is currently reviewing a draft of the document. Once the document is finalized, a decision will be made on the analysis framework to follow and how best to incorporate it into current activities.

<u>Significant Results</u>

Residue Recovery

The Project Advisory Group review and TRB review resulted in two major comments about the original paper submitted in Q3 2008. The following is a summary of those comments and how they were addressed in Q4 2008:

1. Comparison of the residue properties to the un-aged base binder alone is inadequate because it is inconsistent with the material placed in the field and does not provide any insight regarding the reason for the increased stiffness and brittleness of the emulsion residue.

Response: Main sources of variation in the increased stiffness and brittleness of the emulsion residue were identified as effects of the emulsifier and oxidative aging. The base materials were subjected to the same aging conditions and testing procedures as the emulsion residues. Furthermore, the base materials were also rolling thin film oven (RTFO) aged to provide a means of comparison. Based on rheological evaluation of the base materials at these different states of aging and comparison to the results previously published for the emulsion residues, it was clear that the recovery method produces a residue with properties that fall between those of the cured base asphalt (aged 48 hours) and the RTFO-aged base binder. Given these findings, the research team concluded that aging is the significant contributor to the differences in emulsion residue properties relative to the base binder.

2. The research does not include any moisture loss over time or data related to the water remaining in the emulsion residue at the end of the recovery process.

   Response: Rheological performance of the materials as a function of recovery time was used to evaluate the proposed residue recovery method. Comparison of these properties to those of the base asphalts oven-cured for 48 hours and RTFO-aged provides a frame of reference from which to evaluate the material produced by the recovery method. Based on the testing results, it is clear that the residue produced consists of material that falls within a similar range of performance relative to the base asphalts at various aging levels. Thus, from a performance standpoint, the presence of any water at the end of the 48-hour recovery time does not have a significant effect.

Updates of results previously presented in the ARC Q3 2008 report are shown in figure E1c-2.1 (MSCR testing) and figure E1c-2.2 (strain sweep testing).

Elastic recovery indicates the ability of a material to recover from strain during rest periods in the MSCR testing protocol. In general, unmodified materials will not exhibit elastic recovery. Figure E1c-2.1 shows residues for the latex-modified emulsion (CRS-1HP) and polymer-modified emulsion (LMCRS-2) exhibit approximately 17% and 15% strain recovery, respectively. These results are consistent with those obtained for both the base binder cured for 48 hours (about 20% recovery) and the RTFO-aged material (about 17% recovery). As expected, the unmodified emulsion and base material show 0% recovery. The conditions for the MSCR testing were a testing temperature of 60 ^{o}C and a stress level of 3200 kPa.

Evaluation of $G^*/\sin(\delta)$ at 12% strain of the proposed recovery method also provides a means of comparison for the aging experienced by the emulsion residue relative to that of the base binder subjected to similar conditions and RTFO-aged. The results are presented in figure E1c-2.2.

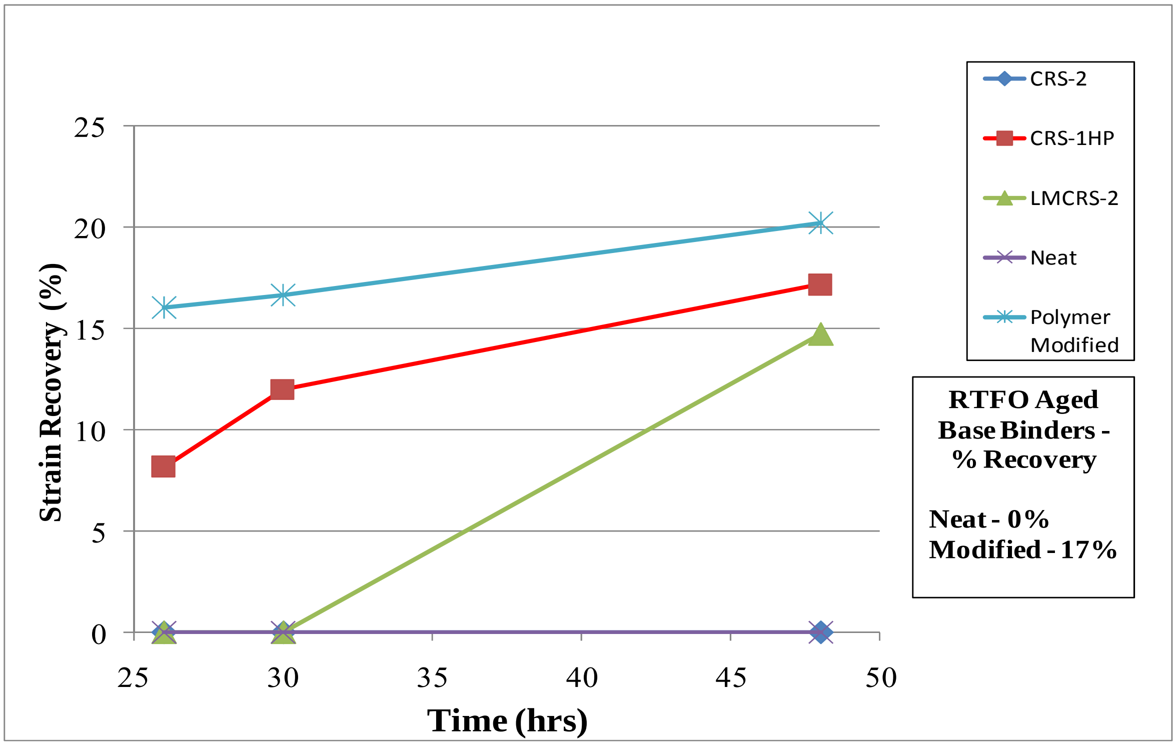


Figure E1c-2.1. Graph. Percent strain recovery for different emulsions as a function of residue recovery time.

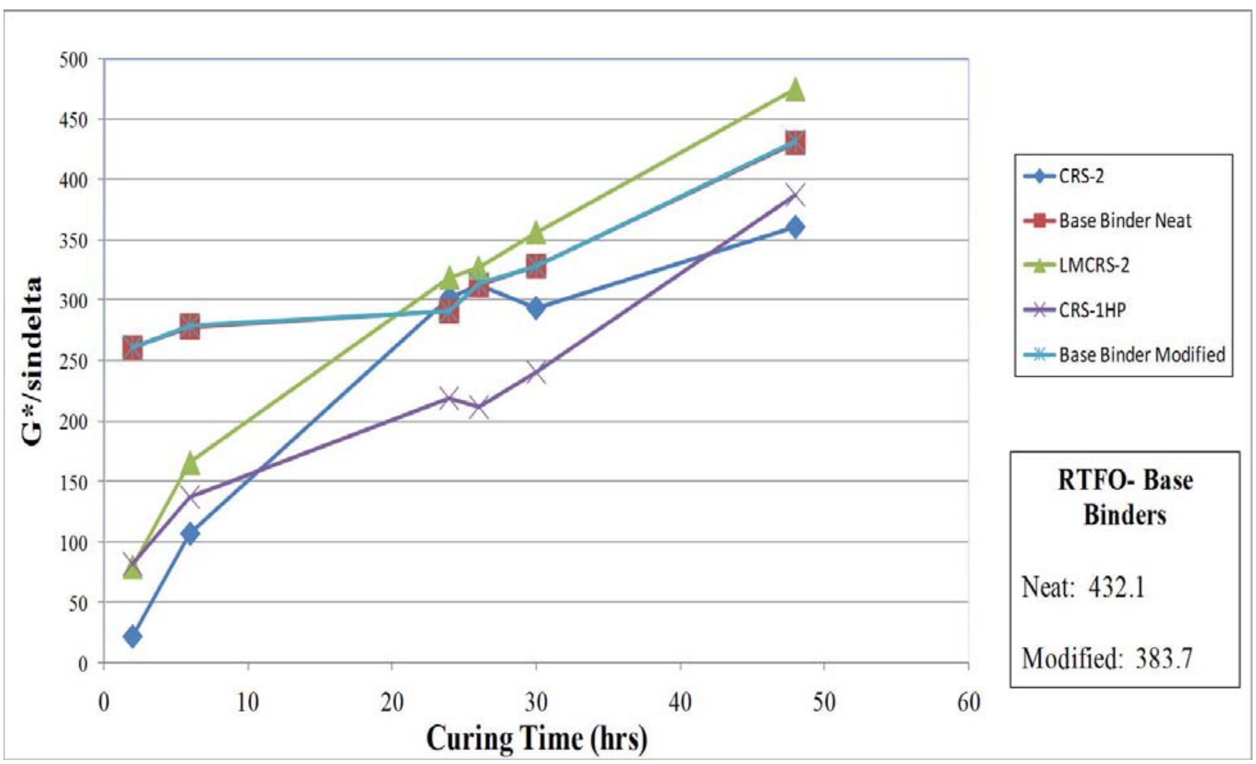


Figure E1c-2.2. Graph. G*/sin(δ) of the emulsion residue as a function of recovery time.

Aging under the residue recovery conditions resulted in equal values of G*/sin(δ) for the neat asphalt and 11% higher for the modified asphalt relative to the RTFO-aged materials. Performance of all the emulsions over recovery time mirrors that of the base asphalts, with the parameter G*/sin(δ) steadily increasing. Values of G*/sin(δ) for the CRS-2, CRS-1HP and LMCRS-2 were within 20% of the values obtained for the neat and polymer-modified base binders, indicating that recovery procedure produces residues in a range of performance between base asphalts subjected to the same condition and RTFO-aged materials.

Development of Construction Properties of Emulsions—Curing Rate and Adhesion: Evaluation of the ASTM D7000 Sweep Test Method

The equipment to perform the ASTM D7000 sweep test was set up. Initial testing focused on using a combination of two aggregate mineralogies (limestone and granite) of the same gradation and a CRS-1HP emulsion. The sweep test samples were prepared according to the ASTM D7000 standard and allowed to cure at 35 ºC for time intervals of 6, 24 and 30 hours. Coefficients of variation for all tests were well below 10%, indicating that repeatable results were obtained.

In figure E1c-2.3, the initial results show differences of approximately 8% and 4% for the granite and limestone chips, respectively. These differences are not adequately significant to differentiate between good and poor performance; therefore, evaluation of the same materials at shorter curing times (1 to 2 hours) is currently under way. If significant differences in performance are not seen, the conditions of the sweep test will be made more severe to provide the intended differences in performance. The research team will also continue to investigate potential modifications to the sweep test procedure based on other ongoing research efforts.

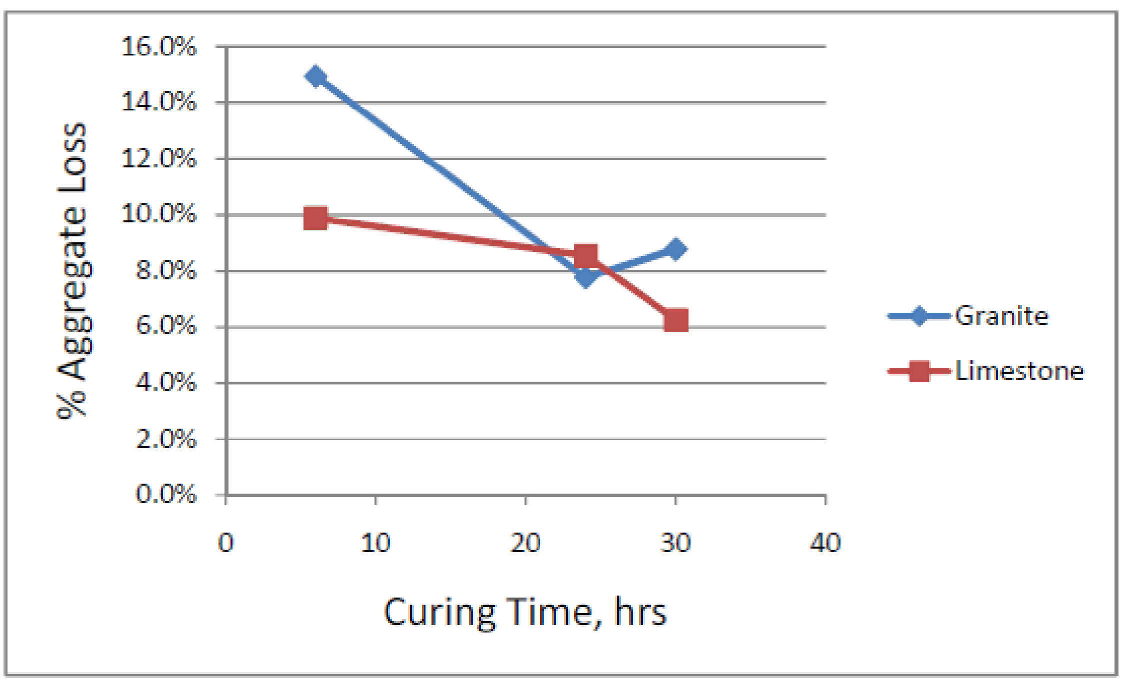


Figure E1c-2.3. Graph. Percent aggregate retention as a function of time for granite and limestone chips applied to a CRS-1HP emulsion.

Development of Construction Properties of Emulsions—Curing Rate and Adhesion: Adhesion Testing

Development of the PATTI test continued in the past quarter with efforts focused on making modifications to the stub geometry, testing machine and sample preparation procedures.

- *Stub geometry.* Geometry was enlarged from a 12.5 mm diameter to a 20 mm diameter pull stub with the intention of increasing the sensitivity of the test to changes in adhesive strength as curing time increases.
- *Equipment modifications.* A graduated flow controller was added in-line between the source of the air pressure and the PATTI to provide more precise control of the loading rate applied to the specimen.
- *Sample preparation procedures.* Procedures were standardized to reduce testing variability and to minimize intralaboratory variability when University of Stellenbosch begins testing.

The changes were evaluated through testing of a CRS-1HP emulsion cured on a granite substrate at 35 ºC. Tests were conducted after 2, 6 and 30 hours. As a reference, the test was also conducted on the base binder. Examination of the failure surface after testing showed that after the 6- and 30-hour curing times, there was difficulty establishing the bond between the emulsion and the pull stub. Each failure only showed a bond at approximately 50% of the stub surface for the 6-hour curing time and 10% of the stub after 30 hours of curing. As expected, the inability of the emulsion surface to fully bond to the stub affected the ability of the test to measure the development of adhesion as shown in figure E1c-2.4.

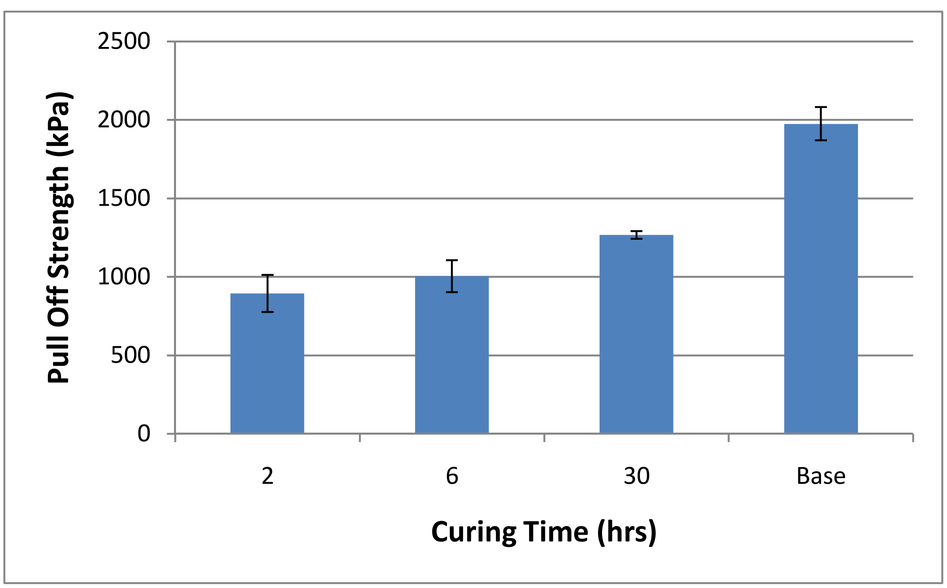


Figure E1c-2.4. Graph. Adhesion testing results for CRS-2 emulsion after 2-, 6- and 30-hour curing times.

As shown in figure E1c-2.4, comparison of the test results after 6 and 30 hours of curing are about 50% of the pull-off strength of the base binder. These large differences are believed to be due to an inability of the stub to bond properly to the emulsion.

Significant Problems, Issues and Potential Impact on Progress

The difficulties in establishing a proper bond between the pull stub and the emulsion surface must be addressed. The research team will investigate different stub application temperatures and bonding materials to ensure a proper bond is consistently established between the emulsion and the pull stub. This situation was unforeseen as the bond at the surface of the stub has not been a problem in the past for hot applied binders.

The literature review report has been delayed an additional three months due to the added scope related to the energy and waste minimization efforts previously referenced. Researchers decided that a full literature review report covering the application of emulsions to chip seals and the energy implications of using emulsions would be submitted at the end of Year 2.

Work Planned Next Quarter

Work next quarter will focus on the following tasks:

- *Emulsion residue testing.* The research team will develop and implement a testing protocol for evaluation of emulsion residues. The framework will be based on the Federal Lands Bureau (FLH) protocols developed by Drs. King and Lewandowski. The research team had initial input in the development of the original protocols and will modify procedures based on recommendations in the final report.
- *Emulsion setting and adhesion.* The research team will finalize protocols for the adhesion test and begin collecting data. Development of both adhesion and rheological properties of the emulsion will be related to chip seal performance as measured by the DSR. If necessary, the sweep test procedure will be modified to provide a range of performance suitable for establishing performance guidelines.
- *Emulsion viscosity, breaking behavior and storage stability.* The research team will begin to develop procedures and evaluation parameters for measuring the breaking rate, viscosity and storage stability of an emulsion using the Brookfield Rotational Viscometer.
- *Energy analysis.* The research team will:
    - Complete the literature review, including recommendations for an analysis methodology, and submit it to the Project Advisory Group for review.
    - Continue collaborative efforts with OPUS Consulting and the Australian Road Research Board.

CATEGORY E2: DESIGN GUIDANCE

Work element E2a: Comparison of Modification Techniques (UWM)

Work Done This Quarter

The work plan for this element has been restructured to include manufacturer-prepared modified binders. The team will seek modifiers that 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. Based on recent industry review and communications with industry contacts, the research team is considering the possibility of using plastomers to replace some of the elastomer-based additives, such as styrene-butadiene-styrene (SBS). This idea was initiated based on the concerns by agencies and industry regarding the supply of SBS in the market and the dependence of the supply on other fuel-refining conditions. Partial replacement of SBS and the combination of plastomers and elastomers in modifying asphalts were evaluated.

Significant Results

The team has selected a number of suppliers and will start requesting materials from manufacturers early next quarter. Testing methods and procedures to evaluate various storage and durability properties have been finalized.

Work Planned Next Quarter

The research team plans to begin collecting and testing materials next quarter.

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

Work Done This Quarter

This work element is a joint project led by University of Nevada, Reno and supported by University of Wisconsin–Madison. The UNR team completed the Superpave mix design for the California-Handley Ranch aggregates and evaluated the impact of the three extraction methods (i.e. centrifuge, reflux, and ignition) on the physical properties of the aggregates by comparing their measured properties before and after extraction. 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, and Micro-Deval.

The materials for both the Nevada-andesite and the California-Handley Ranch aggregates were prepared and shipped to FHWA for AIMS testing.

NCAT completed the testing of the physical properties of the extracted aggregates from the two selected sources from the East using the three extraction methods.

Additionally, the UNR team evaluated the impact of reflux and centrifuge on the properties of recovered binder from the California–Handley Ranch mix according to the process shown in figure E2b.1.

The UNR team reviewed the notes from the RAP ETG meeting held in Phoenix Arizona on October 28-29 and integrated the following comments in the current experimental plan:

- Determine whether the changes in FAA are due to changes in G_{sb} or particle shapes. This will be achieved by first calculating the FAA with the original G_{sb} and then with the extracted sample G_{sb}.
- Check for the impact of mixing on the properties of the aggregates. This will be achieved by mixing the virgin aggregate with water (no asphalt) in the mixer and then re-evaluate their properties.
- For the selected best extraction procedure, evaluate the impact of solvent types on the aggregate properties.

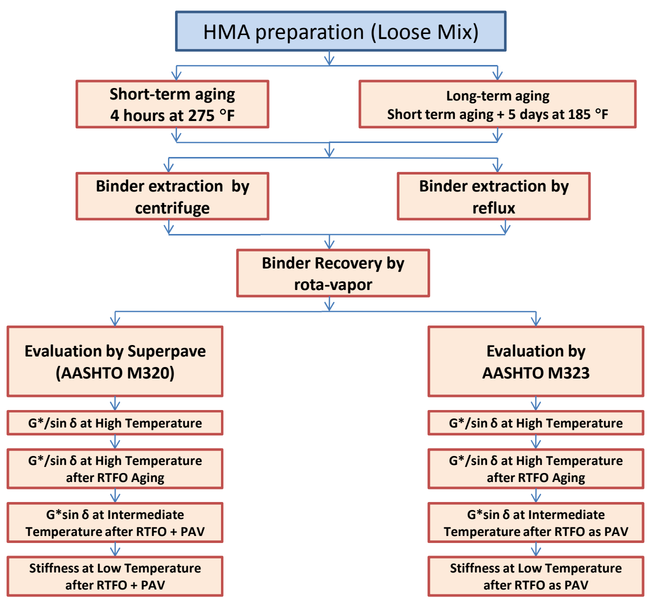


Figure E2b.1 Binder evaluation sketch

The UNR team prepared a report summarizing the findings of the UNR graduate student site visit to UWM. The report summarized the RAP mortar specimens' preparation and testing procedures along with UNR observations and suggestions. As a result, the following experimental plan will be conducted concurrently by UNR and UWM to validate the RAP mortar procedure:

A. *Evaluate the Properties of the Natural RAP:*

- Select two sources of RAP: S. Carolina RAP, and Palm Dale, 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.

B. *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.

C. *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.

D. *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.

During this quarter, the experimental design for testing mortars made with RAP (-#8) was expanded. Two binders and two RAP sources were added to the work plan. The binders were PG58-28 from CRM and PG64-22 from Flint Hills. The RAP came from South Carolina and from Palm Springs, California. They have been classified as “unmodified stiff” and “unmodified very stiff,” respectively.

Gradation has been taken into account. The natural material was sieved and separated for each sieve under #8, and the percent retained was calculated. The natural material was put in a container to be burned in the ignition oven.

The sample and mortar preparation process was finalized. The test variability has been reduced as much as possible. Raw steel Teflon-coated molds were used to prepare the samples. The dimension of the mold is 10 mm by 12.7 mm. Two layers of Teflon tape were added to the side bar to ease the demolding process.

The influences by different test parameters, such as the dimension and weight of sample and test force, were checked. In addition, changes were made to the testing procedure. A thickness of 10 mm was used in the Bending Beam Rheometer (BBR) software to avoid converting the test result—based on a thickness of 6.35 mm—to the real thickness of 10 mm. This binder was tested from 200 mN to 980 mN, depending on the PG grade, aging of binder and the test temperature. The load applied to test mortars remained 4,000 mN.

This test was applied under different temperatures: 0 ºC, -3 ºC, -6 ºC and -9 ºC. Similar equations based on fresh RAP and artificial RAP were obtained, and these are in further need of review.

The UWM research team reviewed different models developed for mastics or mixtures based on volume; air voids; and properties of aggregate, filler and asphalt binder. These models were found to be inappropriate for mortar samples because they are too complex for practical application. They do suggest, however, that the property of mortar has a fixed relationship with the property of asphalt binder. In the testing procedure, all the mortar samples have the same gradation of aggregate, air voids (zero), and percent volume of asphalt binder and aggregate. Therefore, the stiffness of the mortar should only depend on the stiffness of binder. An Excel spreadsheet with linear, polynomial and logarithmic regression models was developed to use in analyzing the test data.

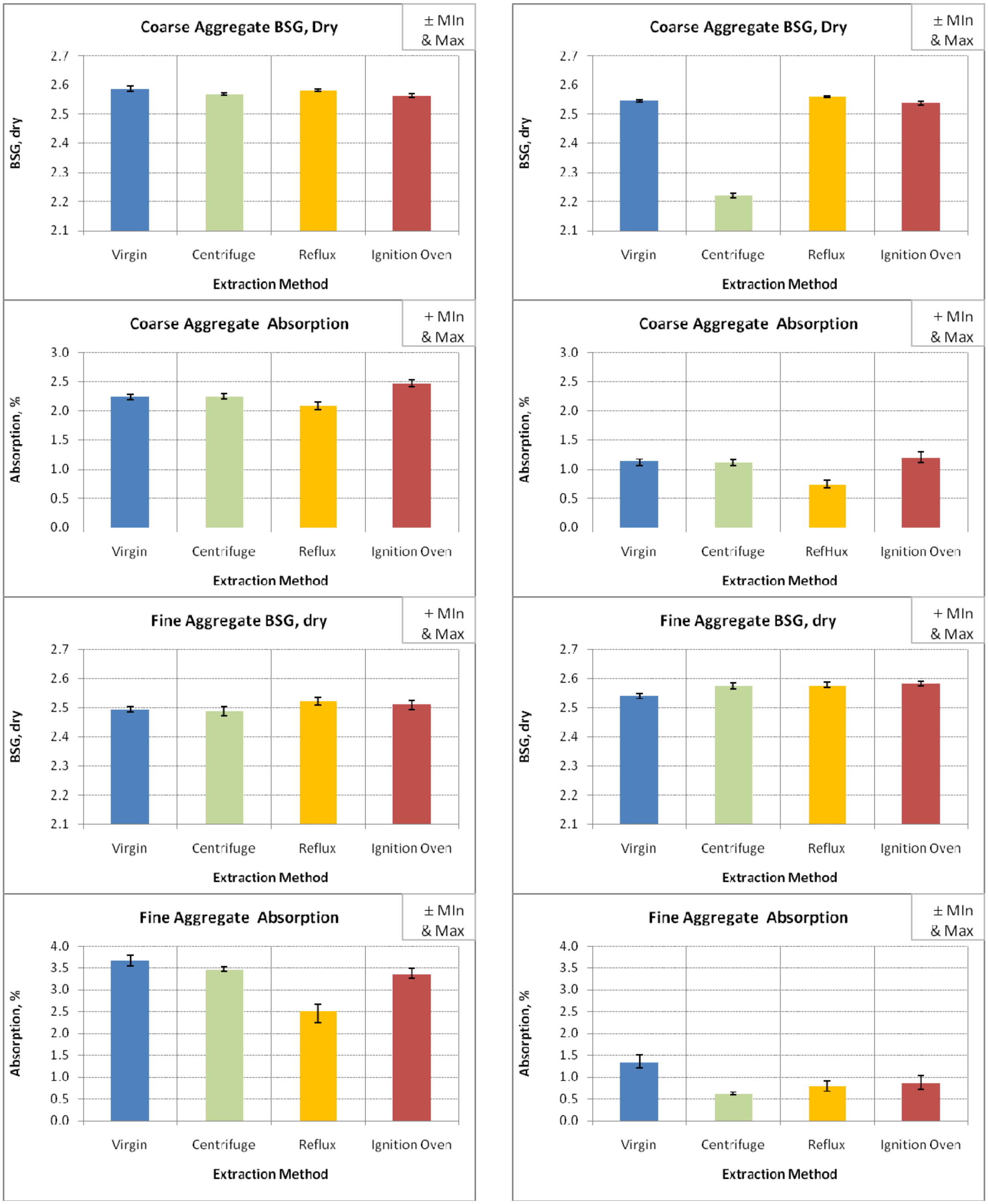
Significant Results

Figure E2b.2 shows selected results for the Nevada-andesite and the CA-Handley Ranch aggregates.

The modeling spreadsheet for BBR mortars is still in progress; additional work is required to find equations to convert mortar stiffness to binder stiffness.

More testing data were obtained with the expansion of the experimental design. Testing procedure development and improvements follow:

- The research team developed a step-by-step procedure for mold setup, mortar preparation and sample preparation.
- The binder samples are now prepared with the same dimension of the mortar samples.
- Mortar is now prepared in quantities enough for two to three test samples, which helps avoid the creation of excess mortar that would then need to be reheated.
- The blended binder is now tested to ensure the blending chart can be used to calculate the stiffness of blended binder based on the fresh and aged binder.
- By testing binder samples at 0 ºC, shift factors according to time-temperature superposition are necessary.



Nevada-Andesite Aggregates CA-Handley Ranch Aggregates

Figure E2b.2 Specific gravity and absorption of fine and coarse aggregates (AASHTO T84 and AASHTO T85)

Significant Problems, Issues and Potential Impact on Progress

The third source of aggregate from South Dakota is no longer in production therefore it was excluded from the experimental plan.

While the research team has witnessed a reduction in the variability of the samples and an increase in data consistency, additional tests need to be done to complete the experimental design.

Equations derived from the binder-mortar correlation to obtain the stiffness of aged binder in natural RAP are not providing the desired results. This is addressed in the work planned for the next quarter.

Work Planned for Next Quarter

UNR will collect the test results for the two aggregate sources from the East from NCAT and will analyze the data of the various aggregate sources using statistical tools.

UNR will write a report summarizing the findings of both UNR and NCAT test results on the impact of extraction method on the physical properties of aggregates.

UNR will evaluate the impact of mixing on the properties of the virgin aggregate.

Next quarter, the research team will run more tests on the mortar to achieve higher consistency and to lower the variability of the data.

The team also plans to establish an equation to convert mortar stiffness into binder stiffness. A logarithmic model is suggested to correlate binder and mortar stiffness, but the linear and polynomial regression models will still be considered in the research team's future work.

Cited References

Bautista, E. G., S. Mangiafico, and H. U. Bahia, 2009, Evaluation of Rheological Properties of Binders in RAP Without Extraction and Recovery. Paper submitted for presentation and publication, Annual Meeting of the Transportation Research Board 2009.

Work element E2c: Critically Designed HMA Mixtures (UNR)

Work Done This Quarter

The UNR team analyzed the calculated deviator and confining stresses from the 3D-Move responses of the PG64-22 and the PG52-22 mixtures under the moving 18-wheel truck at 60, 40, and 20 mph. Additionally, the 3D-Move runs for the PG64-22 mix and the PG52-22 mix under a braking 18-wheel truck at 20 and 2 mph are completed.

The mix design for the Lockwood aggregate source with PG58-22 binder was completed along with the dynamic modulus master curve and damping ratio.

A report with recommendations for the magnitude of the deviator and confining stresses for the flow number of HMA mixtures test was submitted to the mix ETG for consideration in the new provisional AASHTO standard test method.

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.

Significant Results

Figures E2c.1 and E2c.2 show the calculated maximum deviator and confining stresses in the PG64-22 and PG52-22 HMA layers and under the tandem driving axle, respectively. Furthermore, tables E2c.1 and E2c.2 show the maximum stresses along with the sum of the maximum deviator and confining stresses (i.e. total vertical stress).

In the case of the PG64-22 mix, the maximum deviator stress and confining stress varied from 69-102 psi and 27-47 psi, respectively. The total vertical stress varied from 109-129 psi. In the case of the PG52-22 mix, the maximum deviator stress and confining stress varied from 74-94 psi and 28-39 psi, respectively. The total vertical stress varied from 109-124 psi. Except in the case of the 4-inch HMA layer, an increase in the deviator stress and a decrease in the confining stress were observed with the increase in temperature.

For both mixtures, the impact of speed on the maximum deviator stress was more significant in the case of 4" HMA layer at 40 and 50°C while the impact of speed on the maximum confining stress was more significant in the case of 6 and 8" HMA layers. Figures E2c.3 and E2c.4 show the total vertical, deviator, and confining stresses along with their expected variations (i.e. error bars) due to speed. Since vehicle speed induced only minor variations in the magnitude of the deviator and confining stresses, it was decided to use the average values of the three speed levels.

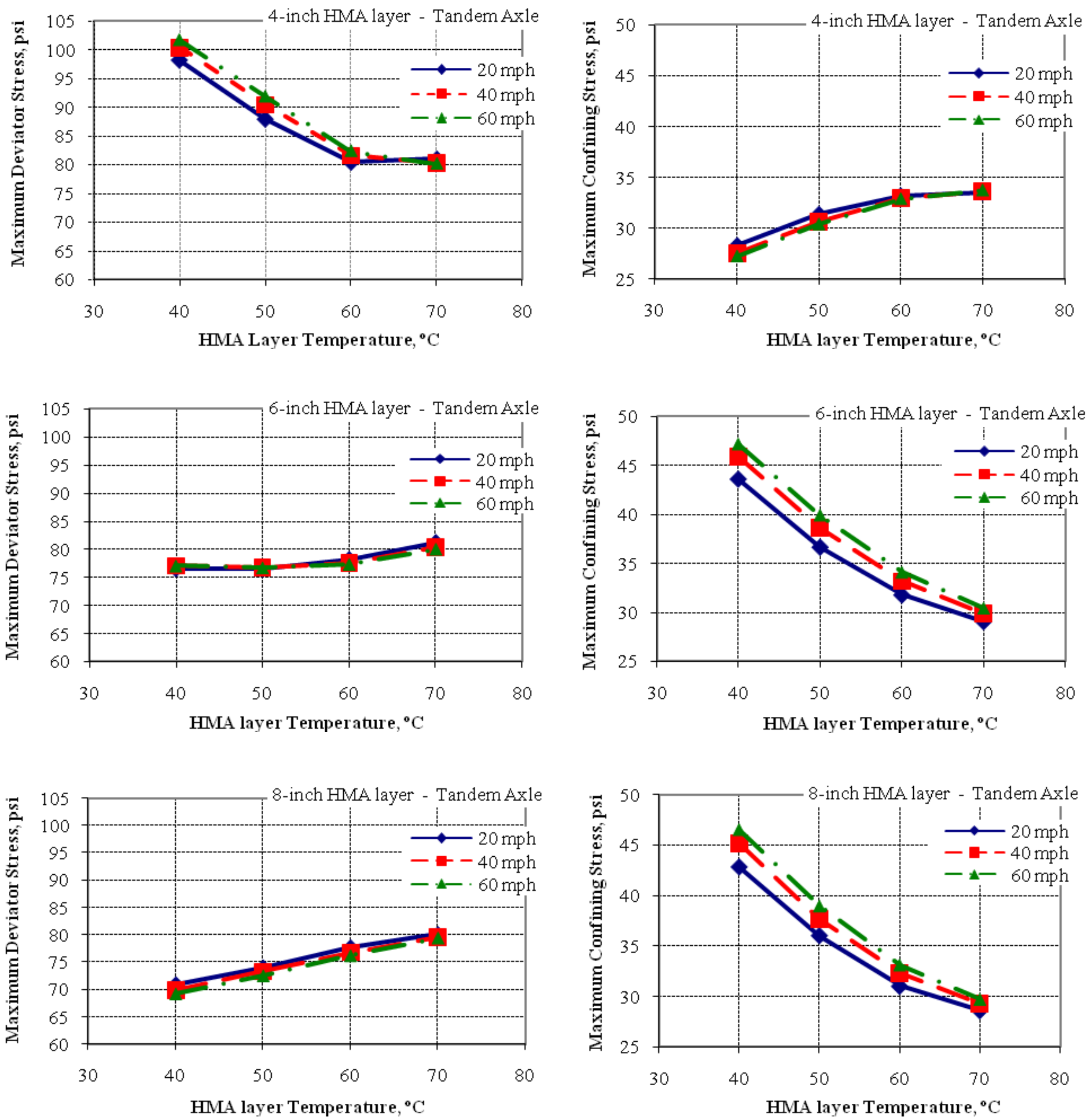


Figure E2c.1. Maximum deviator and confining stresses at 2-inch below the pavement surface of the PG64-22 mix

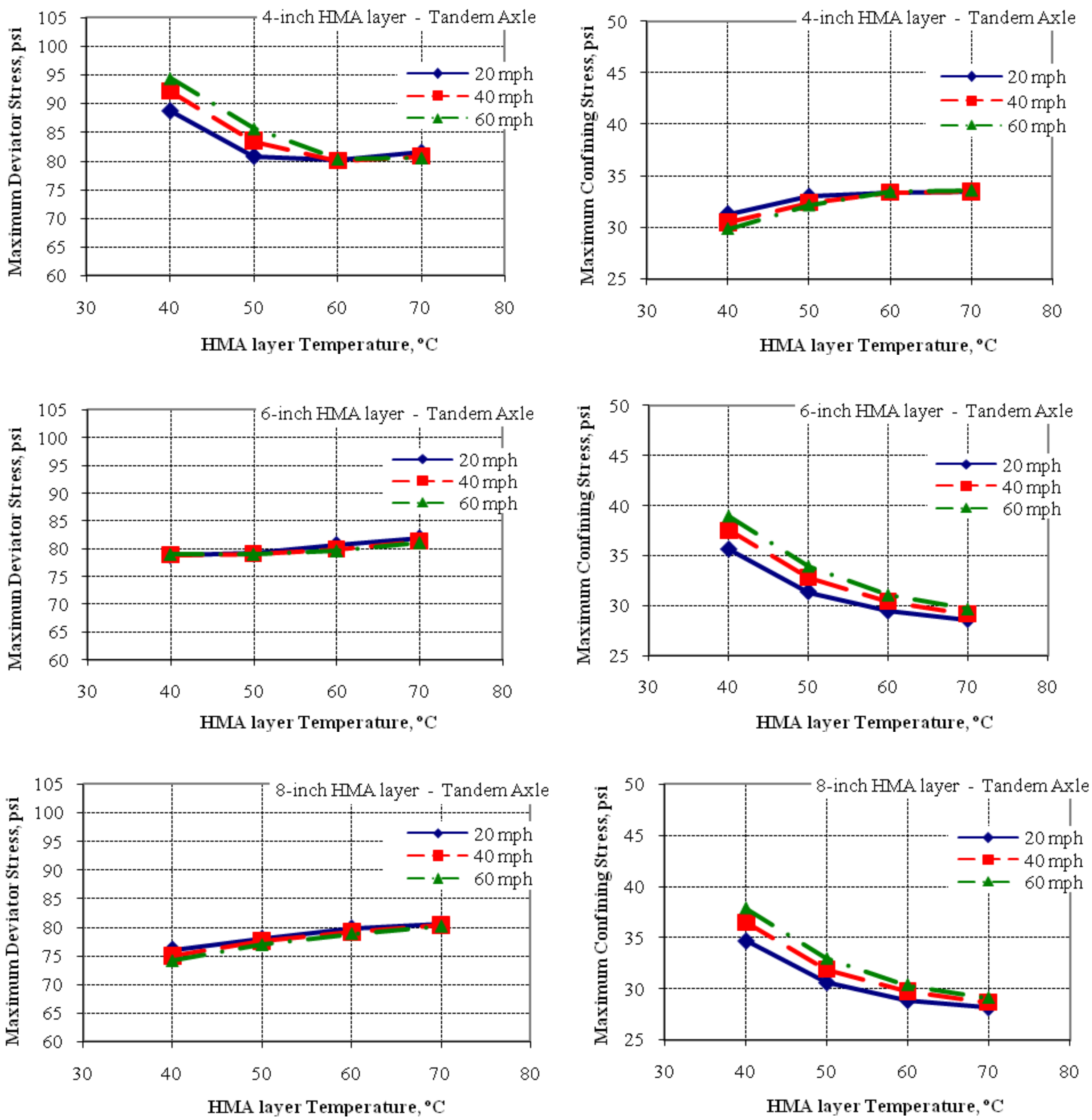


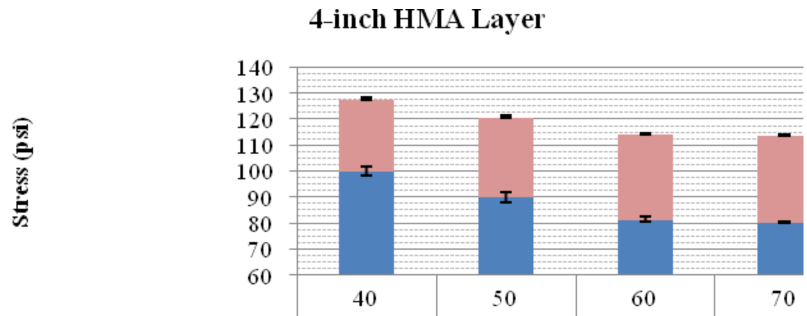
Figure E2c.2. Maximum deviator and confining stresses at 2-inch below the pavement surface of the PG52-22 mix

Table E2c.1 Summary of the maximum deviator and confining stresses at 2” below the pavement surface of the PG64-22 mix.

HMA layer temperature (ºC)	HMA layer thickness (in)	18-wheel traveling speed (mph)	Max deviator stress, σ_d (psi)	Max confining stress, σ_c (psi)	Total vertical stress, $\sigma_d + \sigma_c$ (psi)
40	4	20	98.1	28.3	126
		40	100.5	27.6	128
		60	101.8	27.3	129
	6	20	76.6	43.6	120
		40	77.0	45.9	123
		60	77.0	47.2	124
	8	20	70.9	42.8	114
		40	69.8	45.2	115
		60	69.2	46.5	116
50	4	20	87.9	31.4	119
		40	90.4	30.7	121
		60	91.9	30.4	122
	6	20	76.6	36.7	113
		40	76.7	38.6	115
		60	76.7	39.9	117
	8	20	74.0	36.0	110
		40	73.3	37.7	111
		60	72.5	39.0	111
60	4	20	80.4	33.2	114
		40	81.5	32.9	114
		60	82.4	32.9	115
	6	20	78.2	31.8	110
		40	77.5	33.2	111
		60	77.3	34.1	111
	8	20	77.7	31.0	109
		40	76.7	32.3	109
		60	76.1	33.1	109
70	4	20	80.9	33.5	114
		40	80.2	33.6	114
		60	80.2	33.8	114
	6	20	81.1	29.1	110
		40	80.3	29.9	110
		60	79.9	30.4	110
	8	20	80.1	28.6	109
		40	79.6	29.2	109
		60	79.4	29.7	109

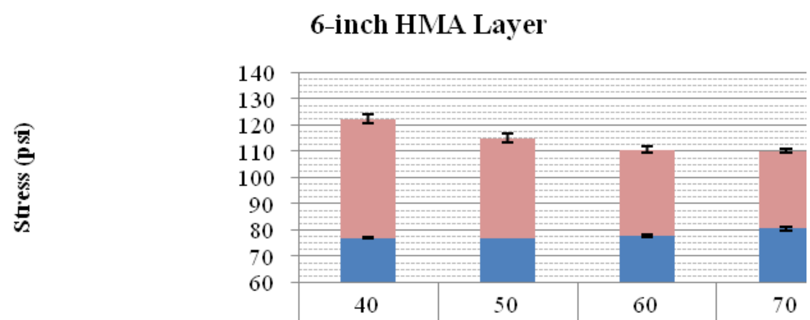
Table E2c.2 Summary of the Maximum Deviator and Confining Stresses at 2" below the Pavement Surface of the PG52-22 Mix.

HMA layer temperature (ºC)	HMA layer thickness (in)	18-wheel traveling speed (mph)	Max deviator stress, σ_d (psi)	Max confining stress, σ_c (psi)	Total vertical stress, $\sigma_d + \sigma_c$ (psi)
40	4	20	88.7	31.3	120
		40	92.2	30.4	123
		60	94.4	29.8	124
	6	20	78.8	35.7	114
		40	78.9	37.5	116
		60	79.0	39.0	118
	8	20	76.1	34.7	111
		40	74.9	36.5	111
		60	74.2	37.9	112
50	4	20	80.9	33.0	114
		40	83.5	32.4	116
		60	85.6	32.1	118
	6	20	79.1	31.4	110
		40	79.1	32.8	112
		60	79.1	33.9	113
	8	20	78.0	30.6	109
		40	77.5	31.9	109
		60	77.0	33.0	110
60	4	20	80.2	33.4	114
		40	80.0	33.4	113
		60	80.3	33.4	114
	6	20	80.7	29.4	110
		40	80.0	30.4	110
		60	79.7	31.1	111
	8	20	79.8	28.9	109
		40	79.1	29.7	109
		60	78.9	30.4	109
70	4	20	81.5	33.5	115
		40	80.8	33.5	114
		60	80.5	33.6	114
	6	20	81.9	28.6	110
		40	81.3	29.1	110
		60	81.1	29.7	111
	8	20	80.6	28.2	109
		40	80.3	28.7	109
		60	80.2	29.1	109



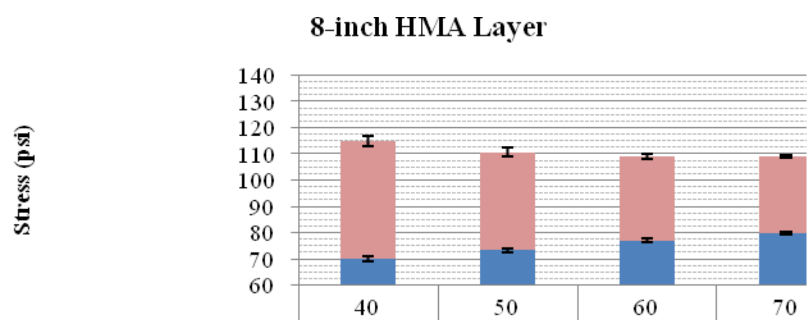
	40	50	60	70
Total Vertical Stress	128	121	114	114
Average Confining Stress	28	31	33	34
Average Deviator Stress	100	90	81	80

HMA Temperature, °C



	40	50	60	70
Total Vertical Stress	123	115	111	110
Average Confining Stress	46	38	33	30
Average Deviator Stress	77	77	78	80

HMA Temperature, °C

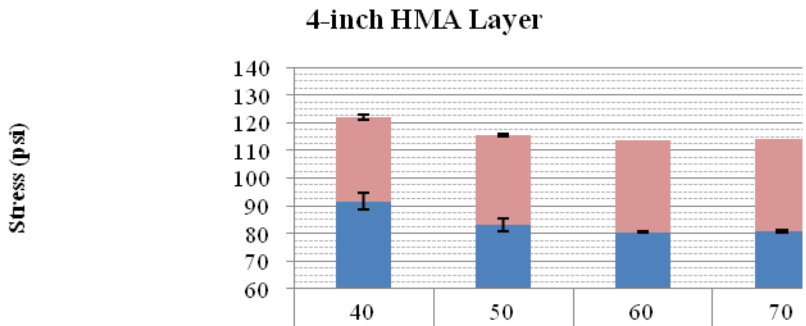


	40	50	60	70
Total Vertical Stress	115	111	109	109
Average Confining Stress	45	38	32	29
Average Deviator Stress	70	73	77	80

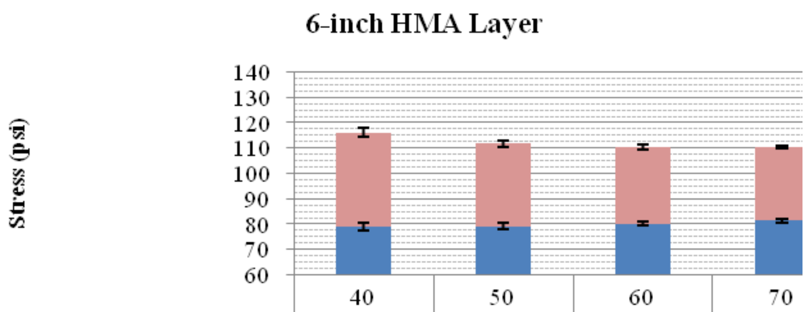
HMA Temperature, °C

Figure E2c.3. Average Maximum deviator, confining, and total stresses of the various pavement structures - PG64-22 mix

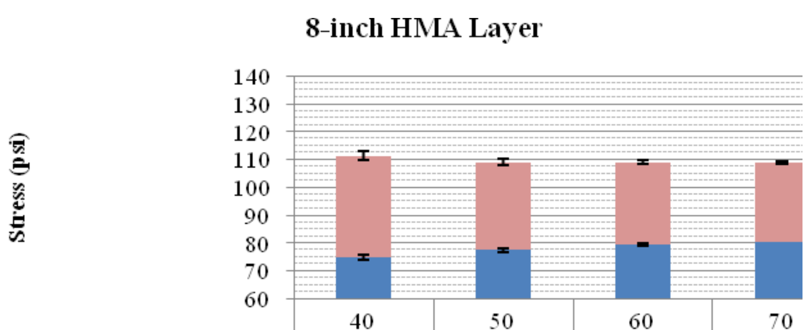
4-inch HMA Layer



HMA Temperature, °C	40	50	60	70
Total Vertical Stress	122	116	114	114
Average Confining Stress	30	33	33	33
Average Deviator Stress	92	83	81	81



HMA Temperature, °C	40	50	60	70
Total Vertical Stress	116	112	110	110
Average Confining Stress	37	33	30	29
Average Deviator Stress	79	79	80	81



HMA Temperature, °C	40	50	60	70
Total Vertical Stress	111	109	109	109
Average Confining Stress	36	32	30	29
Average Deviator Stress	75	77	79	80

Figure E2c.4. Average Maximum deviator, confining, and total stresses of the various pavement structures – PG52-22 mix

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.

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

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

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. Estimated pulse time at 2-inch below pavement surface.

HMA Mix	HMA layer temperature (ºC)	18-wheel travelling 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

Significant Problems, Issues and Potential Impact on Progress

The 3D-Move runs are taking more time than what it was anticipated for 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.

Work Planned for Next Quarter

The calculations of the 3D-Move model will continue to cover all the loading conditions that were described in the experimental plan for this work element.

Evaluate the field HMA mixtures from the WesTrack sections in the laboratory for permanent deformation characteristics under the repeated load triaxial test.

Work element E2d: Thermal Cracking Resistant Mixes for Intermountain States (UNR & UWM)

Work Done This Quarter

This work element is a joint project led by University of Nevada, Reno and supported by University of Wisconsin–Madison. The UNR team continued the long-term oven aging process for the following binders as described in the experimental plan for this work element:

- Unmodified PG64-22
- Polymer modified PG64-28 (using the same PG64-22 crude source) that meets the specs of UT, NV, and CA.

Additionally, the aged binders were tested for rheological properties.

The UNR team continued working on the analyses of the air and pavement temperature profiles data from the LTPP Seasonal Monitoring Program (SMP) and Westrack pavement sections.

Efforts at UW–Madison this quarter include parts of Subtask E2d-2, “Identify the Causes of the Thermal Cracking,” and Subtask E2d-3, “Identify an Evaluation and Testing System.” These are described below.

The new design for the dilatometric cells of the all-in-one device was finalized and a prototype cell was built (figure E2d.1). New gaskets were obtained to maintain a better seal at low temperatures. New connectors for pressure transducers were put into use as well.

Pneumatic and electronic connections for the Single-Edge Notched Bending (SENB) equipment were completed, and new pressure gages were obtained.

Some tests with the Asphalt Binder Cracking Device (ABCD) were performed as part of a ruggedness test for the machine. This was done in collaboration with Dr. Sang-Soo Kim of EZ Asphalt Technology.

Figure E2d.1. New cell prototype for the glass transition temperature measurement equipment.

<u>Significant Results</u>

Figure E2d.2 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.3 shows the measured G*sinδ for the aged PG64-22 asphalt binder at different temperatures and curing times. Similar data are produced for the PG64-28 polymer modified asphalt binder.

The multiple stress recovery (MSCR) test was conducted on the aged asphalt binders according to AASHTO TP70-07. Figure E2d.4 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 found to be less than the average percent recovery at 3.2 kPa which is the opposite trend of what is expected. The results were mainly due to the combination of both the aging of the asphalt binder and the low applied creep stress level (i.e. 0.1 kPa). Therefore, it was decided to rerun the MSCR test at 3.2 kPa and 10 kPa creep stress levels.

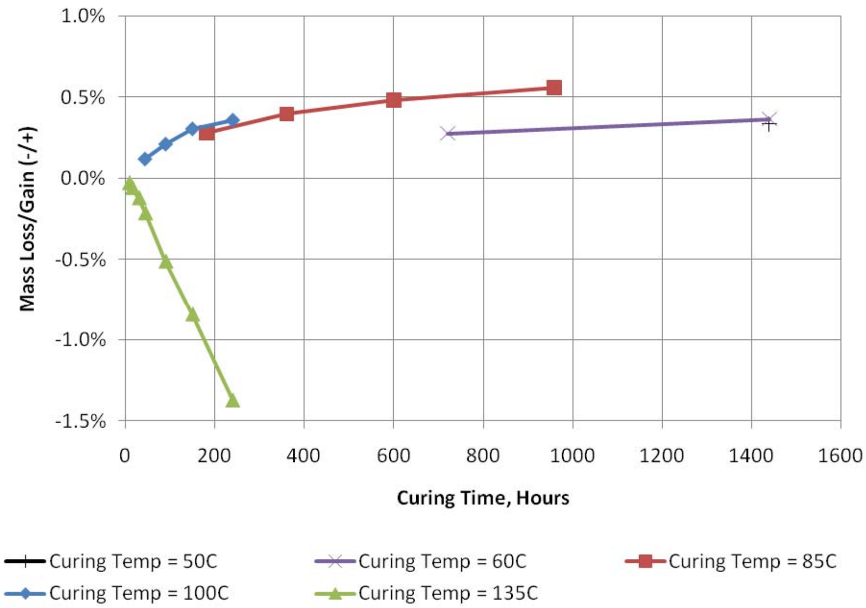


Figure E2d.2. PG64-22 Mass loss/gain at various curing temperatures and times.

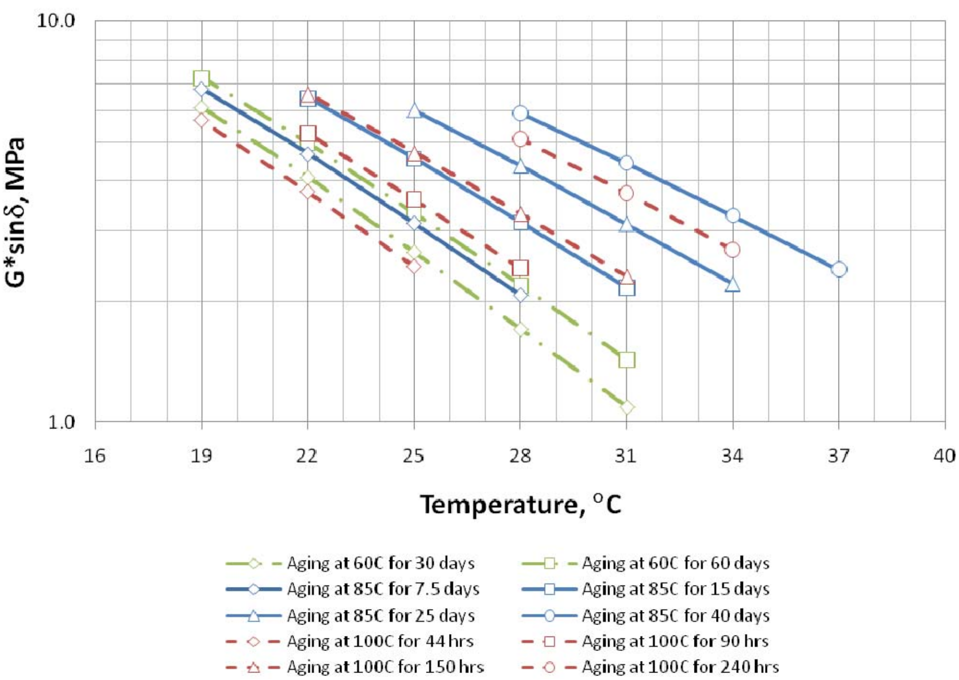


Figure E2d.3. G*sinδ for the PG64-22 at various temperatures and curing times.

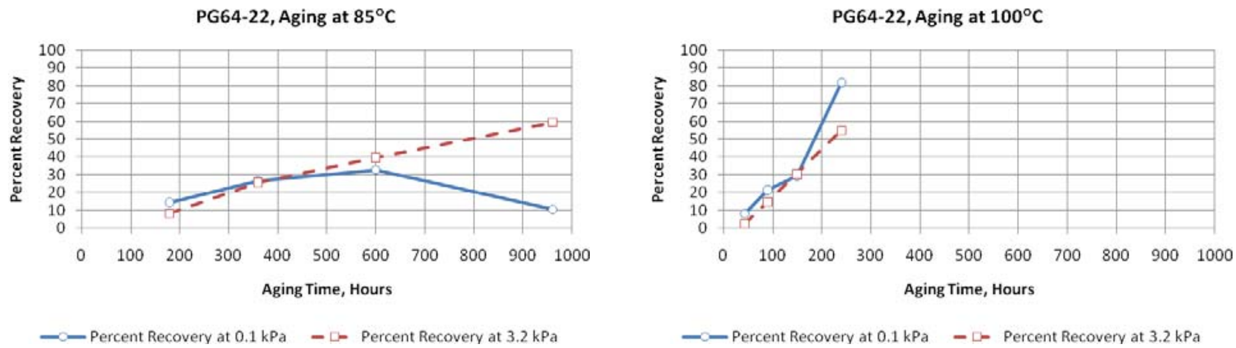


Figure E2d.4. Percent recovery of the PG64-22 asphalt binder from the MSCR test.

The UNR-team completed the calculations for the pavement temperature rates for all the LTPP SMP sections. Additionally, the data from the LTPP SMP sections were checked against the information provided by the LTPPBind software version 3.1. Table E2d.1 shows the minimum air and pavement temperatures from the LTPP SMP sections and the LTPPBind software. A difference was observed between the two sets of data (i.e. LTPP SMP and LTPPBind software). The difference is mainly related to the number of years of the collected data. Some SMP locations were eliminated from the analysis for sensor reading problems.

The proper working of the new configuration for the cells of the glass transition temperature equipment was tested successfully. Two additional cells were ordered to perform testing on multiple samples and to use a dummy sample to check the temperature in real time.

The modification of the Bending Beam Rheometer (BBR) load frame for SENB testing was completed, and its functioning has been verified. The new pressure gages provide sufficient air bearing, and the load cell and linear variable differential transformer (LVDT) outputs are correctly read by the normal BBR software. The motor is working and it is correctly controlled through its software.

Significant Problems, Issues and Potential Impact on Progress

The investigation on the impact of TSRST specimen size and shape has been delayed because of the limited availability of the equipment and the extensive use of liquid nitrogen as a cooling agent. The existing TSRST equipment set-up at UNR is in the process to be upgraded with a chiller and a control unit based on compressed air to replace the liquid nitrogen cooling agent.

Although significantly improved, the sealing of the cells has shown some problems, especially with connecting the pressure sensors. Recent efforts seem to have solved the issue, which has nonetheless delayed the experimental plan. Moreover, some delays at the manufacturing facility have slowed the production of the two copies of the cell.

The air bearing pressure for the SENB equipment is sufficient; however there is still some friction in the shaft internal lodging, which makes the calibration process impossible because the applied force is not constant. The reason for this remains unknown. The instrument will be further examined for construction defects or possible misalignment.

Table E2d.1 Summary of Air and Pavement Temperatures from the LTPP SMP Sections and the LTPPBind Data.

LTPP Seasonal Monitoring Program (SMP)										LTPPBind Software Data (version 3.1)					
Section	**City**	**State**	**Sensor No.**	**Sensor Depth (mm)**	**Sensor Installation Date**	**Data Range**	**Number of Years of Data**	**Min Air Temp Reading (°C)**	**Min Pavement Temp Reading (°C)**	**Number of Years of Data**	**Min Air Temp Average (°C)**	**Min Air Temp (°C)**	**Min Air Temp Standard Deviation S_{air}, (°C)**	**Pavement Temp at 98% reliability (°C)**	**Pavement Temp at 50% reliability (°C)**
40113	Kingman	AZ	1	15	8/15/1995	8/15/95 - 9/13/95, 11/11/95 - 12/6/95, 1/10/96 - 8/14/96, 11/6/97 - 3/2/98, 4/9/98 - 7/15/98	1.5	-4.8	-4.2	25	-8.8	-15.5	3.1	-9.12	-2.82
40113	Kingman	AZ	2	47	8/15/1995	8/15/95 - 9/13/95, 11/11/95 - 12/6/95, 1/10/96 - 8/14/96, 11/6/97 - 3/2/98, 4/9/98 - 11/10/98	1.5	-4.8	-1.3	25	-8.8	-15.5	3.1	-7.52	-1.23
40113	Kingman	AZ	3	80	8/15/1995	8/15/95 - 9/13/95, 11/11/95 - 12/6/95, 1/10/96 - 8/14/96, 11/6/97 - 3/2/98, 4/9/98 - 11/17/98	1.5	-4.8	0.6	25	-8.8	-15.5	3.1	-6.50	-0.20
40113	Kingman	AZ	1	25	11/30/1999	1/19/02 - 4/30/02	0.27	-6.5	-4.2	25	-8.8	-15.5	3.1	-8.52	-2.22
40113	Kingman	AZ	2	53	11/30/1999	No Data	--	-6.5	--	25	-8.8	-15.5	3.1	-7.31	-1.01
40113	Kingman	AZ	3	80	11/30/1999	12/6/01 - 1/1/02	1	-6.5	2.9	25	-8.8	-15.5	3.1	-6.50	-0.20
40113	Kingman	AZ	1	43	5/1/2002	5/1/02 - 4/15/03	0.96	-3.3	-0.8	25	-8.8	-15.5	3.1	-7.68	-1.38
40113	Kingman	AZ	2	71	5/1/2002	No Data	--	-3.3	--	25	-8.8	-15.5	3.1	-6.74	-0.44
40113	Kingman	AZ	3	98	5/1/2002	5/30/02 - 11/4/02	0.42	-3.3	12.4	25	-8.8	-15.5	3.1	-6.07	0.23
40113	Kingman	AZ	1	43	4/16/2003	4/16/03 - 10/4/04	1.46	-4.5	-2.2	25	-8.8	-15.5	3.1	-7.68	-1.38
40113	Kingman	AZ	2	73	4/16/2003	4/16/03 - 10/4/04	1.46	-4.5	-0.7	25	-8.8	-15.5	3.1	-6.69	-0.39
40113	Kingman	AZ	3	103	4/16/2003	4/16/03 - 10/4/04	1.46	-4.5	0.5	25	-8.8	-15.5	3.1	-5.96	0.34
40114	Kingman	AZ	1	12	8/16/1995	8/17/95 - 8/13/96, 11/04/97 - 2/19/98, 3/26/98 - 4/24/98	1.42	-4.9	-3.7	25	-8.8	-15.5	3.1	-9.33	-3.04
40114	Kingman	AZ	2	80	8/16/1995	8/17/95 - 8/13/96, 11/04/97 - 2/19/98, 3/26/98 - 4/24/98	1.42	-4.9	-1.5	25	-8.8	-15.5	3.1	-6.50	-0.20

LTPP Seasonal Monitoring Program (SMP)										LTPPBind Software Data (version 3.1)					
Section	City	State	Sensor No.	Sensor Depth (mm)	Sensor Installation Date	Data Range	Number of Years of Data	Min Air Temp Reading (°C)	Min Pavement Temp Reading (°C)	Number of Years of Data	Min Air Temp Average (°C)	Min Air Temp (°C)	Min Air Temp Standard Deviation S_{air}, (°C)	Pavement Temp at 98% reliability (°C)	Pavement Temp at 50% reliability (°C)
40114	Kingman	AZ	3	149	8/16/1995	8/17/95 - 8/13/96, 11/04/97 - 2/19/98, 3/26/98 - 4/24/98	1.42	-4.9	0.1	25	-8.8	-15.5	3.1	-5.13	1.17
40114	Kingman	AZ	1	25	11/30/2001	12/01/01 - 4/30/02	0.42	-7.2	-4.3	25	-8.8	-15.5	3.1	-8.52	-2.22
40114	Kingman	AZ	2	90	11/30/2001	12/01/01 - 4/30/02	0.42	-7.2	-0.9	25	-8.8	-15.5	3.1	-6.25	0.05
40114	Kingman	AZ	3	155	11/30/2001	12/01/01 - 4/30/02	0.42	-7.2	2.1	25	-8.8	-15.5	3.1	-5.03	1.27
40114	Kingman	AZ	1	43	5/1/2002	5/1/02 - 10/5/04	2.42	-6.4	-1.4	25	-8.8	-15.5	3.1	-7.68	-1.38
40114	Kingman	AZ	2	108	5/1/2002	5/1/02 - 10/5/04	2.42	-6.4	2.3	25	-8.8	-15.5	3.1	-5.86	0.44
40114	Kingman	AZ	3	185	5/1/2002	5/1/02 - 10/5/04	2.42	-6.4	5.8	25	-8.8	-15.5	3.1	-4.61	1.68
41024	Flagstaff	AZ	1	13	8/21/1995	10/12/95 - 11/16/95	0.08	-17.6	11.8	13	-29.8	-38.5	4.8	-26.39	-18.07
41024	Flagstaff	AZ	2	130	8/21/1995	9/1/95 - 8/15/96	0.9	-17.6	-0.2	13	-29.8	-38.5	4.8	-22.56	-14.25
41024	Flagstaff	AZ	3	247	8/21/1995	9/1/95 - 8/15/96	0.9	-17.6	2.3	13	-29.8	-38.5	4.8	-21.03	-12.72
41024	Flagstaff	AZ	1	13	3/17/1997	No Data	--	-17.6	--	13	-29.8	-38.5	4.8	-26.39	-18.07
41024	Flagstaff	AZ	2	130	3/17/1997	No Data	--	-17.6	--	13	-29.8	-38.5	4.8	-22.56	-14.25
41024	Flagstaff	AZ	3	247	3/17/1997	No Data	--	-17.6	--	13	-29.8	-38.5	4.8	-21.03	-12.72
41024	Flagstaff	AZ	1	13	7/7/1997	No Data	--	-17.6	--	13	-29.8	-38.5	4.8	-26.39	-18.07
41024	Flagstaff	AZ	2	130	7/7/1997	11/16/97 - 2/3/98	0.3	-17.6	-1.3	13	-29.8	-38.5	4.8	-22.56	-14.25
41024	Flagstaff	AZ	3	247	7/7/1997	No Data	--	-17.6	--	13	-29.8	-38.5	4.8	-21.03	-12.72
41024	Flagstaff	AZ	1	13	2/3/1998	No Data	--	-8.3	--	13	-29.8	-38.5	4.8	-26.39	-18.07
41024	Flagstaff	AZ	2	130	2/3/1998	2/4/98 - 11/19/98	0.8	-8.3	1.2	13	-29.8	-38.5	4.8	-22.56	-14.25
41024	Flagstaff	AZ	3	247	2/3/1998	No Data	--	-8.3	--	13	-29.8	-38.5	4.8	-21.03	-12.72
81053	Delta	CO	1	13	7/1/1993	10/15/93 - 5/8/95, 3/29/97 - 5/21/97, 7/21/97 - 7/25/97	1.6	-18	-11.2	31	-21.8	-33	5.0	-21.94	-13.37
81053	Delta	CO	2	61	7/1/1993	10/15/93 - 5/8/95, 9/22/96 - 9/26/97	2.5	-18	-9.1	31	-21.8	-33	5.0	-19.72	-11.15
81053	Delta	CO	3	109	7/1/1993	10/15/93 - 5/8/95, 9/22/96 - 9/26/97	2.5	-18	-6.6	31	-21.8	-33	5.0	-18.52	-9.95

LTPP Seasonal Monitoring Program (SMP)										LTPPBind Software Data (version 3.1)					
Section	City	State	Sensor No.	Sensor Depth (mm)	Sensor Installation Date	Data Range	Number of Years of Data	Min Air Temp Reading (°C)	Min Pavement Temp Reading (°C)	Number of Years of Data	Min Air Temp Average (°C)	Min Air Temp (°C)	Min Air Temp Standard Deviation S_{air}, (°C)	Pavement Temp at 98% reliability (°C)	Pavement Temp at 50% reliability (°C)
161010	Idaho Falls	ID	1	23	9/30/1993	10/22/93 - 5/22/95, 9/29/96 - 1/24/97	2	-26.4	-16.7	33	-26.8	-36.5	5.0	-26.47	-17.89
161010	Idaho Falls	ID	2	137	9/30/1993	10/22/93 - 5/22/95, 9/29/96 - 1/24/97	2	-26.4	-14.5	33	-26.8	-36.5	5.0	-23.16	-14.59
161010	Idaho Falls	ID	3	250	9/30/1993	10/22/93 - 5/22/95, 9/29/96 - 1/24/97	2	-26.4	-11.9	33	-26.8	-36.5	5.0	-21.72	-13.15
300114	Great Falls	MT	1	25	7/12/2000	No Data	--	-30.4	--	35	-32.9	-41.5	4.2	-31.20	-23.63
300114	Great Falls	MT	2	91	7/12/2000	No Data	--	-30.4	--	35	-32.9	-41.5	4.2	-28.91	-21.34
300114	Great Falls	MT	3	156	7/12/2000	No Data	--	-30.4	--	35	-32.9	-41.5	4.2	-27.70	-20.13
300114	Great Falls	MT	1	25	5/14/2001	5/23/01 - 12/11/01	0.6	-32.2	-4.7	35	-32.9	-41.5	4.2	-31.20	-23.63
300114	Great Falls	MT	2	91	5/14/2001	5/23/01 - 9/29/03	2.4	-32.2	-14.5	35	-32.9	-41.5	4.2	-28.91	-21.34
300114	Great Falls	MT	3	156	5/14/2001	5/23/01 - 9/29/03	2.4	-32.2	-10.8	35	-32.9	-41.5	4.2	-27.70	-20.13
300114	Great Falls	MT	1	25	9/29/2003	9/30/03 - 9/22/04	1	-39.9	-26.2	35	-32.9	-41.5	4.2	-31.20	-23.63
300114	Great Falls	MT	2	98	9/29/2003	9/30/03 - 9/22/04	1	-39.9	-21.1	35	-32.9	-41.5	4.2	-28.75	-21.18
300114	Great Falls	MT	3	172	9/29/2003	9/30/03 - 9/22/04	1	-39.9	-16.9	35	-32.9	-41.5	4.2	-27.47	-19.90
308129	Ryegate	MT	1	3	8/12/1992	9/1/93 - 5/18/95	1.7	-37.5	-21.4	35	-33.6	-41	3.9	-32.56	-25.35
308129	Ryegate	MT	2	37	8/12/1992	9/1/93 - 5/18/95, 6/1/97 - 8/25/97	1.9	-37.5	-19.6	35	-33.6	-41	3.9	-30.40	-23.19
308129	Ryegate	MT	3	71	8/12/1992	9/1/93 - 5/18/95, 6/1/97 - 8/25/97	1.9	-37.5	-17.4	35	-33.6	-41	3.9	-29.21	-22.00
320101	Battle Mountain	NV	1	25	10/8/1996	11/10/96 - 7/15/97	0.7	Not Provided	-9.10	33	-24.7	-39.50	5.1	-24.02	-15.32
320101	Battle Mountain	NV	2	83	10/8/1996	11/10/96 - 7/15/97	0.7	Not Provided	-6.80	33	-24.7	-39.50	5.1	-21.92	-13.22
320101	Battle Mountain	NV	3	140	10/8/1996	11/10/96 - 7/15/97	0.7	Not Provided	-3.80	33	-24.7	-39.50	5.1	-20.77	-12.07
320101	Battle Mountain	NV	1	25	11/19/1999	12/1/99 - 4/30/02	2.3	Not Provided	-8.80	33	-24.7	-39.5	5.1	-24.02	-15.32
320101	Battle Mountain	NV	2	83	11/19/1999	12/1/99 - 4/17/02	2.3	Not Provided	-5.90	33	-24.7	-39.5	5.1	-21.92	-13.22

LTPP Seasonal Monitoring Program (SMP)										LTPPBind Software Data (version 3.1)					
Section	**City**	**State**	**Sensor No.**	**Sensor Depth (mm)**	**Sensor Installation Date**	**Data Range**	**Number of Years of Data**	**Min Air Temp Reading (°C)**	**Min Pavement Temp Reading (°C)**	**Number of Years of Data**	**Min Air Temp Average (°C)**	**Min Air Temp (°C)**	**Min Air Temp Standard Deviation S_{air}, (°C)**	**Pavement Temp at 98% reliability (°C)**	**Pavement Temp at 50% reliability (°C)**
320101	Battle Mountain	NV	3	140	11/19/1999	12/1/99 - 12/17/00, 3/1/01 - 11/28/01, 3/19/02 - 4/30/02	1.8	Not Provided	-3.30	33	-24.7	-39.5	5.1	-20.77	-12.07
320101	Battle Mountain	NV	1	25	5/1/2002	5/1/02 - 7/9/02	0.2	Not Provided	3.50	33	-24.7	-39.5	5.1	-24.02	-15.32
320101	Battle Mountain	NV	2	83	5/1/2002	5/17/02 - 9/22/02	0.3	Not Provided	16.00	33	-24.7	-39.5	5.1	-21.92	-13.22
320101	Battle Mountain	NV	3	140	5/1/2002	5/1/02 - 11/28/02	0.6	Not Provided	1.00	33	-24.7	-39.5	5.1	-20.77	-12.07
351112	Hobbs	NM	1	25	4/5/1994	6/20/94 - 11/14/94, 1/1/95 - 6/27/95, 12/1/96 - 4/15/97, 6/1/97 - 8/31/97, 2/2/00 - 9/16/00	2.1	-14.1	-7.50	35	-13.3	-19.0	3	-10.97	-4.78
351112	Hobbs	NM	2	76	4/5/1994	6/20/94 - 11/14/94, 1/1/95 - 6/27/95, 12/1/96 - 4/15/97, 6/1/97 - 8/31/97, 2/2/00 - 9/16/00	2.1	-14.1	-6.20	35	-13.3	-19.0	3	-9.06	-2.87
351112	Hobbs	NM	3	127	4/5/1994	6/20/94 - 11/14/94, 1/1/95 - 6/27/95, 12/1/96 - 4/15/97, 6/1/97 - 8/31/97, 2/2/00 - 9/16/00	2.1	-14.1	-4.50	35	-13.3	-19.0	3	-7.95	-1.75
469187	Faith	SD	1	23	7/18/1994	7/18/94 - 6/26/95, 10/25/96- 9/23/97	1.8	-31.8	-25.10	33	-30.6	-36.5	3.7	-28.15	-21.18
469187	Faith	SD	2	65	7/18/1994	7/18/94 - 6/26/95, 10/25/96- 9/23/97	1.8	-31.8	-22.60	33	-30.6	-36.5	3.7	-26.44	-19.47
469187	Faith	SD	3	106	7/18/1994	7/18/94 - 6/26/95, 10/25/96- 9/23/97	1.8	-31.8	-20.80	33	-30.6	-36.5	3.7	-25.42	-18.45
481077	Estelline (Memphis Weather Station)	TX	1	25	10/25/1993	12/14/93 - 8/7/94, 3/1/95 - 6/6/95, 3/18/97 - 4/17/97	1	-15.4	-6.70	34	-14.8	-21.0	2.7	-12.29	-6.41
481077	Estelline (Memphis Weather Station)	TX	2	65	10/25/1993	12/14/93 - 6/26/94, 3/17/97 - 4/17/97	0.6	-15.4	-4.70	34	-14.8	-21.0	2.7	-10.69	-4.81

LTPP Seasonal Monitoring Program (SMP)										LTPPBind Software Data (version 3.1)					
Section	**City**	**State**	**Sensor No.**	**Sensor Depth (mm)**	**Sensor Installation Date**	**Data Range**	**Number of Years of Data**	**Min Air Temp Reading (°C)**	**Min Pavement Temp Reading (°C)**	**Number of Years of Data**	**Min Air Temp Average (°C)**	**Min Air Temp (°C)**	**Min Air Temp Standard Deviation S_{air} , (°C)**	**Pavement Temp at 98% reliability (°C)**	**Pavement Temp at 50% reliability (°C)**
481077	Estelline (Memphis Weather Station)	TX	3	105	10/25/1993	12/14/93 - 8/1/94, 3/16/95 - 6/6/95	0.8	-15.4	-2.30	34	-14.8	-21.0	2.7	-9.69	-3.81
481122	Floresville	TX	1	13	11/22/1993	1/25/94 - 6/13/95, 9/04/00 - 2/13/01	1.9	-8.2	0.60	34	-7.9	-15.0	2.8	-6.74	-0.75
481122	Floresville	TX	2	40	11/22/1993	1/25/94 - 6/13/95, 11/16/96 - 9/29/97, 9/03/00 - 2/2/01, 11/13/01 - 1/28/02, 4/15/02 - 7/18/02	3.1	-8.2	-1.80	34	-7.9	-15.0	2.8	-5.28	0.71
481122	Floresville	TX	3	67	11/22/1993	1/25/94 - 5/13/94, 9/3/00 - 1/25/01, 11/13/01 - 1/28/02, 4/15/02 - 7/18/02	1.2	-8.2	2.50	34	-7.9	-15.0	2.8	-4.33	1.65
481122	Floresville	TX	1	13	7/19/2002	No Data	--	3.5	--	34	-7.9	-15.0	2.8	-6.74	-0.75
481122	Floresville	TX	2	40	7/19/2002	7/19/02 - 11/19/02	0.3	3.5	22.30	34	-7.9	-15.0	2.8	-5.28	0.71
481122	Floresville	TX	3	67	7/19/2002	7/19/02 - 11/19/02	0.3	3.5	11.30	34	-7.9	-15.0	2.8	-4.33	1.65
491001	Bluff	UT	1	5	8/5/1993	11/4/93 - 5/1/95	1.4	-14.2	-8.40	35	-19.6	-30.0	5.1	-20.68	-11.98
491001	Bluff	UT	2	65	8/5/1993	11/4/93 - 1/6/95	1.1	-14.2	-10.00	35	-19.6	-30.0	5.1	-17.70	-9.00
491001	Bluff	UT	3	126	8/5/1993	11/4/93 - 1/6/95	1.1	-14.2	-11.40	35	-19.6	-30.0	5.1	-16.29	-7.59
491001	Bluff	UT	1	15	9/4/1996	9/12/96 - 11/30/96, 4/24/97 - 9/24/97	1	-15.0	-8.00	35	-19.6	-30.0	5.1	-19.90	-11.20
491001	Bluff	UT	2	75	9/4/1996	9/12/96 - 11/30/96, 4/24/97 - 9/24/97	1	-15.0	-7.20	35	-19.6	-30.0	5.1	-17.41	-8.71
491001	Bluff	UT	3	136	9/4/1996	9/12/96 - 11/30/96, 4/24/97 - 9/24/97	1	-15.0	-6.80	35	-19.6	-30.0	5.1	-16.12	-7.42
561007	Cody	WY	1	13	8/10/1993	10/19/93 - 5/17/95	1.6	-27.0	-14.80	31	-29.4	-38.5	4	-28.10	-20.77
561007	Cody	WY	2	39	8/10/1993	10/19/93 - 5/17/95, 2/19/97 - 3/07/97	1.6	-31.5	-15.10	31	-29.4	-38.5	4	-26.68	-19.35
561007	Cody	WY	3	65	8/10/1993	10/19/93 - 5/17/95, 9/24/96 - 9/30/97	2.6	-31.5	-20.40	31	-29.4	-38.5	4	-25.75	-18.42

Work Planned Next Quarter

Continue the aging process of binders and continue measuring the properties of the aged binders.

Continue the analysis of the air temperature profiles data from the LTPP SMP sections and the Westrack. Prepare a table summarizing the determined minimum and maximum air and pavement temperature along with the calculated air and pavement temperature rates.

Check whether the LTPPBind data for air temperatures can be obtained and analyzed.

After the new dilatometric cells for the glass transition temperature device are built, the experimental plan will be initiated and carried out. Tests will be run on both binders and mixtures.

The cause for the malfunctioning of the SENB machine will be sought, identified and fixed. The calibration of the machine will then be performed and the testing stage will be initiated.

The possibility of including the ABCD test procedure in the work plan will be evaluated based on the relevance of the results obtained.

Fourier transform infrared (FTIR) spectroscopy tests will be performed by using the equipment in UW–Madison's Department of Physics.

Work element E2e: Design Guidance for Fatigue and Rut Resistance Mixtures (AAT)

Work Done This Quarter

No effort was expended this Quarter on this work element pending final selection of the core asphalts, aggregates, and modifiers. The core materials should be included in the final experimental plans developed for this work element.

Significant Results

Improvements have been identified for the following models developed in NCHRP Project 9-25:

(1) Hirsch Model for dynamic modulus,
(2) Resistivity Model for rutting resistance,
(3) Continuum Damage Fatigue Model
(4) Permeability Model

Preliminary experimental plans have been developed to address the needed model improvements.

Significant Problems, Issues and Potential Impact on Progress

This work element is approximately 6 months behind the proposed Year 2 schedule. This delay can be made up during the remaining years for the project by accelerating the laboratory testing schedule.

Work Planned Next Quarter

Final experimental designs will be prepared using the final core materials selected by the Asphalt Research Consortium.

Engineered Materials Year 2

	Year 2 (4/2008-3/2009)												Team
	4	5	6	7	8	9	10	11	12	1	2	3	
(1) High Performance Asphalt Materials													
E1a: Analytical and Micro-mechanics Models for Mechanical behavior of mixtures													TAMU
E1a-1: Analytical Micromechanical Models of Binder Properties										P	JP	P	
E1a-2: Analytical Micromechanical Models of Modified Mastic Systems										P	JP	P	
E1a-3: Analytical Models of Mechanical Properties of Asphalt Mixtures			P	P	JP					P	JP	P	
E1a-4: Analytical Model of Asphalt Mixture Response and Damage										P	JP	P	
E1b: Binder Damage Resistance Characterization													UWM
E1b-1: Rutting of Asphalt Binders													
E1b-1-1: Literature review													
E1b1-2: Select Materials & Develop Work Plan		DP, P											
E1b1-3: Conduct Testing								P, JP					
E1b1-4: Analysis & Interpretation						JP						JP	
E1b1-5: Standard Testing Procedure and Recommendation for Specifications													
E1b-2: Feasibility of Determining rheological and fracture properties of thin films of asphalt binders and mastics using nano-indentation													UWM
E1b-2i. Literature Review and Identification of Equipment												P	
E1b-2ii. Exploratory Use of Nanoindentation Devices												D	
E1b-2iii. Conduct of Exploratory Tests on Binder Specimens												P	
E1b-2iv. Compare the Binders Responses with DSR													
E1b-2v. Develop & Design Testing Setup													
E2a: Comparison of Modification Techniques													UWM
E2a-1: Identify modification targets and material suppliers												DP	
E2a-2: Test material properties													
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									D				
E2c-2: Conduct Mixtures Evaluations													
E2c-3: Develop a Simple Test													
E2c-4: Develop Standard Test Procedure													
E2c-5: Evaluate the Impact of Mix Characteristics													
E2d: Thermal Cracking Resistant Mixes for Intermountain States													UWM/UNR
E2d-1: Identify Field Sections													
E2d-2: Identify the Causes of the Thermal Cracking													
E2d-3: Identify an Evaluation and Testing System													
E2d-4: Modeling and Validation of the Developed System													
E2d-5: Develop a Standard													
E2e: Design Guidance for Fatigue and Rut Resistance Mixtures													AAT
E2e-1: Identify Model Improvements													
E2e-2: Design and Execute Laboratory Testing Program					JP					P			
E2e-3: Perform Engineering and Statistical Analysis to Refine Models													
E2e-4: Validate Refined Models													
E2e-5: Prepare Design Guidance													
(2) Green Asphalt Materials													
E2b: Design System for HMA Containing a High Percentage of RAP Material													UNR
E2b-1: Develop a System to Evaluate the Properties of RAP Materials													
E2b-1.b: Develop a System to Evaluate the Properties of the RAP Binder		P		JP									
E2b-2: Compatibility of RAP and Virgin Binders													
E2b-3: Develop a Mix Design Procedure													
E2b-4: Impact of RAP Materials on Performance of Mixtures													
E2b-5: Field Trials													
E1c: Warm and Cold Mixes													UWM
E1c-1: Warm Mixes													
E1c-1i: Effects of Warm Mix Additives on Rheological Properties of Binders													
E1c-1ii. Effects of Warm Mix Additives on Mixture Workability and Stability				JP	P				D		DP	F	
E1c-1iii. Mixture Performance Testing													
E1c-1iv. Develop Revised Mix Design Procedures													
E1c-1v. Field Evaluation of Mix Design Procedures and Performance Recommendations													
E1c-2: Improvement of Emulsions' Characterization and Mixture Design for Cold Bitumen Applications													
E1c-2i. Review of Literature and Standards				JP,P		D			F				
E1c-2ii. Creation of Advisory Group													
E1c-2iii. Identify Tests and Develop Experimental Plan												P, DP	
E1c-2iv. Develop Material Library and Collect Materials.													
E1c-2v. Conduct Testing Plan													
E1c-2vi. Develop Performance Selection Guidelines													
E1c-2vii. Validate Guidelines													
E1c-2viii. Develop CMA Mix Design Procedure													
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 thin films of asphalt binders and mastics using nano-indentation																	
E1b-2i. Literature Review and Identification of Equipment							D	F									
E1b-2ii. Exploratory Use of Nanoindentation Devices						JP											
E1b-2iii. Conduct of Exploratory Tests on Binder Specimens										JP		P					
E1b-2iv. Compare the Binders Responses with DSR														JP			
E1b-2v. Develop & Design Testing Setup															D	P,F	
E2a: Comparison of Modification Techniques																	UWM
E2a-1: Identify modification targets and material suppliers				DP		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			D			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											
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		JP		P				D,F									
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-1.b: Develop a System to Evaluate the Properties of the RAP Binder	P						P	JP									
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		JP,P	D	F,DP													UWM
E1c-1iii. Mixture Performance Testing						JP		P, DP									UW/UNR
E1c-1iv. Develop Revised Mix Design Procedures										JP	P						UW/UNR
E1c-1v. Field Evaluation of Mix Design Procedures and Performance Recommendations														JP	D	P,F	UW/UNR
E1c-2: Improvement of Emulsions' Characterization and Mixture Design for Cold Bitumen Applications																	UWM
E1c-2i: Review of Literature and Standards		JP,P, D	F		D	D											
E1c-2ii: Creation of Advisory Group																	
E1c-2ii: Identify Tests and Develop Experimental Plan				P, DP	D		D										
E1c-2iv. Develop Material Library and Collect Materials.																	
E1c-2v. Conduct Testing Plan						JP	D	P									
E1c-2vi. Develop Performance Selection Guidelines										JP	D	P, F					
E1c-2vii. Validate Guidelines														JP	P		
E1c-2viii. Develop CMA Mix Design Procedure												P					
E1c-2ix. Develop CMA Performance Guidelines														JP	D	F	

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Executable software, code and user manual
Paper submitted to conference or journal
Presentation for symposium, conference or other
Time to make a decision on two parallel paths as to which is most promising to follow througjh

Work planned
Work completed
Parallel topic

PROGRAM AREA: VEHICLE-PAVEMENT INTERACTION

CATEGORY VP1: WORKSHOP

Work element VP1a: Workshop on Super-Single Tires

This work element is complete.

CATEGORY VP2: DESIGN GUIDANCE

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

Work Done This Quarter

As part of an FHWA equipment loan program, the Circular Texture Meter (CTMeter, ASTM) and Dynamic Friction Tester (DFTester, ASTM E1911) were delivered this quarter to the University of Wisconsin–Madison. A representative from Burns Cooley Dennis, Inc. traveled to Madison to train the research staff in the equipment's operation. The UW–Madison team is currently developing a research plan and parametric study involving the new equipment to investigate texture and friction properties of laboratory-prepared specimens.

The CTMeter is a laser profilometer-based system that measures the depth profile of a pavement along a circular path. It outputs a Mean Texture Depth (MTD) over the length of the laser's path, as well as a profile graph to show the relative differences along this path.

The DFTester measures the frictional resistance of the pavement surface with rotating arms that have pads attached to their ends. The output of the test is the coefficient of friction at various speeds between the rotating pads and the pavement surface.

Both of these devices are intended primarily for use in the field on full-scale pavements. When used in the lab, specimens are required to be no smaller than 600 mm × 600 mm. The research team is currently working on incorporating the use of gyratory specimens with the testing devices to develop mix design procedures to address texture and friction.

Work Planned Next Quarter

The research team plans to begin preliminary testing of gyratory specimens using the CTMeter and DFTester. Based on the results of this work, the team will finalize an experimental design for a parametric study involving the effect of nominal maximum aggregate size, percent air voids, aggregate type and other relevant mixture properties on the texture and friction of laboratory-prepared specimens. An extensive collection of loose HMA sampled from field projects in Wisconsin is available for the lab study, providing an opportunity to measure field characteristics for comparison.

CATEGORY VP3: MODELING

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

Work Done This Quarter

Working on the 3D-Move model to make it a menu-driven software. Additionally, the Nevada Automotive Test Center (NATC) was contacted for information on non-uniform tire/pavement contact pressure distribution measurements.

Significant Results

Figures VP3a.1 and VP3a.2 show selected snapshots from the newly developed 3D-Move user friendly interface. Whenever possible, a structure similar to that of the MEPDG software is followed.

The Nevada Automotive Test Center (NATC) supplied UNR with the available information for non-uniform tire/pavement contact pressure distribution measurements. UNR summarized the available information in tables VP3a.1-VP3a.4. Two main set 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 at 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.

Work Planned Next Quarter

Continue working on the 3D-Move model to make it a menu-driven software.
Continue collecting and developing the database for non-uniform tire/pavement contact pressure distribution.

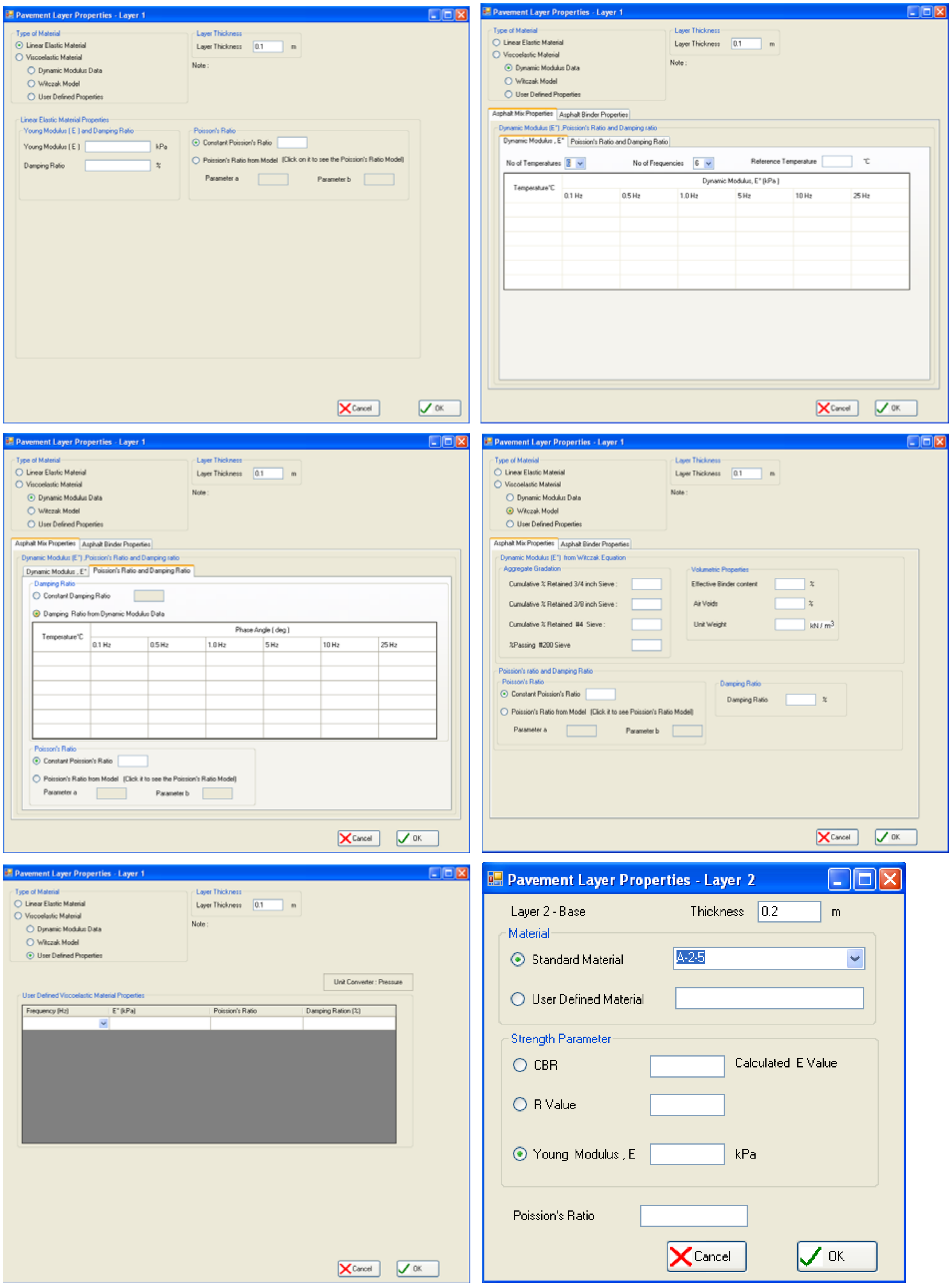

Figure VP3a.1. 3D-Move – selected material properties input windows.

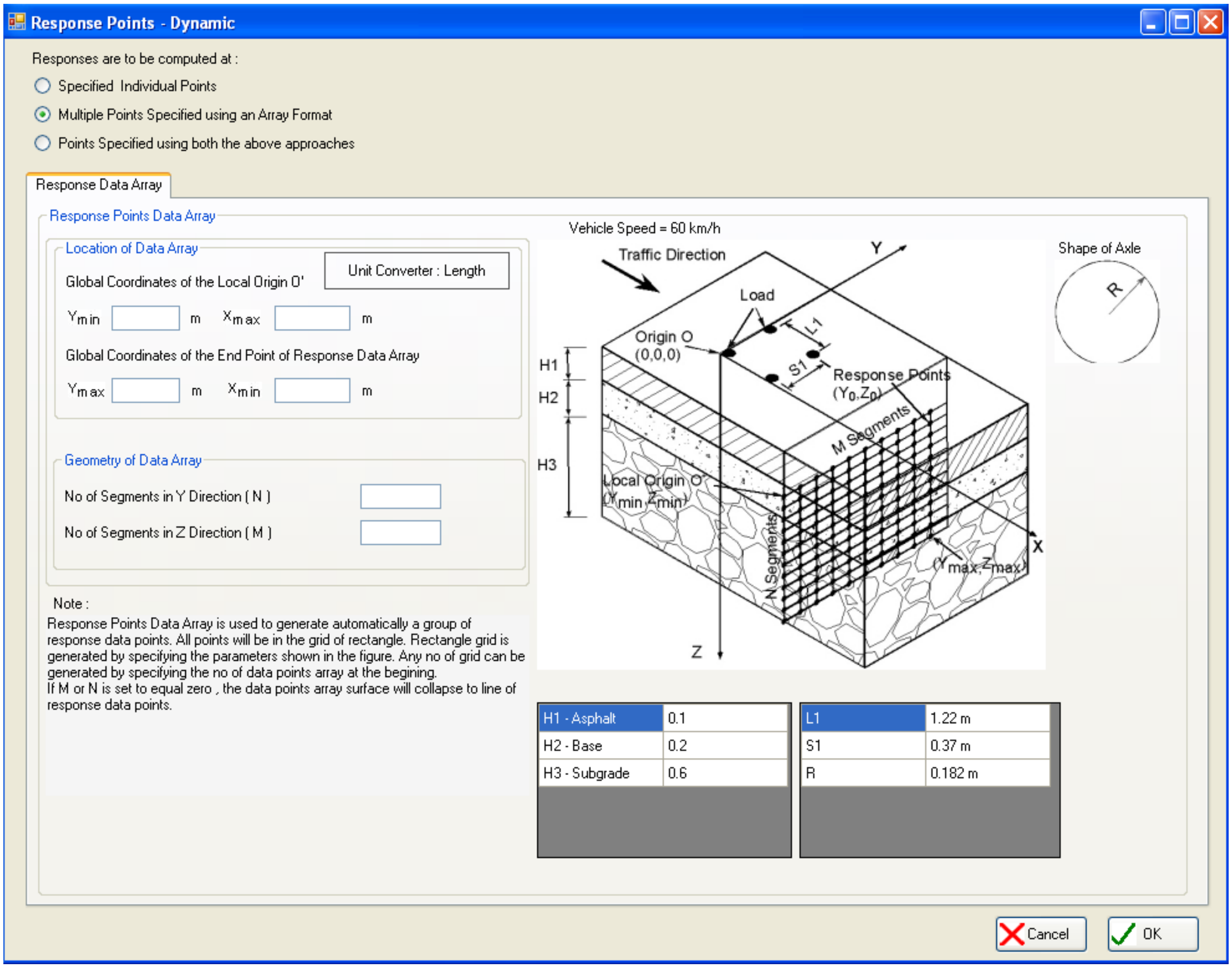

Figure VP3a.2. 3D-Move response points selection.

Table VP3a.1 Summary of the VRSPTA sensor array device data for the evaluated single tires.

Tire Type	Load, kN	Pressure, kPa	Measuring Tire Speed
UCB GOODYEAR 10.00*20 BIAS PLY (Single) (50 Tests)	26	220; 420; 520; 620; 690; 720; 820; 920	All tests were performed at a creep speed (Between 0.315 - 0.330 m/s)
	31	220; 420; 520; 620; 690; 720; 820; 920	
	36	220; 420; 520; 620; 690; 720; 820; 920	
	41	420; 520; 620; 690; 720; 820; 920	
	46	420; 520; 620; 690; 720; 820; 920	
	51	520; 620; 690; 720; 820; 920	
	56	520; 620; 690; 720; 820; 920	
UCB GOODYEAR G159 A,11R22.5 RADIAL TIRE (Single) (50 tests)	26	220; 420; 520; 620; 690; 720; 820; 920	
	31	220; 420; 520; 620; 690; 720; 820; 920	
	36	220; 420; 520; 620; 690; 720; 820; 920	
	41	420; 520; 620; 690; 720; 820; 920	
	46	420; 520; 620; 690; 720; 820; 920	
	51	520; 620; 690; 720; 820; 920	
	56	520; 620; 690; 720; 820; 920	
UCB GOODYEAR 425/65R22.5 WIDEBASE TIRE (Super Single) (24 Tests)	26	500; 700; 900; 1000	
	46	500; 700; 900; 1000	
	49	700	
	56	500; 700; 760; 900; 1000	
	66	500; 700; 900; 1000	
	86	700; 900; 1000	
	106	700; 900; 1000	
UCB BF GOODRICH AIRCRAFT TIRE (Single) (7 Tests)	26	1040	
	36	1040	
	46	1040	
	56	1040	
	86	1040	
	106	1040	
	156	1040	
NATC WESTRACK GOODYEAR 385/65R22.5 G178 RADIAL TIRE (Super Single) (14 tests)	36	500; 700; 900;1000	
	43	700	
	46	500; 700; 900;1000	
	48	830	
	56	500; 700; 900;1000	
NATC WESTRACK 295/75R22.5 RADIAL TIRE (Single) (16 tests)	26	420; 520; 690; 820	
	31	420; 520; 690; 820	
	36	420; 520; 690; 820	
	41	420; 520; 690; 820	

Table VP3a.2. Summary of the VRSPTA sensor array device data for the evaluated dual tires.

Tire Type	Load, kN	Pressure, kPa		Measuring Tire Speed
		Tested Tire (inner Tire)	Other Tire (Outer Tire)	
NATC - WESTRACK GOODYEAR 295/75R22.5 (RADIAL) TIRE (OLD/NEW)	56	690	690	All tests were performed at creep speed (Between 0.315 - 0.330 m/s)
		690	520	
		690	220	
		520	690	
		220	690	
NATC - WESTRACK GOODYEAR 295/75R22.5 (RADIAL) TIRE (NEW/OLD)	56	690	690	
		690	520	
		690	220	
		520	690	
		220	690	
NATC- WESTRACK GOODYEAR 295/75R22.5 (RADIAL) TIRE (NEW/NEW)	56	690	690	
		690	520	
		690	220	
		520	690	
		220	690	

Table VP3a.3. Summary of the Kistler MODULAS device data for the evaluated tires.

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

Table VP3a.4 Summary of the Kistler MODULAS Device Data for the Evaluated Dual Tires with Differential Inflation Pressures.

Tire Type	**Load, kN**	**Pressure, kPa**		**Measuring Tire Speed**
		Tested Tire (inner Tire)	**Other Tire (Outer Tire)**	
GOODYEAR 295/75 R22.5 (Differential Pressure) (48 Tests)	4.45	690	220	All tests were performed at the speeds of 2, 20, 30, and 40 mph
		690	420	
		690	517	
	25	690	220	
		690	420	
		690	517	
	31	690	220	
		690	420	
		690	517	
	36	690	220	
		690	420	
		690	517	

Vehicle-Pavement Interaction Year 2

	Year 2 (4/2008-3/2009)												Team
	4	5	6	7	8	9	10	11	12	1	2	3	
(1) Workshop													
VP1a: Workshop on Super-Single Tires													UNR
(2) Design Guidance													
VP2a: Mixture Design to Enhance Safety and Reduce Noise of HMA													UWM
VP2a-1: Evaluate common physical and mechanical properties of asphalt mixtures with enhanced frictional skid characteristics												DP	
VP2a-2: Evaluate pavement macro- and micro-textures and their relation to tire and pavement noise-generation mechanisms												DP	
VP2a-3: Develop a laboratory testing protocol for the rapid evaluation of the macroand micro-texture of pavements					M&A								
VP2a-4: Run parametric studies on tire-pavement noise and skid response							JP						
VP2a-5: Establish collaboration with established national laboratories specialized in transportation noise measurements. Gather expertise on measurements and analysis													
VP2a-6: Model and correlate acoustic response of tested tire-pavement systems													
VP2a-7: Proposed optimal guideline for design to include noise reduction, durability, safety and costs													
(3) Pavement Response Model Based on Dynamic Analyses													
VP3a: Pavement Response Model to Dynamic Loads													UNR
VP3a-1: Dynamic Loads													
VP3a-2: Stress Distribution at the Tire-Pavement Interface													
VP3a-3: Pavement Response Model													
VP3a-4: Overall Model													

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D: Draft Report	Report delivered to FHWA for 3 week review period.
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Work planned
Work completed
Parallel topic

Vehicle-Pavement Interaction Years 2 - 5	Year 2 (4/08-3/09)				Year 3 (4/09-3/10)				Year 4 (04/10-03/11)				Year 5 (04/11-03/12)				Team
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	
(1) Workshop																	
VP1a: Workshop on Super-Single Tires																	UNR
(2) Design Guidance																	
VP2a: Mixture Design to Enhance Safety and Reduce Noise of HMA																	UWM
VP2a-1: Evaluate common physical and mechanical properties of asphalt mixtures with enhanced frictional skid characteristics				DP													
VP2a-2: Evaluate pavement macro- and micro-textures and their relation to tire and pavement noise-generation mechanisms				DP													
VP2a-3: Develop a laboratory testing protocol for the rapid evaluation of the macroand micro-texture of pavements		M&A		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									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			

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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: VALIDATION

CATEGORY V1: FIELD VALIDATION

Work element V1a: Use and Monitoring of Warm Mix Asphalt Sections (Year 1 start)

Work Done This Quarter

The annual monitoring of the Yellowstone National Park (YNP) hot-mix control and two warm mix asphalt 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.

Work Planned Next Quarter

It is planned to continue to evaluate the aging of the small samples removed from the YNP sections for aging and rheological properties. This work is being conducted in conjunction with work the WRI Fundamental Properties III contract.

Work element V1b: Construction and Monitoring of additional Comparative Pavement Validation sites (Year 1 start)

Work Done This Quarter

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.

Work Planned Next Quarter

It is planned to continue discussions and planning with Manitoba, Canada MIT personnel regarding LTPP SPS-5 sections going out of service and other possible projects.

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 Small Test Track (Later start)

Work Done This Quarter

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.

Work Planned Next Quarter

The ARC members will continue to pursue reasonable accelerated pavement testing opportunities.

Work element V2b: Construction of Validation Sections at the Pecos Research & Testing Center (Later start)

This work element is included to indicate that this may be a possibility for accelerated pavement testing for ARC research because it is a facility in the TAMU system.

CATEGORY V3: R&D VALIDATION

Work element V3a: Continual Assessment of Specifications (UWM)

Work Done This Quarter

Work focused on setting up the elastic recovery testing instrument and evaluating its performance using a selected set of neat and modified binders. The testing results collected show that the results are comparable to other labs and that the instrument is functioning well. The effect of polymer additives and cross-linking additives can be clearly detected in the results. The test was used to generate data to compare to the Multiple Stress Creep and Recovery (MSCR) results and will be used to explain the effect of various procedures used by different state agencies.

Work on the new binder fatigue parameter continued. The technical papers submitted to TRB and AAPT were accepted and comments were received and addressed. Discussions about difficulty with analysis of the results from the Binder Yield Energy Test (BYET) for certain modified asphalts took place with experts in the subject. A proposal to use time sweep rather than the monotonic testing is being considered. The time sweep test at a high strain level can also be modeled to represent the effects of pavement structure on binder fatigue criteria. This type of approach has not resulted in the same kind of data analysis problems mentioned above.

Work on the development of the Single-Edge Notched Bending (SENB) test to measure fracture properties started. The prototype device was modified slightly to improve its capabilities to conduct stiffness and creep rate testing as well as fracture testing. The standard software used for the Bending Beam Rheometer (BBR) could not be used as-is and plans for modifications of data acquisition have been developed. The work for the round robin testing of the Asphalt Binder Cracking Device (ABCD) was completed, and the data were delivered to Professor S. Kim of Ohio University. A plan for comparing the SENB and the ABCD results was discussed and is expected to start next quarter.

Significant Results

The elastic recovery test system setup is complete, and significant data have been collected, which will help in understanding the effects of various additives and cross-linking agents on the response.

Significant challenges are being faced with applying the viscoelastic continuum damage (VECD) approach to the data of some polymer-modified asphalts. An alternative approach of applying a time sweep test to the model has been started.

Testing for binders' cracking temperatures using the ABCD device for a set of binders was completed, and the device's repeatability appears to be very promising. The testing using the modified BBR for the SENB specimen has started, and initial software development is under way.

Significant Problems, Issues and Potential Impact on Progress

The survey of state highway agencies regarding PG Plus specifications has been postponed to next quarter. The research team plans to send a short report about elastic recovery and comparison to the MSCR testing with the survey. Decisions planned for selection of the test conditions of the SENB and the BYET have been postponed to allow the collection of more data before making recommendations. These changes are reflected in the updated Gantt chart.

Work Planned Next Quarter

Work will continue on the elastic recovery test. Data will be analyzed and compared to the MSCR results collected at various stress levels. The focus will be on identifying differences and the benefits of each test system in capturing the effects of modifiers.

The analysis of the BYET and time sweep data and the modeling of both to derive a binder fatigue parameter and fatigue limits will continue. More data from testing of modified asphalts will be gathered and analyzed.

Work will continue on collecting data for the SENB binder fracture test. Development of ideas for deriving a parameter to be used as part of the binder specification for low temperature cracking will also continue.

Work element V3b: Validation of the MEPDG Asphalt Materials Models Using New MEPDG Sites and Selected LTPP Sites (UNR, UWM)

Subtask V3b-1: Design and Build Sections (Start Year 1, Year 2, and Year 3)

Work Done This Quarter

The subgrade and base course materials were received from the HWY 212 project in South Dakota.

Significant Problems, Issues and Potential Impact on Progress

Only three agencies have committed to the construction of MEPDG sites: the Washoe RTC in northern Nevada in 2008, The South Dakota DOT in 2009/2010, and the Wisconsin DOT in 2009. The researchers are facing significant hesitation from the DOTs to use the MEPDG to design and construct HMA pavements. The level of this work element may have to be reduced.

Work Planned Next Quarter

Continue discussions with the states to select field sections for the MEPDG validations sites.

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

Work Done This Quarter

No activity this quarter.

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

Work Done This Quarter

The team continued taking samples from the LTPP binders that were shipped to the University of Wisconsin–Madison. One gallon of each material is being separated for testing to validate new test procedures being developed under the ARC. Table V3b-3.1 gives a list of these materials; the ones highlighted have already been sampled.

Table V3b-3.1. Status of sampling from LTPP binders.

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	PG 76-22
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	PG 76-22
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	PG 16-23
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	PG 76-22
MO	9A	290901	WF	51.6	BC02A01	64-28
NE	9	310902	DF	65.5		AC
NC	9A	370960	WN	73.1	BC01A60	PG 76-22
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

Work Planned Next Quarter

Sampling is expected be completed in the next quarter. Original materials will be shipped back to the FHWA Materials Reference Library for storage while the team begins evaluating sampled binders for rheological properties to verify their listed PG grade.

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

Work Done This Quarter

No activity this quarter.

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

Work Done This Quarter

No activity this quarter.

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

This is a Year 3 start.

Validation Year 2	Year 2 (4/2008-3/2009)												Team
	4	5	6	7	8	9	10	11	12	1	2	3	
(1) Field Validation													
V1a: Use and Monitoring of Warm Mix Asphalt Sections													WRI
V1b: Construction and Monitoring of additional Comparative Pavement Validation sites													WRI
(2) Accelerated Pavement Testing													
V2a: Accelerated Pavement Testing including Scale Model Load Simulation on small test track (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.						P					D	F	
V3a-2: Detailed analysis of all PG-Plus tests being proposed or in use today, documentation of benefits and costs of these tests, and comparison with new tests											P		
V3a-3: Development of protocols for new binder tests and database for properties measured													
V3a-4: Development of specification criteria for new tests based on field evaluation of construction and performance													
V3a-5: Interviews and surveys for soliciting feedback on binder tests and specifications												JP	
V3b: Validation of the MEPDG Asphalt Materials Models and Early Verification of Technologies Developed by ARC using new MEPDG Sites and Selected LTPP sites													UNR/UWM/ WRI
V3b-1: Design and Build Sections													UNR
V3b-2: Additional Testing													
V3b-3: Select LTPP Sites to Validate New Binder Testing Procedures										P			UWM
V3b-4: Testing of Extracted Binders from LTPP Sections													
V3b-5: Review and Revisions of Materials Models													
V3b-6: Evaluate the Impact of Moisture and Aging													

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Work planned
Work completed
Parallel topic

Validation Years 2 - 5	Year 2 (4/08-3/09)				Year 3 (4/09-3/10)				Year 4 (04/10-03/11)				Year 5 (04/11-03/12)				Team
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	
(1) Field Validation																	
V1a: Use and Monitoring of Warm Mix Asphalt Sections																	WRI
V1b: Construction and Monitoring of additional Comparative Pavement Validation sites																	WRI
(2) Accelerated Pavement Testing																	
V2a: Accelerated Pavement Testing including Scale Model Load Simulation on small test track																	WRI
V2b: Construction of validation sections at the Pecos Research & Testing Center																	WRI
(3) R&D Validation																	
V3a: Continual Assessment of Specification																	UWM
V3a-1: Evaluation of the PG-Plus practices and the motivations for selecting the “plus” tests.		P		D, F													
V3a-2: Detailed analysis of all PG-Plus tests being proposed or in use today, documentation of benefits and costs of these tests, and comparison with new tests				P	D												
V3a-3: Development of protocols for new binder tests and database for properties measured						JP				P							
V3a-4: Development of specification criteria for new tests based on field evaluation of construction and performance						D		P	P			JP	P		JP		
V3a-5: Interviews and surveys for soliciting feedback on binder tests and specifications									P		JP		P		D	F	
V3b: Validation of the MEPDG Asphalt Materials Models and Early Verification of Technologies Developed by ARC using new MEPDG Sites and Selected LTPP sites																	UNR/UWM
V3b-1: Design and Build Sections									D, F								
V3b-2: Additional Testing																	
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	

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Work planned
Work completed
Parallel topic

PROGRAM AREA: TECHNOLOGY DEVELOPMENT

Work element TD1: Prioritize and Select Products for Early Development (Year 1)

Work Done This Quarter

None. This work element was completed last Quarter.

Significant Results

Six early technology development projects have been identified and all have received favorable ratings from the ETGs.

Significant Problems, Issues and Potential Impact on Progress

None

Work Planned Next Quarter

None

Work element TD2: Develop Early Products (Year 2)

Work Done This Quarter

Work continued on the Simplified Continuum Damage Fatigue project. The research team continued preparing a draft standard test method for Simplified Continuum Damage Fatigue Testing. This method is in the format of an AASHTO standard test method. It describes the testing and analysis that are required to generate fatigue curves for asphalt concrete mixtures. The accompanying spreadsheet for the analysis has been improved. The draft standard method is approximately 75 percent complete.

Significant Results

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.

Significant Problems, Issues and Potential Impact on Progress

None

Work Planned Next Quarter

The draft standard test method for the continuum damage fatigue test will be completed and the practice will be applied to fatigue data from several mixtures. Work will be initiated on a ruggedness test plan for the continuum damage fatigue test.

Work element TD3: Identify Products for Mid-Term and Long-Term Development (Years 2, 3, and 4)

Work Done This Quarter

The research team continued to review interim research products to identify potential mid-term and long-term development projects.

Significant Results

None

Significant Problems, Issues and Potential Impact on Progress

None

Work Planned Next Quarter

The research team with continue to review interim research products to identify potential mid-term and long-term development projects.

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

This activity is planned for later in the project.

PROGRAM AREA: TECHNOLOGY TRANSFER

CATEGORY TT1: OUTREACH AND DATABASES

Work element TT1a: Development and Maintenance of Consortium Website (Duration: Year 1 through Year 5)

Work Done This Quarter

The ARC website was maintained and updated. The revised ARC year 2 work plan and the ARC master list of references are uploaded to the ARC website. The UWM personnel and bios were updated.

Work Planned Next Quarter

Continue maintaining and updating the ARC website.

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

Work Done This Quarter

The third ARC Newsletter was prepared and distributed this quarter. The ARC Newsletter is also available at the ARC website, www.ARC.unr.edu.

Work Planned Next Quarter

It is planned to prepare and distribute the fourth ARC Newsletter during the next quarter.

Work element TT1c: Prepare Presentations and Publications

Work Done This Quarter

The UNR team submitted a report on the loading conditions for the Flow number test for review by the Mix and Construction ETG members.

Presentations

F. T. Aragao, Y. Kim, and D. H. Allen. "Fracture Modeling of Asphalt Concrete Mixtures Considering Material Heterogeneity and Viscoelasticity." 10th U.S. National Congress on Computational Mechanics (USNCCM), Columbus, OH (to be presented).

Bommavaram, R., Bhasin, A., and Little, D.N. "Use of Dynamic Shear Rheometer to Determine the Intrinsic Healing Properties of Asphalt Binders", Presented at the *88th Annual Meeting, Transportation Research Board*, Washington, D.C., 2009.

Mr. Michael Harnsberger made a presentation at the RAP ETG meeting in Phoenix, Arizona on the "Compatibility of Asphalt Component Materials". The presentation was based on work being conducted in the ARC and in the WRI Fundamental Properties of Asphalts and Modified Asphalts III contract.

Y. Kim, J. S. Lutif, and D. H. Allen. "Determination of Representative Volume Elements of Asphalt Concrete Mixtures and Their Numerical Validation through Finite Element Method." *Presented at the 88th Transportation Research Board Annual Meeting*, Washington D.C.

Luo, R. and Lytton, R. L. (2009) "Inverse and Forward Self-Consistent Micromechanics Models of Asphalt Mixtures." The 88th Transportation Research Board Annual Meeting, Washington, D.C.

J. Lutif, F. Souza, Y. Kim, and D. H. Allen. "Multiscale Modeling of Asphalt Mixtures Subjected to Fracture and Damage." 10th U.S. National Congress on Computational Mechanics (USNCCM), Columbus, OH (to be presented).

Dr. Peter Sebaaly made a presentation on the progress of the work on Subtask E2b-1.a: "Develop a System to Evaluate the Properties of RAP Aggregates," at the RAP ETG meeting in Phoenix, Arizona on October 29.

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

Publications

F. T. Aragao, Y. Kim, and D. H. Allen. "Mechanistic Modeling of Fracture in Viscoelastic Bituminous Mixtures Based on Cohesive Laws" (to be submitted)

H. Bahia, R. Delgadillo, and A. Motamed, "Performance of Modified Asphalt Binder and Mixtures under Increased Truck Loading Limits." The 4th International Gulf Conference on Roads, 2009.

Emil G. Bautista, Salvatore Mangiafico, & Hussain U. Bahia, "Evaluation of Rheological Properties of Binders in RAP without Extraction and Recovery." Transportation Research Board 88th Annual Meeting Compendium of Papers, 2009.

Bhasin, A., Little, D.N., Bommavaram, R., and Greenfield, M. L. "Use of Molecular Dynamics to Investigate Self-Healing Mechanisms in Asphalt Binders" *Journal of Testing and Materials,* American Society of Civil Engineers (In review).

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

Caro, S., Masad, E., Bhasin, A., and Little, D.N. “A Coupled Micromechanical Model of Moisture-Induced Damage in Asphalt Mixtures”, *Journal of Testing and Materials,* American Society of Civil Engineers (In Review).

Christensen, Donald W., “Analysis of HMA Fatigue Data Using The Concepts of Reduced Loading Cycles and Endurance Limit.” Accepted for publication by the Association of Asphalt Paving Technologists, 2009.

Andrew J. Hanz, Zelalem Arega, & Hussain U. Bahia, “Rheological Evaluation of Emulsion Residues Recovered Using Newly Proposed Evaporative Techniques.” Transportation Research Board 88th Annual Meeting Compendium of Papers, 2009.

Carl M. Johnson, Hussain U. Bahia, & Haifang Wen, “Practical Application of Viscoelastic Continuum Damage Theory to Asphalt Binder Fatigue Characterization.” Accepted for publication by the Association of Asphalt Paving Technologists, 2009.

Y. Kim, F. T. S. Aragão, D. H. Allen, and D. N. Little. “Damage Modeling of Bituminous Mixtures through Computational Micromechanics and Cohesive Zone Fracture.” *Canadian Journal of Civil Engineering*, under review

J. Lee, J. Lutif, and Y. Kim. “Representative Volume Elements of Asphalt Concrete Mixtures with Damage” (to be submitted).

Luo, R., and Lytton, R. L. (2008). “Characterization of the Tensile Viscoelastic Properties of an Undamaged Asphalt Mixture.” Journal of Transportation Engineering, American Society of Civil Engineers (ASCE), submitted for publication.

Arash Motamed, Menglan Zeng, Hussain Bahia, and Rodrigo Delgadillo, “Effects of Increased Loading Level and Time on Rutting Resistance of Modified Asphalt Binders and Mixtures.” The Canadian Technical Asphalt Association 53rd Annual Conference, 2008.

Robert L. Schmitt, Carl M. Johnson, Hussain U. Bahia, & Andrew J. Hanz, “Effects of Temperature and Compaction Effort on Field and Lab Densification of HMA.” Accepted for publication by the Association of Asphalt Paving Technologists, 2009.

Vasconcelos, K.L., Bhasin, A., and Little, D.N. “Influence of Reduced Production Temperatures on the Adhesive Properties of Aggregates and Laboratory Performance of Fine Aggregate-Asphalt Mixtures”, *International Journal of Road Materials and Pavement Design* (In Review).

Haifang Wen & Hussain U. Bahia, "Characterizing Fatigue of Asphalt Binders Using Continuum Damage Mechanics." Accepted for publication and presentation at the Transportation Research Board 88th Annual Meeting, 2009.

Work Planned Next Quarter

It is anticipated that several presentations may be made on current ARC research at the Mix and Construction ETG meeting in Irvine, CA. One possible subject is a presentation on the loading conditions for the Flow number test.

Work element TT1d: Development of Materials Database (Duration: Year 2 through Year 5)

Work Done This Quarter

The UNR team continued the work on developing the Microsoft Access database tables according to the ERD diagram. Work was also performed on converting the ARC website from a static to a dynamic web site using the Microsoft Active Server Pages (ASP.NET) web application.

Significant Results

Created both the ASP.NET web application and the database site and started 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.

Work Planned Next Quarter

Continue the work on the database and the dynamic web site.

Work element TT1e: Development of Research Database (Duration: Year 2 through Year 5)

Work Done This Quarter

Uploaded the revised ARC year 2 work plans and the ARC quarterly technical progress report to the ARC website.

Work Planned Next Quarter

Upload the ARC year 3 work plans and the ARC quarterly technical progress report to the ARC website.

Work Element TT1f: Workshops and Training

Work Done This Quarter

No activity this quarter.

Work Planned Next Quarter

No activities are planned for the next quarter.

Technology Transfer	Year 2 (4/2008-3/2009)												Team
	4	5	6	7	8	9	10	11	12	1	2	3	
(1) Outreach and Databases													
TT1a: Development and Maintenance of Consortium Website													UNR
TT1b: Communications													UNR
TT1c: Prepare presentations and publications													UNR
TT1d: Development of Materials Database													UNR
TT1d-1: Identify the overall Features of the Web Application TT1d-2: Identify Materials Properties to Include in the Materials Database TT1d-3: Define the Structure of the Database TT1d-4: Create and Populate the Database													
TT1e: Development of Research Database													UNR
TT1e-1: Identify the Information to Include in the Research Database TT1e-2: Define the Structure of the Database TT1e-3: Create and Populate the Database													
TT1f: Workshops and Training													UNR

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Work planned
Work completed
Parallel topic

Technology Transfer	Year 2 (4/08-3/09)				Year 3 (4/09-3/10)				Year 4 (04/10-03/11)				Year 5 (04/11-03/12)				Team
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	
(1) Outreach and Databases																	
TT1a: Development and Maintenance of Consortium Website																	UNR
TT1b: Communications																	UNR
TT1c: Prepare presentations and publications																	ALL
TT1d: Development of Materials Database																	UNR
TT1d-1: Identify the overall Features of the Web Application																	
TT1d-2: Identify Materials Properties to Include in the Materials Database																	
TT1d-3: Define the Structure of the Database																	
TT1d-4: Create and Populate the Database							SW, v. β	SW									
TT1e: Development of Research Database																	UNR
TT1e-1: Identify the Information to Include in the Research Database																	
TT1e-2: Define the Structure of the Database																	
TT1e-3: Create and Populate the Database																	
TT1f: Workshops and Training																	UNR

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Work planned
Work completed
Parallel topic