Western Research INSTITUTE

Asphalt Research Consortium

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By
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INTRODUCTION

This document is the Quarterly Report for the period of April 1 to June 30, 2011 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. The Quarter of April 1 to June 30, 2011 is first quarter of the Year 5 contract year. Reviewers may want to reference the previous Annual Work Plans and many other documents that are posted on the ARC website, www.ARC.unr.edu. The more detailed information about the research such as approaches to test method development, data collection, and analyses will be reported in research publications as part of the deliverables. This quarterly report contains updates to the Table of Deliverables and the Table of Journal Papers that were presented in the Year 5 Work Plan.

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

Several ARC members attended and made presentations at the RAP Expert Task Group meeting and the WMA TWG held on May 10 - 13, 2011 at the Beckman Center in Irvine, California. An update on the RAP and WMA research being conducted by the ARC was presented.

WORK PLANNED FOR NEXT QUARTER

Several ARC members will attend and make presentations at the 48th Petersen Asphalt Research Conference and the 2011 Pavement Performance Prediction Symposium in Laramie, Wyoming in July.

ARC members are planning to attend and make presentations at the Binder, Mix & Construction, and Fundamental Properties & Advanced Models ETG meetings planned for Dartmouth, Massachusetts during the week of September 19 – 23, 2011.

PROGRAM AREA: MOISTURE DAMAGE

CATEGORY M1: ADHESION

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

Work Done This Quarter

In this quarter, the research team compared bond strength measurements obtained with the Bitumen Bond Strength (BBS) test with fundamental thermodynamic parameters that quantify the bond strength of asphalt-aggregate systems, such as work of cohesion and work of debonding. These parameters were calculated based on contact angle measurements using the Sessile Drop Method with different liquids of known surface energy components.

The Young-Dupre equation described in previous quarterly reports was used to estimate the surface energy of the asphalt binders and aggregates. By using the estimated surface free energy of both binder and aggregates, the work of cohesion and work of debonding was calculated and compared to BBS results. The experimental results showed that the BBS and surface properties of different asphalt binders are generally in agreement. The selected probe liquids were distilled water, ethylene glycol, and formamide, which were chosen for their immiscibility with the asphalt binder and differing surface free energy components (Wei et al. 2010).

Significant Results

Figure M1a.1 shows a comparison between the pull-off strength results after wet conditioning for 96 hours and the work of cohesion (i.e., $2\gamma_{binder}$) of asphalt binders with limestone aggregate. It can be seen that higher work of cohesion results in higher pull-off strength. Note that the BBS results used for this comparison correspond to cohesive mode failure only.

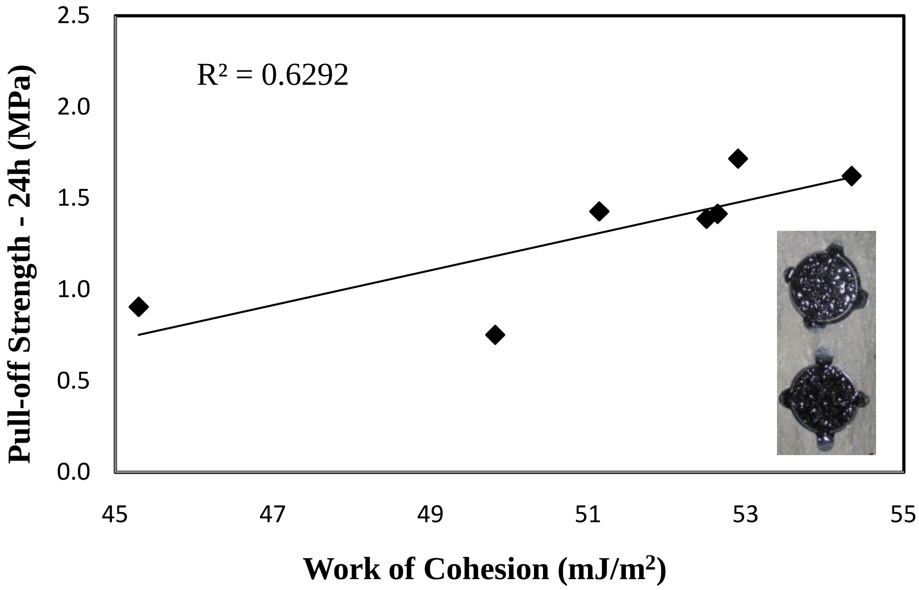

Figure M1a.1. Graph. Comparison between pull-off strength and work of cohesion of asphalt binders that showed cohesive failure with limestone aggregate after wet conditioning.

If the displacement of an asphalt binder from the aggregate surface is a thermodynamically favorable process then it must be associated with a reduction in the free energy of the system (i.e., the total work done during the displacement process must be less than zero) (Bhasin 2006). The energy associated with the displacement of asphalt by water from asphalt-aggregate interface (i.e., work of debonding) can be expressed in terms of the components of surface energy of water, aggregate, and asphalt binder.

The work of debonding, calculated from surface energy measurements, and the loss of pull-off strength in the BBS were compared for asphalt-aggregate systems with adhesive failure (figure M1a.2). A fair correlation was observed between BBS adhesive failure results and the thermodynamic based parameter. As expected, higher loss of bond strength implies higher work of debonding. Furthermore, figure M1a.3 indicates that higher work of debonding corresponds to lower bond strength of the asphalt-aggregate system after moisture conditioning.

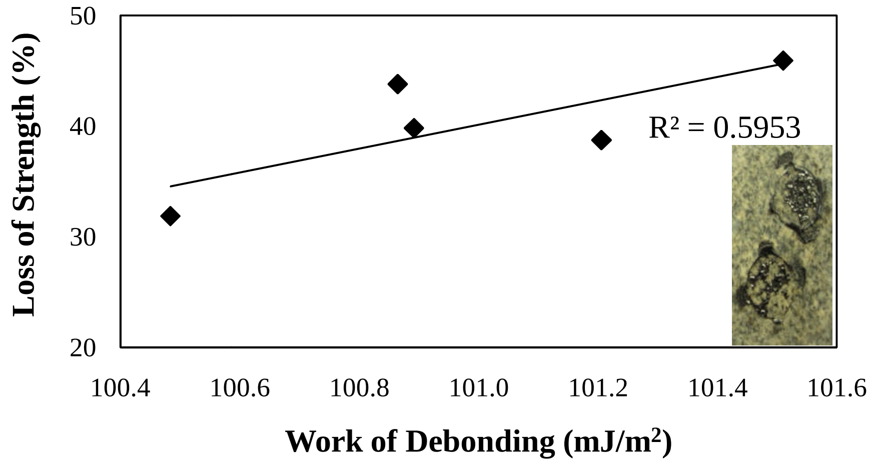

Figure M1a.2. Graph. Comparison between loss of strength and work of debonding of asphalt binders that showed adhesive failure with granite aggregate after wet conditioning.

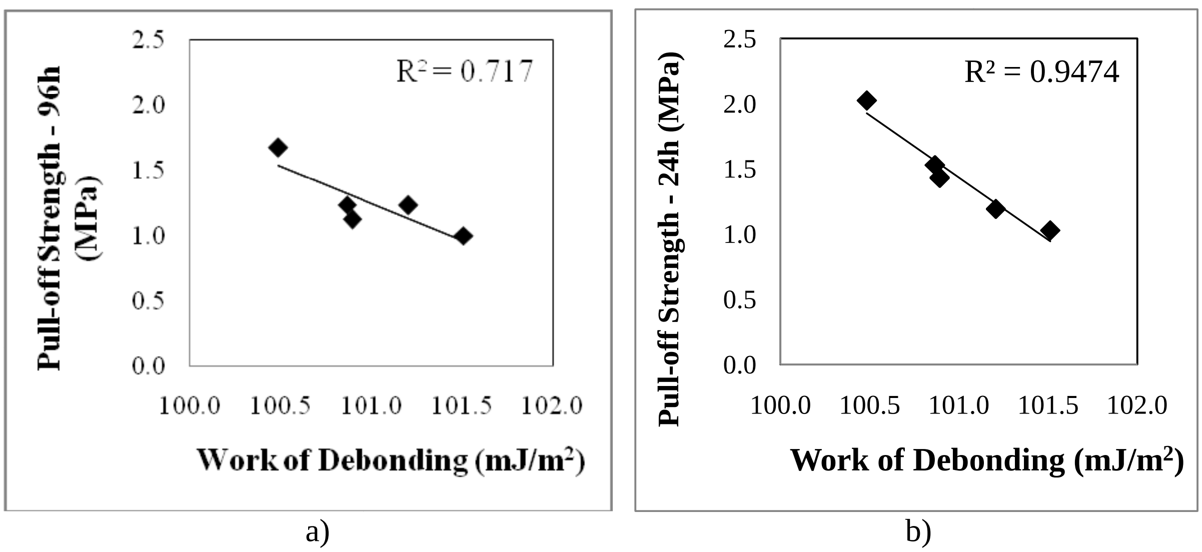

Figure M1a.3. Graph. Comparison between pull-off strength and work of debonding of binders with adhesive failure with granite after a) 96 hours and b) 24 hours of conditioning.

Work Planned Next Quarter

Efforts will focus on the validation of the BBS test procedure with mixture TSR testing results. Also, a detailed procedure to correct the bond strength obtained in the BBS due to binder stiffness will be developed. The research team will work in collaboration with Consortium partners to include information related to the development and implementation of the Bitumen Bond Strength (BBS) test as a chapter in a consolidated report for Moisture Damage work element.

Cited References

Bhasin, A., 2006, *Development of Methods to Quantify Bitumen-Aggregate Adhesion and Loss of Adhesion Due to Water*. Ph.D. Dissertation, Texas A&M University, College Station, Texas.

Wei, Jianming, Xiaosheng Huang, and Yuzhen Zhang, 2010, Influence of Commercial Wax on Performance of Asphalt. *Journal of Materials in Civil Engineering*, 760-766.

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

The main goal of this subtask is to provide material property inputs required in other work elements as required. Any data obtained from this subtask will be included in the material properties database. In the last quarter surface free energy of some aggregates and asphalt binders that are being used to develop test methods were measured.

Significant Results

None.

Significant Problems, Issues and Potential Impact on Progress

None.

Work Planned Next Quarter

Work on this subtask will be conducted in conjunction with and as required by other work elements.

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

Work Done This Quarter

Work reported under subtask M2a-2 (work of cohesion) also applies to this subtask.

Significant Results

See subtask M2a-2.

Significant Problems, Issues and Potential Impact on Progress

None

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

Work Done This Quarter

This work element was completed and findings were reported in previous quarterly reports. There was no activity this quarter.

Work Planned Next Quarter

None.

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

Work Done This Quarter

This work element was completed and findings were reported in previous quarterly reports. There was no activity this quarter.

Work Planned Next Quarter

None.

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)

Note about Subtask M2a-1: Per the Year 5 work plan, the objectives of this work element will be accomplished in other tasks.

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

Work Done This Quarter

In the previous quarter the AFM nano-mechanics system was modified by the addition of an environmental chamber that can be used to heat or cool the sample in a controlled inert/dry (or other) atmosphere while probing to measure mechanical properties. A dry atmosphere surrounding the sample is needed to minimize meniscus forces associated with the thin film of moisture that accumulates on sample surfaces. When probing at nanometer scale, this surface moisture has a strong effect on mechanical properties measurements due to its dominance over other surface interactions, particularly when the sample surface is cooled to below ambient temperature.

A series of force/displacement curves (FDC) was collected at three temperatures for an asphalt sample under a dry nitrogen blanket. The probing motion associated with these FDC was generated by Z-axis movement of the nano-positioning stage with feedback electronics in the AFM locked out. This technique generates FDC that are completely free of detectable instrument hysteresis. When the effects of moisture and instrument hysteresis are eliminated, interpretation of FDC type data becomes much easier and more reliable. FDC data collected with this system will provide a good deal of quantifiable information with respect to adhesive and cohesive (and also, ductile/brittle transition) properties of the sample material.

FDC data collected as a function of sample type, sample temperature, and probe rate will be used in conjunction with new nano-rheology (rheologic phase angle data) and imaging techniques that have been developed under this subtask to measure work of adhesion/cohesion, and hopefully, to provide some insight into how microstructuring and phase separation effect these properties.

Significant Results

Figure M2a-2.1 shows a typical example of a FDC collected on a glass substrate using the system described above. Conventional AFM FDC data is collected as cantilever response vs. Z-axis piezo position. With our system we collect cantilever response and Z-axis position independently as a function of time. For the figure presented, we folded (from the point of maximum deflection) our cantilever response data back upon itself to generate the type of FDC that is more generally familiar. Note that the trace and retrace lines lie on top of each other for the loading/unloading portion of the force/displacement lines shown in the figure. This is the type of response that would be expected for a hard elastic material in the absence of instrument hysteresis. When collected with the AFM, FDC typically exhibit some hysteresis even on a hard elastic surface. The hysteresis in the AFM measurements is associated with differences in the way that a piezo-electric stack responds to the application of positive and negative voltages. This hysteresis tends to be sensitive to changes in the stack extension/retraction rate and temperature such that significant calibration efforts can be needed to eliminate its effect from the collected data.

Experiments in which mechanical properties are measured with an AFM typically begin with measurements collected on a hard surface. These measurements generate a cantilever response factor which is used to convert the change in voltage output from the photo-detector array into a corresponding change in cantilever position. When the system is subsequently used to probe a softer (more compliant) surface, the calibrated cantilever response is used to determine how deeply the probe has penetrated into the surface. This penetration depth is then critically used to establish the contact area upon which the adhesive forces act.

Figures M2a-2.2, M2a-2.3, and M2a-2.4 show examples of FDC collected for SHRP core asphalt AAA-1 at 22° C, 44° C, and -4° C respectively. In these figures the Z-axis displacement is represented by the red line labeled “stage” in the legend, and the corresponding cantilever response is shown by the blue line labeled “probe” in the figure. Both lines are recorded as voltage signals with 1-volt equal to 1-μm for the red (stage) line, and 1-volt equal to ~0.044- μm for the blue (probe) line. The X-axis in the figure represents time in seconds. For each FDC, the stage was extended to a maximum position and then retracted with the whole motion at a steady rate. The maximum stage extension was adjusted to provide differing amounts of loading at the contact between the tip and the sample in the various FDC collected.

Following the blue line from left to right as the stage extends and retracts we see initially a flat line where the tip has not made contact with the surface. As the distance between the probe tip and the sample surface decreases we see a sudden deflection of the cantilever in the direction of the surface. This small negative deflection results when attractive forces between the tip and the surface exceed the force exerted by the cantilever spring and is commonly referred to as “jump to contact”. With the tip in contact the cantilever spring immediately begins to bend in the opposite direction in response to the advancing surface to which the tip is essentially attached. This portion of the curve represents the contact loading part of the FDC. For this part of the curve, the measured cantilever deflection summed with the corresponding distance that the probe tip has penetrated the surface is equal to the applied displacement (stage extension) for any amount of stage extension. The maximum of this line corresponds to the maximum of contact loading as well as the maximum of tip penetration for a given extension/retraction cycle. The slope of the contact loading line, compared to the slope on a non-compliant (glass in this case) surface, gives a measure of the stiffness of the probed material.

The blue line from its maximum to where it crosses the zero-deflection line represents the unloading of the contact and also contains information regarding plastic deformation at the sample surface. The negative deflection of the cantilever spring as the surface continues to pull away from the probe tip represents the maximum of adhesive (or cohesive) strength of the contact between the tip and the sample. The area enclosed by this line and the axis is equal to the work of adhesion (Cappella and Dietler 1999). Tip and sample surface energies can then be related to the measured adhesive force through the contact area. However, in order to determine the contact area it is necessary to evaluate the deformation of the sample surface in the contact region. This evaluation requires the selection and application of the appropriate contact model, a task which is not completely straight forward for viscoelastic materials such as asphalt. The selection of the appropriate contact model is influenced by material properties which in turn are a function of temperature and probe rate.

Other information contained in the FDC, and pertinent to this project, relate to elastic and plastic deformation (i.e. the distance between the loading and unloading lines) and the ductile/brittle characteristics of the sample (i.e. the sharpness of the break from contact after the maximum negative cantilever deflection). All of the force curves reported here were collected using a cantilever with a nominal spring constant of 14-N/m and a 10-μm diameter glass bead tip.

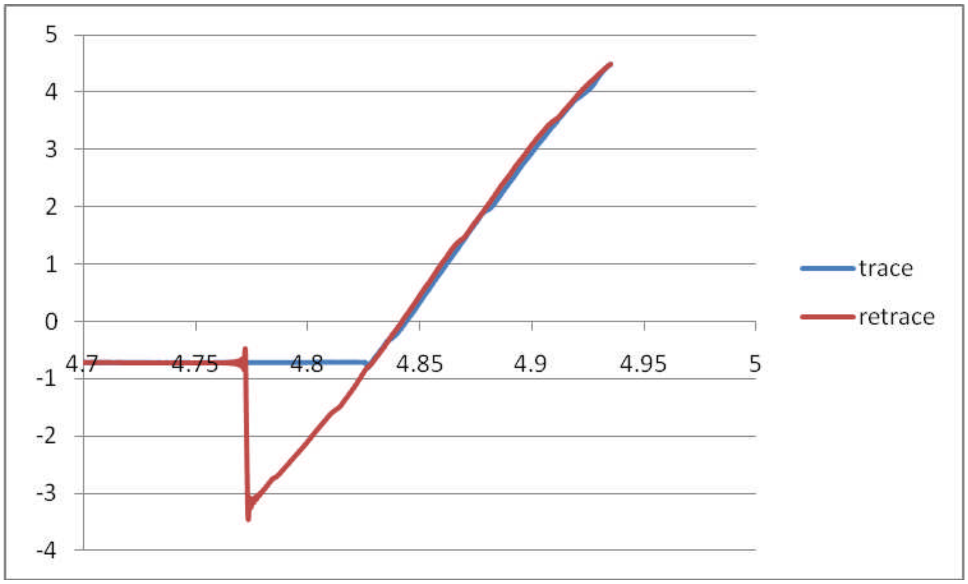

Figure M2a-2.1. A typical example of a FDC collected on a glass substrate using the modified AFM/nano-positioning stage system.

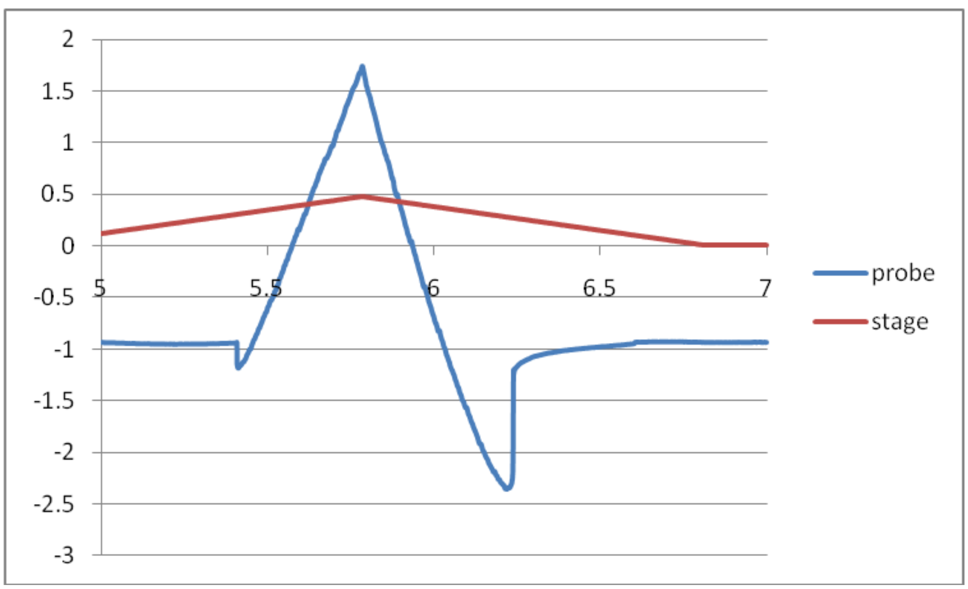

Figure M2a-2.2. FDC (as collected) for SHRP core asphalt AAA-1 at ambient temperature.

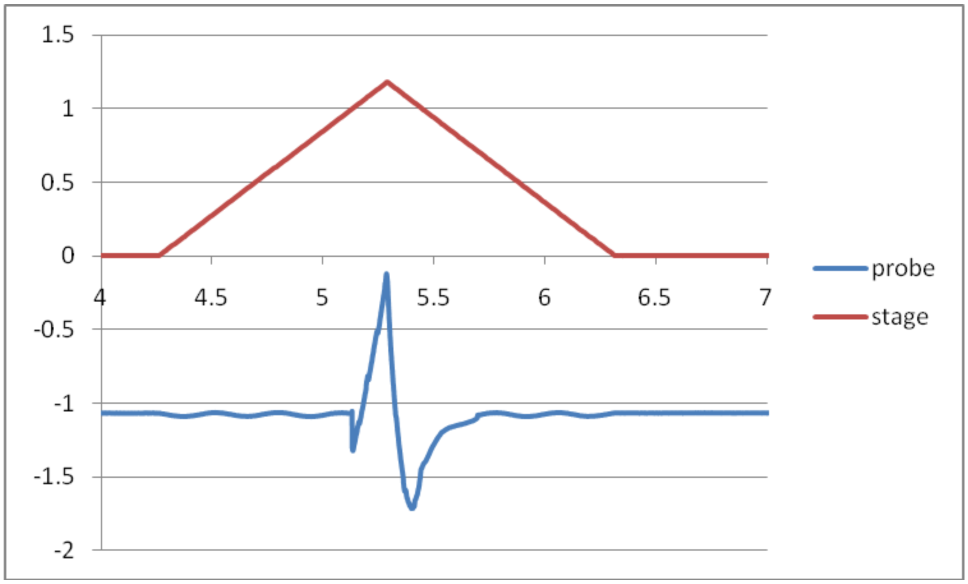

Figure M2a-2.3. FDC (as collected) for SHRP core asphalt AAA-1 at 44° C.

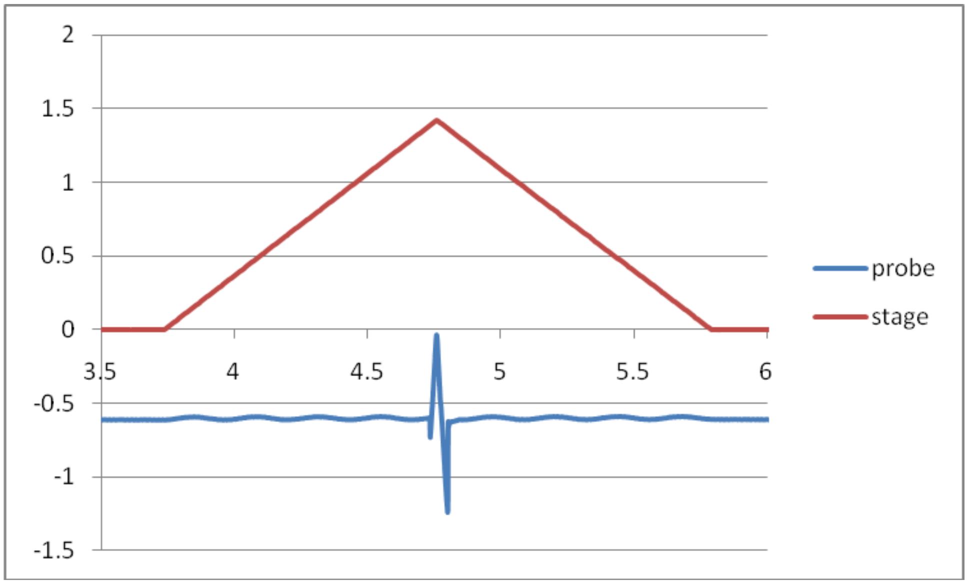

Figure M2a-2.4. FDC (as collected) for SHRP core asphalt AAA-1 at -4° C.

The FDC collected at ambient temperature (figure M2a-2.2) shows an example in which a moderate loading force was applied after the tip/sample contact. The FDC indicates some elastic and plastic deformation of the surface as evidenced by the change in slope between the loading and the unloading lines. Some ductile behavior is indicated by the curved portion of the cantilever response before it returns to zero after the initial break. The FDC collected at 44° C (figure M2a-2.3) shows a smaller applied load as well as much greater penetration and significant ductility when compared to the ambient temperature FDC. The FDC shown in figure M2a-2.4 was collected at -4° C. This curve shows an example of very light loading, essentially no penetration of the surface, and an apparently brittle contact.

To derive work of adhesion/cohesion from FDC data the appropriate contact model must be applied (Grierson et al. 2005; Xu et al. 2007). When a compliant surface exhibiting strong short range adhesion is probed with a "large" diameter sphere the JKR contact model accurately describes the contact area. For a stiff material with weak adhesion probed by a "small" diameter sphere the DMT model is applied. These models differ only with regard to the value of a multiplication constant (-1.5 for JKR contact, -2 for DMT). The models represent opposite end of a continuum description of contact mechanics that is believed to be accurate for contacts down to a few nanometers in size (Grierson et al. 2005). We believe that the choice of a model will be temperature dependant, and that a single model will probably not be adequate to cover the temperature range that is pertinent with respect to asphalt performance. A series of curve-fits to measured data will be used to determine the best contact models for this project.

Significant Problems, Issues and Potential Impact on Progress

None.

Work Planned Next Quarter

Work will continue toward collecting and analyzing FDC data with emphasis on contact modeling as a function of temperature. We will begin to combine some of the techniques developed in this project to provide a more complete understanding of asphalt adhesion/cohesion as it relates to asphalt type, temperature, loading frequency, and substrate properties.

Cited References

Cappella, B., and G. Dietler, 1999, Force –distance curves by atomic force microscopy. *Surface Science Reports*, 34, 1-104.

Grierson, D.S., E.E. Flater, R.W. Carpick, 2005, Accounting for the JKR-DMT transition in adhesion and friction measurements with atomic force microscopy. *Journal of Adhesion Science Technology*, 19, No. 3-5, 291-311.

Xu, Dewei, K.M. Liechti, K. Ravi-Chandar, 2007, On the modified Tabor parameter for the JKR-DMT transition in the presence of a liquid meniscus. *Journal of Colliod and Interface Science*, 315, 772-785.

Work Element M2b: Impact of Moisture Diffusion in Asphalt Mixtures

Subtask M2b-1: Measurements of Diffusion in Asphalt Binders and Mixtures (TAMU)
Subtask M2b-2: Kinetics of Debonding at the Binder-Aggregate Interface (TAMU)

<u>Work Done This Quarter</u>

There was no activity this quarter.

<u>Work Planned Next Quarter</u>

We have accomplished significant portions of this work element including measurement of diffusion through binders and fine aggregate matrix. Further work will be conducted if prioritized based on the requirements from other work elements.

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

The remaining activity is reported under Work Element M1a.

CATEGORY M3: AGGREGATE SURFACE

Work Element M3a: Aggregate Surface Characterization (TAMU)

<u>Work Done This Quarter</u>

This work element was completed and findings were reported in previous quarterly reports. There was no activity this quarter.

CATEGORY M4: MODELING

Work Element M4a: Micromechanics Model (TAMU)

Subtask M4a-1: Model Development

<u>Work Done This Quarter</u>

In the last quarter, we reported parametric analyses of the microstructure model incorporated with moisture damage by varying several primary material characteristics (i.e., diffusion coefficient and degradation model parameters) that affect moisture-dependent fracture behavior of asphalt mixtures. During this quarter, we have extended the parametric analyses to consider significance of air voids in the model and the effects of adhesive fracture (i.e., interfacial fracture between aggregate and matrix) as a separate mode of moisture damage in addition to cohesive failure (i.e., fracture within matrix phase). Model simulation results clearly demonstrated the role of air voids on the moisture damage of asphalt mixtures. Parametric simulations conducted with different sets of degradation parameters for the two different fracture modes (cohesive and adhesive) presented reasonable damage characteristics of the asphalt mixtures. This confirms that the sequentially-coupled moisture damage model has been well developed as a tool to examine the influence of the different physical, mechanical, and geometrical material properties of the asphalt mixture ingredients on the overall moisture-related mechanical performance of asphaltic composites.

With all outcomes from this subtask, we have written a final report. It includes all key components including the constitutive theory, modeling methodology, testing protocols developed, resulting test data, and various model simulations for calibration, validation, and application through the parametric analyses. The report is currently 80% completed.

Significant Problems, Issues and Potential Impact on Progress

None.

Work Planned Next Quarter

In the next quarter we will finish the final report and submit it to Texas A&M University.

Work Element M4b: Analytical Fatigue Model for Mixture Design (TAMU)

This work element is addressed under Work Element F2b.

Work Element M4c: Unified Continuum Model (TAMU)

Work Done This Quarter

The work done this quarter focused on completing the development of a thermodynamic-based moisture-induced damage model that takes into consideration the effects of moisture diffusion and pore-water pressure that accelerates crack evolution and propagation due to presence of moisture. Both energetic and dissipative processes are clearly distinguished through this thermodynamic framework. Moreover, three-dimensional micromechanical moisture-damage simulations have been started. These simulations can be used to conduct virtual moisture-damage simulation experiments.

Significant Results

None

Significant Problems, Issues and Potential Impact on Progress

The ARC 2x2 experimental data for validating the moisture-induced damage modeling is not available yet.

Work Planned Next Quarter

The focus of the next quarter is on completing the development of thermodynamic framework that takes into consideration the different degradation mechanisms due to presence of moisture in asphalt mixtures. This thermodynamic framework is necessary in order to correctly consider the different moisture-induced damage mechanisms and the coupling between them. Moreover, work will continue on conducting three-dimensional micromechanical moisture-damage simulations. Virtual specimens based on the 2x2 ARC validation plan will be generated using X-ray CT and the finite element method.

CATEGORY M5: MOISTURE DAMAGE PREDICTION SYSTEM (All, TAMU lead)

Work on individual components such as test methods and micromechanics models required in the system is complete. The components will be put together in the form of a methodology towards the end of this project.

TABLE OF DECISION POINTS AND DELIVERABLES FOR MOISTURE DAMAGE

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
M1a-5: Propose a novel testing protocol (UWM)	Draft Report	Development and Implementation of the Bitumen Bond Strength test for Moisture Damage Characterization	1/10	8/11	Additional analysis/verification on the BBS test is included: operator sensitivity data, validation with TSR mixture testing and comparison with contact angle measurements. Report has been consolidated as one chapter and suggested to be included in TAMU report for moisture damage.
	Final Report	Report in 508 format on the use of the Bitumen Bond Strength test for Moisture Damage Characterization	1/11	9/11	Additional analysis/verification data is included and therefore additional time is required
M1b-2: Work of Adhesion at Nano-Scale using AFM (WRI)	Test Method	A method to determine surface roughness of aggregate and fines based on AFM	12/30/11		N/A
M1b-3: Identify mechanisms of competition between water and organic molecules for aggregate surface (TAMU)	Draft Report	Final report documenting the testing protocol and findings of experiments on asphalt-aggregate interactions	10/31/10	10/31/11	Program activity delayed in order to redirect critical manpower to PANDA development
	Final Report		4/30/12		
M1c: Quantifying Moisture Damage Using DMA (TAMU)	AASHTO procedure	AASHTO procedure for preparing Fine Aggregate Matrix (FAM) specimens for the DMA testing	9/30/10	Complete	N/A
	Draft Report	Use of the method to characterize various mixtures with comparison to field performance	12/31/10		
	Final Report		3/31/11	6/30/11	Report to be made 508 compliant
M2a-2: Work of Cohesion at Nano-Scale using AFM (WRI)	Test Method	A method to determine ductile-brittle properties via AFM measurements	12/30/11		N/A

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
M2b-1: Measurement of diffusion of water through thin films of asphalt binders and FAM (TAMU)	Draft Report	Mechanism and model for the diffusion of moisture through films of asphalt binder, methods to measure diffusivity in binders and mortars, and the influence of wet-dry cycles on the cumulative moisture induced damage.	6/30/10	Complete	
	Final Report		9/30/11	12/31/11	The dissertation was completed at TAMU and needs editing for 508 format
M3a: Aggregate Surface Characteristics (TAMU)	Research report	Report on methods and experimental findings and utility of methodology and findings	6/30/10	Complete	
	Research report	Describes implementation of findings into PANDA and expands experiments to characterization for four aggregates used for validation experiments	6/30/11		
M4a: Micro-mechanics Model (TAMU)	Draft Report	Numerical micromechanical model of moisture-induced damage in asphalt mixtures. This report will include the algorithm and modeling method.	Sep-11		
	Final Report		Sep-11	Mar-12	
M4a: Micromechanics Model Development (Moisture Damage) (UNL)	Models and Algorithm	Cohesive zone modeling with moisture damage of asphalt mixtures considering mixture microstructure: modeling methodology, constitutive theory, testing protocols, test data, model simulation/calibration/validation, and user-friendly manuals.	3/31/11	No change	N/A
	Draft report		06/30/11		
	Final report		12/31/11		
M4a: Lattice Micromechanics Model (NCSU)	Draft Report	Documenting development of lattice micromechanical model	2/14/12		N/A
	Final Report	Documenting development of lattice micromechanical model	8/14/12		
M4a: Model to Bridge Continuum Damage and Fracture (NCSU)	Draft Report	Documenting development of continuum damage-to-fracture model	N/A	2/14/12	N/A
	Final Report	Documenting development of continuum damage-to-fracture model	2/14/12	8/14/12	

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<tr><th>Name of Deliverable</th><th>Type of Deliverable</th><th>Description of Deliverable</th><th>Original Delivery Date</th><th>Revised Delivery Date</th><th>Reason for changes in delivery date</th></tr>
<tr><td rowspan="3">M4c: Unified Continuum Model (TAMU)</td><td>Models and Algorithm</td><td></td><td>6/30/11</td><td>12/31/11</td><td>Model needs to be updated based on calibration with experimental measurements</td></tr>
<tr><td>Draft Report</td><td>Draft Report on the moisture-damage modeling</td><td>9/30/11</td><td></td><td></td></tr>
<tr><td>Final Report (M5, M4c, F1b-1, F1c, F1d-8, F3c, and V3c)</td><td>Report in 508 format that describes a comprehensive and integrated approach to assessing moisture damage on three scales; binder and aggregate components, fine aggregate matrix with DMA and in the full mix – Alternative to more sophisticated PANDA approach</td><td>03/31/12</td><td>6/30/12</td><td>N/A</td></tr>
<tr><td rowspan="4">M5: Moisture Damage Prediction System (All)</td><td>Protocol</td><td>Protocol for implementation of component selection</td><td>6/30/11</td><td></td><td></td></tr>
<tr><td>Experimental method</td><td>Experimental method for measuring moisture damage resistance of full mixture</td><td>9/30/11</td><td></td><td></td></tr>
<tr><td>Draft Report (M5, M4c, F1b-1, F1c, F1d-8, F3c, and V3c)</td><td rowspan="2">Report in 508 format that describes a comprehensive and integrated approach to assessing moisture damage on three scales; binder and aggregate components, fine aggregate matrix with DMA and in the full mix – Alternative to more sophisticated PANDA approach</td><td>12/31/11</td><td></td><td></td></tr>
<tr><td>Final Report (M5, M4c, F1b-1, F1c, F1d-8, F3c, and V3c)</td><td>3/31/12</td><td>6/30/12</td><td>Preparation of a comprehensive report.</td></tr>
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Moisture Damage Year 5

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

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

LEGEND

Deliverable codes	Deliverable Description
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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 (TAMU)

Work Done This Quarter

This task was completed in the last quarter.

Significant Results

The results demonstrated that a multiplicative relationship exists between the ideal and practical work of fracture. The relationship between these two quantities depends on binder compliance, loading rate, and temperature. This work has validated that the ideal work of fracture, which is calculated from surface energy, is a fundamental property than can be used to rank asphalt-aggregate systems based on their resistance to fracture under dry and wet conditions.

Significant Problems, Issues and Potential Impact on Progress

None

Work Planned Next Quarter

This subtask is completed.

Work Element F1b: Viscoelastic Properties (Year 1 start)

Subtask F1b-1: Viscoelastic Properties under Cyclic Loading (UT and TAMU)

Work Done This Quarter

In this quarter the UT team has completed the modeling of interaction nonlinearity in asphalt binders. The results and analysis were documented in a journal paper titled "Constitutive Modeling of the Interaction Nonlinear Viscoelastic Response in Asphalt Binders", which will be submitted for publication to the *Journal of Mechanics of Time-Dependent Materials.* This study includes the validation of the proposed model under different types of loading including oscillatory and monotonic. The oscillatory loading tests were conducted at different stress levels and frequencies. Figures F1b-1.1 and F1b-1.2 show the model validation for two different loading conditions by comparing the linear and nonlinear predictions with the laboratory measurements for asphalt binder PG 76-22. As can be seen the predictions from nonlinear model are in good agreement with the laboratory measurements. These validations of interaction-based constitutive model further corroborated the hypothesis of interaction nonlinearity in asphalt binders.

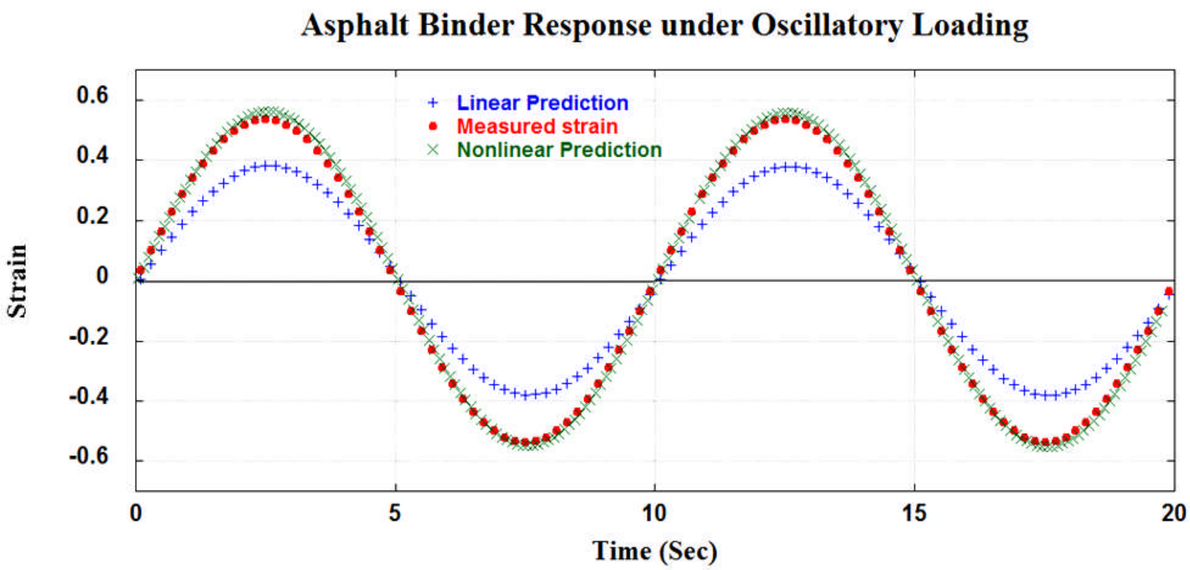


Figure F1b-1.1. The comparison of model predictions and laboratory measurements for asphalt binder PG 76-22, at 48.1 kPa shear stress level, 0.1 Hz, and 28°C.
The average measured first normal stress difference (N_1) was 151 kPa.

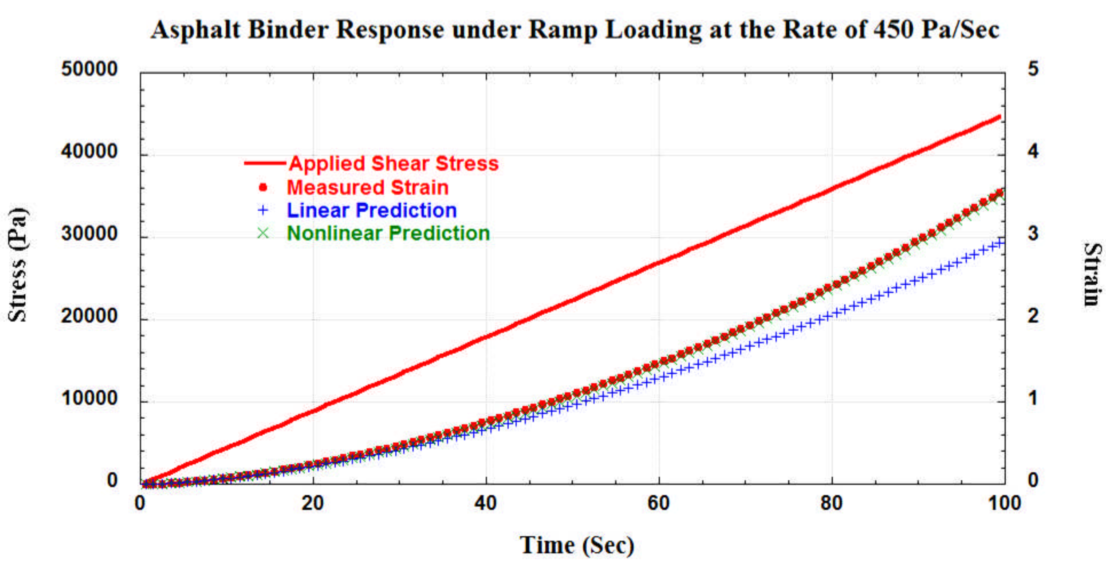


Figure F1b-1.2. The comparison of model predictions and laboratory measurements for asphalt binder PG 76-22 under ramp loading with the rate of 450 Pa/Sec at 28°C.
Where N_1 is the first normal stress difference.

In parallel to this research, we conducted some preliminary tests to measure the bulk modulus of asphalt binders, as a time-dependent material property. The poker chip test geometry was used to carry on the experiment, using Instron ElectroPuls E1000 test instrument. The material response was measured under a step strain load in compression.

The aforementioned model allows for a more accurate constitutive model for computational method. In addition, a new nonlinear, viscoelastic model for asphalt binders based on the stress relaxation data was developed at TAMU. The model is a purely mechanical model and does not take into account the thermal and aging effect of asphalt binders. Therefore, we fit the model to experimental data developed by Narayan et al. (2011) at each temperature and age condition separately.

Significant Results

Schapery's nonlinear viscoelastic model was used to quantify the influence of interaction nonlinearity. The validations of interaction-based constitutive model further corroborated the hypothesis of interaction nonlinearity in asphalt binders.

It is expected that this understanding of nonlinear response combined with the nonlinear viscoelastic model improve the accuracy of computational micromechanics models.

The model based on stress relaxation data was found to fit the experimental results quite well. The agreement with the experimental data obtained with this model was much better than those obtained with the models used by Krishnan and Rajagopal (2005) and Narayan et al. (2010) with the error measures of the fits several times smaller.

Since the model captures the response of asphalt binders quite well, we believe it has the potential to distinguish and characterize asphalt binders. However, this model has been evaluated for only one set of experimental data - the stress relaxation data recorded by Narayan et al. (2011). It is necessary to test this model against experimental data from other types of tests such as creep, oscillatory tests, etc. It should also be noted that this model does not capture certain features of the nonlinear viscoelastic behavior of asphalt binders such as shear thickening/ shear thinning behavior, stress overshoots in steady shear flows, etc. However, the model can be extended to include these complexities.

The model can be expressed as:

$$(\{\tau-\eta D\}\cdot\{\tau-\eta D\})^n\,\{\tau-\eta D\}+\lambda\overset{\triangledown}{\tau}=\mu\,(D\cdot D)^n\,D+\lambda\eta\,\overset{\triangledown}{D}$$

Where τ is the deviatoric part of the Cauchy stress **T**. The torque and the normal force relaxation curves of this model in torsion asymptotically approach straight lines of slope $\frac{1}{2n}$ in the log-log scale as $t \to \infty$. Due to the presence of ηD, the model exhibits a jump in stress shear corresponding to a jump in rate o shear in shear flow.

Significant Problems, Issues and Potential Impact on Progress

None.

Work Planned Next Quarter

In the next quarter we plan to complete the tests and analysis related to the measurement of bulk modulus. We will conduct the poker-chip tests on asphalt binders to measure the time dependency of bulk modulus. In parallel to laboratory experimentation, we will analyze the data to come up with an appropriate aspect ratio and strain level that eliminates the effect of singular point at the edge of the specimen.

Validate the ability of the model to predict the response of the two asphalt binders selected for validation as well as selected polymer modified binders selected in conjunction with UWM.

References

Krishnan, J. M., and K. R. Rajagopal, 2005, On the mechanical behavior of asphalt. *Mechanics of Materials*, 37(11), 1085-1100.

Narayan, S. P. A., K. A. Venkata Nag, J. Murali Krishnan, A. Deshpande, and K. R. Rajagopal. On the transient response of asphalt binders. *Submitted for publication*, 2010.

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

Work Done This Quarter

The reader is referred to Work Elements F2c and E1a.

Work Planned Next Quarter

The reader is referred to Work Elements F2c and E1a.

Work Element F1c: Aging

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

Work Done This Quarter

No work this quarter.

Significant Results

N/A

Significant Problems, Issues and Potential Impact on Progress

There are no problems or issues.

Work Planned Next Quarter

Review of the literature and work on other research projects is ongoing.

Subtask F1c-2: Develop Experimental Design (TAMU)

Work Done This Quarter

No work this quarter.

Significant Results

None.

Significant Problems, Issues and Potential Impact on Progress

The planned experiments using ARC core binders is underway, as well as measurements on mixtures fabricated using other binders.

Work Planned Next Quarter

Measurements of mixture rheology and fatigue continue. Also, rheological measurements of binders extracted and recovered from these mixtures will be made as part of the effort to link binder oxidation to changes in mixture properties.

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

Work Done This Quarter

Measurements of Recovered Binder Properties

Measurements of the WRI test section sites await delivery of the field cores.

Measurements of ARC Binder Kinetics Parameters

Work Done This Quarter

Three ARC binders (NuStar PG 67-22, PG 76-22 from Atlanta and Valero PG 64-16 from Benicia) were aged in pressure oxidation vessels (POV) according to the experimental design in the work plan. The aging temperatures were controlled at 59.2, 70.0, 79.8, and 92.4 °C, with variations of 0.6 °C around the set points. The aging pressure was one atmosphere air. Kinetics data in terms of carbonyl area (CA) were obtained and analyzed.

Analysis of Kinetics Data

For each binder, both fast-rate and constant-rate kinetics data were obtained. These CA kinetics data, at all four temperatures, were used to globally optimize the model parameters in the proposed asphalt oxidation kinetics model:

$$CA = CA_{tank} + M\,[1 - \exp(-k_f t)] + k_c t$$
$$k_f = A_f \exp(-E_{af}/RT)$$
$$k_c = A_c \exp(-E_{ac}/RT)$$

where $M=(CA_0 - CA_{tank})$, CA_{tank} is the carbonyl area of the tank asphalt, CA_0 is the initial jump (intercept of constant-rate line), k_f and k_c are two reaction constants that are temperature dependent according to the Arrhenius equation, A_f and E_{af} are frequency factor and activation energy for the fast-rate reaction, and A_c and E_{ac} are frequency factor and activation energy for the constant-rate reaction. In summary, this model has six model parameters: CA_{tank}, CA_0, A_f, E_{af}, A_c, and E_{ac}, among which CA_{tank} is measured directly before the aging experiments, and the remaining five model parameters were obtained from the global optimization process. Table F1c-3.1 shows the five optimized model parameters and CA_{tank}.

Table F1c-3.1. Model parameters for three ARC asphalts.

Binder	**CA_0**	**A_f (1/Day)**	**E_{af} (KJ/mol)**	**A_c (CA/Day)**	**E_{ac} (KJ/mol)**	**CA_{tank}**
NuStar PG 67-22	0.752	1.04×10^{8}	55.8	3.70×10^{9}	76.1	0.620
NuStar PG 76-22	0.762	4.51×10^{6}	44.9	1.79×10^{8}	67.1	0.650
Valero PG 64-16	1.071	2.26×10^{8}	60.2	1.10×10^{11}	86.9	0.770

Using the model parameters, asphalt oxidation at one atmosphere air pressure can be calculated using the proposed kinetics model, given the aging temperatures. Figure F1c-3.1 demonstrates the very good match between model calculation and experimental results for NuStar PG 67-22 at all four temperatures. The other two binders showed similarly good comparisons.

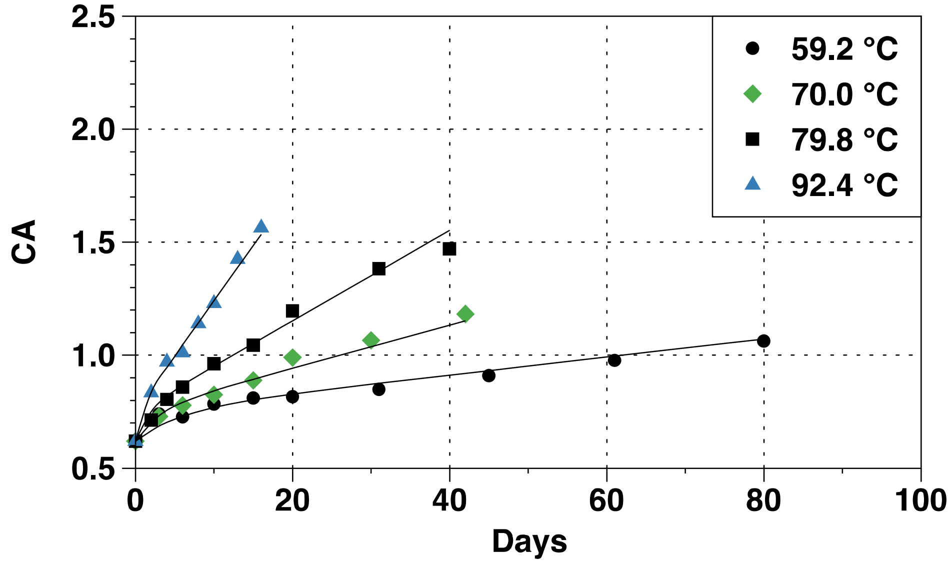


Figure F1c-3.1. Comparison of model calculations (solid lines) of CA to experimental data (symbols) for NuStar PG 67-22.

Significant Results

N/A

Significant Problems, Issues and Potential Impact on Progress

There are no problems or issues.

Work Planned Next Quarter

DSR tests will be conducted on these three binders and hardening susceptibilities (change in viscosity with oxidation) will be obtained. Furthermore, three SHRP asphalts (AAA-1, AAD-1, and AAM-1) will be aged in POV according to the experimental design in the previous work plan. Kinetics data will be obtained and analyzed to provide estimates of the model parameters. Additionally, model calculations of pavement temperature variation with time and depth will be made for a number of national locations for archiving in a temperature database. The calculations will be based on measured climate data (hourly temperature and solar radiation, plus wind speed), together with our transport model of pavement temperature (Han et al. 2011).

Cited References

Han, Rongbin, Xin Jin, and C. J. Glover, 2011, Modeling Pavement Temperature for Use in Binder Oxidation Models and Pavement Performance Prediction. *Journal of Materials in Civil Engineering*, 23(4), 351-359.

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

Work Done This Quarter

The reader is referred to Work Elements F1b-2, F2c, and E1a.

Work Planned Next Quarter

The reader is referred to Work Elements F1b-2, F2c, and E1a.

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

Work Done This Quarter

No additional work on this subtask was conducted this quarter.

Work Planned Next Quarter

The effort to establish polymer degradation kinetics due to oxidation is being reviewed and appears to be an intractable problem.

Work Element F1d: Healing (TAMU)

Subtask F1d-1: Critical review of the literature
Subtask F1d-2: Material selection
Subtask F1d-3: Experiment design
Subtask F1d-4: Test methods to measure properties related to healing
Subtask F1d-5a: Testing of materials and validating healing model
Subtask F1d-5b: Thermodynamic model for healing in asphalt binders

Work Done This Quarter

In the previous quarters we reported a DSR based test procedure designed to measure the overall healing in FAM specimen as a function of damage level prior to rest periods and duration of rest periods. In this quarter, in addition to continued measuring of overall healing on different mixes, we also ran verification tests to demonstrate the surface curve of healing potential to be artifact free. Partial validation that this procedure is artifact free was reported in the previous quarterly report. Additional verification tests were designed and conducted in this quarter using the viscoelastic continuum damage (VECD) theory to unify results from tests conducted at different amplitude, frequency and mode into one unique fatigue curve and are primarily proposed to eliminate systematic errors in the procedure if any. We have completed tests on four different FAM mixes and we will continue to test two more in the coming quarters.

Completing the current experiment design will allow us to measure and validate the healing response and eventually predict the gain in number of load cycles to failure for a given combination of loading and rest periods.

Significant Results

Based on the verification tests done so far we have been successful in demonstrating the healing potential surface to be artifact free and largely dependent on the material and not the test procedure.

Significant Problems, Issues and Potential Impact on Progress

None.

Work Planned Next Quarter

We will continue to measure intrinsic healing and refine the methodology, especially for shorter rest periods. We also plan to investigate the possibility of a faster method to determine the healing surface for a particular mix along with a method to back calculate the gain in terms of load cycles for given loading-rest period combination.

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

Work Done This Quarter

The research team has continued to use the strain controlled time sweep with a single rest period for the measurements of healing potential. A few modifications to the procedure have been made. Previously, a standard one hour rest period was used. To shorten the testing time, the standard rest period duration has been reduced to 30 minutes. Additionally, a healing rate is proposed in place of the healing index discussed in the past quarter. The healing rate incorporates the rest period duration. A depiction of the definition of healing rate is provided in figure F1d-6.1.

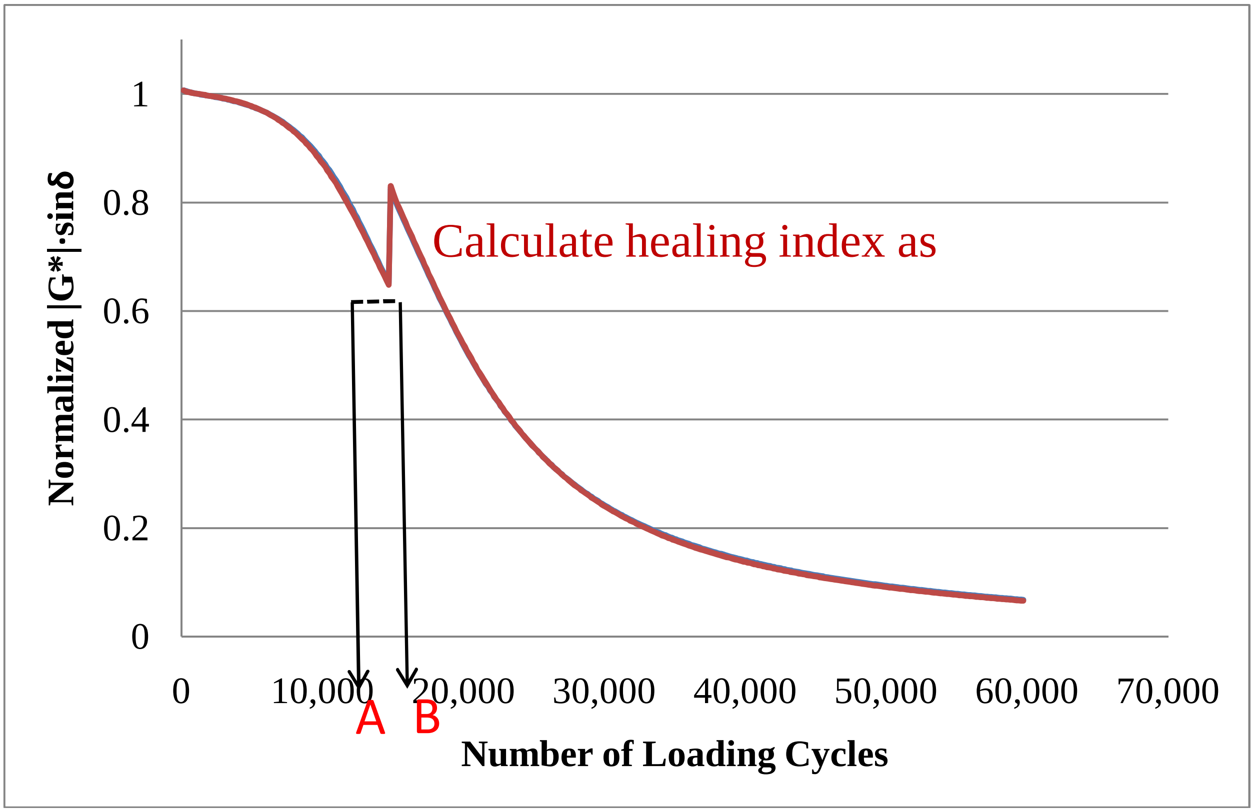


Figure F1d-6.1. Graph. Depiction of healing rate calculation.

The research team has begun investigating the effect of modification, base binder, and strain on the healing rate. To eliminate stiffness effects, all binders were tested at an iso-stiffness temperature. The iso-stiffness condition selected was |G*|·sinδ = 6.5 MPa. A summary of the binders tested thus far is provided in table F1d-6.1. All binders were subjected to strain controlled time sweep testing with and without rest at both 2% and 3% strain amplitudes. Rest periods were inserted when a 35% reduction in |G*|·sinδ was reached.

Table F1d-6.1. Binders included in study.

Binder	Base Binder	Modification	High Temperature Grade
A0	A	None	PG 64
A3	A	SBS with X-linking	PG70
E0	E	None	PG 64
E1	E	SBS with X-linking	PG 70
E2	E	SBS with X-linking	PG 76

<u>Significant Results</u>

Figure F1d-6.2 provides a depiction of typical results. Results demonstrate the test is repeatable and capable of distinguishing between different binders.

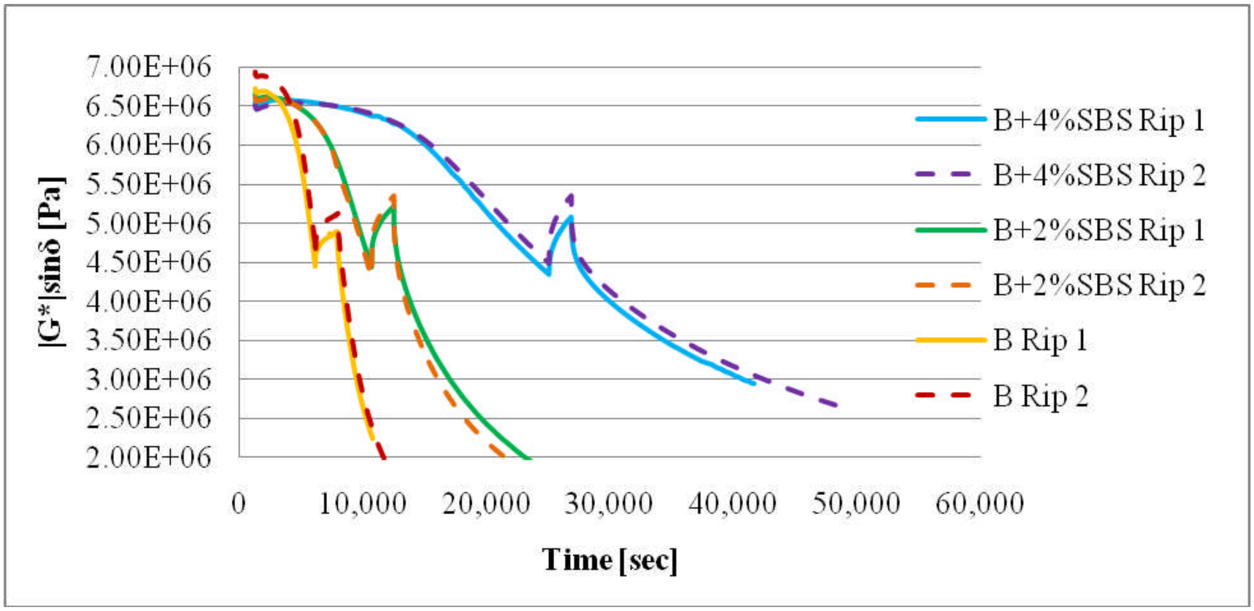


Figure F1d-6.2. Graph. Typical results.

Results of healing rates at 2% and 3% strain for all binders tested are provided in tables F1d-6.2 and F1d-6.3, respectively. Results are also provided graphically in figure F1d-6.3. Results demonstrate good repeatability. It is clear that modification increases the healing rate while the base binder seems to have little effect. Also, increasing strain appears to increase healing rate.

Table F1d-6.2. Healing rate results at 2% strain.

Binder	Healing Rate [%]		Average [%]	Coef. of Variation
	Rep. 1	Rep. 2		
A0	5.73	5.99	5.86	3.14%
A3	11.01	10.52	10.77	3.22%
E0	5.73	5.56	5.65	2.13%
E1	9.28	9.28	9.28	0.00%
E2	8.77	8.09	8.43	5.70%

Table F1d-6.3. Healing rate results at 3% strain.

Binder	Healing Rate [%]		Average [%]	Coef. of Variation
	Rep. 1	Rep. 2		
A0	6.42	6.58	6.50	1.74%
A3	16.96	16.5	16.73	1.94%
E0	7.29	7.09	7.19	1.97%
E1	12.96	13.55	13.26	3.15%
E2	12.63	12.55	12.59	0.45%

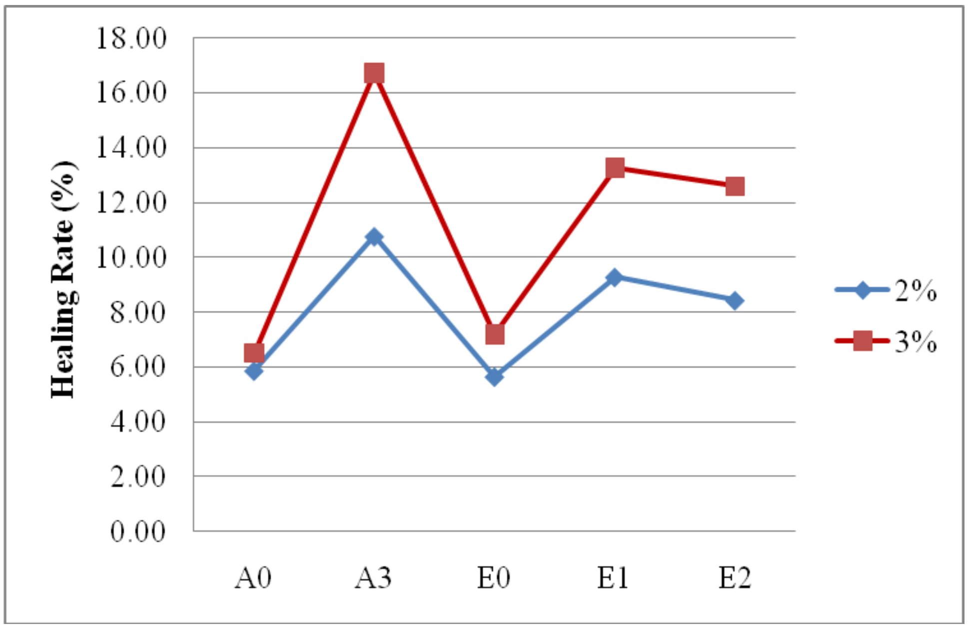


Figure F1d-6.3. Graph. Healing rate results.

An analysis of variance (ANOVA) was conducted to verify graphical findings that binder modification and strain significantly affect healing rate. Results are provided in table F1d-6.4. Based on P-values, base binder is insignificant while both strain and modification are significant factors. These results provide promising evidence that the newly developed procedure and healing rate parameter are able to determining relative healing capabilities.

Table F1d-6.4. ANOVA results.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Base	1	1.535	5.029	5.029	2.84	0.113
Strain	1	53.040	53.040	53.040	29.97	0.000
Modification	2	161.609	161.609	80.805	45.66	0.000
Error	15	26.544	26.544	1.770		
Total	19	242.728				

S = 1.33026   R-Sq = 89.06%   R-Sq(adj) = 86.15%

Significant Problems, Issues and Potential Impact on Progress

None.

Work Planned Next Quarter

The research team will test at a different iso-stiffness condition ($|G^*|\cdot\sin\delta$ = 2 MPa) to determine the effect of stiffness on healing rate. The effect of different modification types on healing rate will also be investigated. Additionally, the effect of inclusion of rest periods on the relationship between strain and number of cycles to failure will be investigated.

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

Work Done This Quarter

The emphasis of this subtask is to integrate the results from Subtasks M1b-2 and M2a-2, and other pertinent past experimental work where physico-chemical properties including chemical potentials and phase separation phenomena can be used in the asphalt microstructure model discussed in Work Element F3a. The data generated from these analyses is discussed and incorporated into the chemo-mechanical models of asphalt and asphalt mastic structures in Work Element F3a.

Significant Results

See Work Element F3a.

Significant Problems, Issues and Potential Impact on Progress

None

Work Planned Next Quarter

Activity is in Subtask is included in the discussion in Work Element F3a.

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

Work Done This Quarter

In this quarter, a general thermodynamic framework for coupling damage and micro-damage healing has been proposed. Special attention has been placed on the proper estimation of the energy recovered during the healing process. The micro-damage healing model that has been derived based on this thermodynamic framework has been verified against many of the ALF experimental data. Work is still undergoing to relate the associated material parameters to fundamental properties (e.g. surface energy, bond strength, length of the healing process zone) based on micro-mechanical arguments.

Significant Results

The proposed thermodynamic framework can be effectively used in deriving various forms of constitutive models for bituminous materials by only assuming mathematical expressions for the stored energy and the rate of energy dissipation. It is anticipated that this thermodynamic framework will be widely used by researchers to derive robust constitutive models for different materials.

Significant Problems, Issues and Potential Impact on Progress

None

Work Planned Next Quarter

The main focus of the coming quarter is on further validation of the micro-damage healing model against the ARC 2x2 experimental data.

CATEGORY F2: TEST METHOD DEVELOPMENT

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

Work Done This Quarter

This quarter, the investigation of the effect of filler types on mastic fatigue was completed. In addition, statistical analysis was performed on data generated in previous quarters to investigate the effect of modification and fillers on the fatigue performance of asphalt binders. An analysis of variance (ANOVA) was conducted to determine which are the main effects as well as possible interactions. The analysis was based on the assumption that the errors (i.e., residuals) in the statistical model that describe fatigue performance as a function of type and level of modification, are normally distributed with a mean of zero. Violation of these assumptions can be easily investigated by examining the residual plots. An adequate model will show no obvious pattern in the plot of residuals. The normality was checked by constructing the normal probability plot of the residuals. If the error distribution is normal, the plot will resemble a straight line.

Two types of Styrene-Butadiene-Styrene (SBS): linear and radial, and two types of Elvaloy: 4170 and AM, were used in the analysis. In order to quantify the differences between the effect of the linear and radial SBS and between Elvaloy 4170 and Elvaloy AM on fatigue performance, Tukey's test were also performed. Factors were considered significant for p-values lower than 0.05.

The controlled variables for this analysis are:

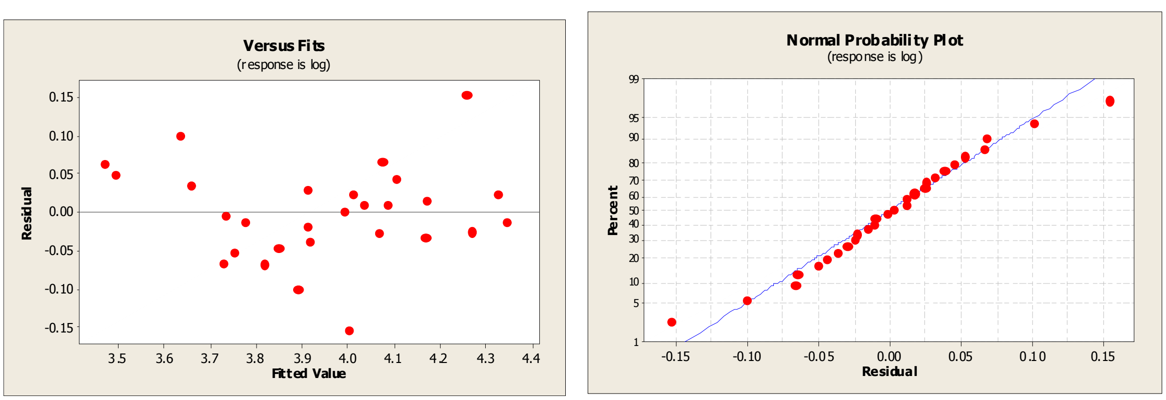
- Binder type: Flint Hills (FH) and CRM
- Type of the polymer: Neat, linear SBS (LSBS),radial SBS (RSBS), Elvaloy 4170, Elvaloy AM, PE1, PE2, Poly-phosphoric Acid (PPA)
- Modification level: low and high
- Filler type: calcite (CA2), dolomite (DS2), limestone (LS2)

The controlled response was the number of cycles to failure determined from the Linear Amplitude Sweep (LAS) test at 5% strain for both binder and mastics.

Significant Results

A preliminary analysis of the residual plots showed that the assumption of random distribution of errors was violated and therefore a logarithmic transformation of the controlled response was applied. The normality plot and the residual plot are shown in figure F2a.1. The statistical model selected was appropriate, as indicated by figure F2a.1.

The analysis of variance revealed that the fatigue life is highly affected by binder type, polymer type and level of modification (p-value lower than 0.5), as shown in table F2a.1.



(a) (b)

Figure F2a.1. Graph. (a) Plot of residuals versus fitted values (b) Normality plot of residuals.

Table F2a.1. ANOVA of the effect of modification on fatigue of asphalt binders.

Factor	**p-value**
Binder	0.000
Polymer Type	0.000
Modification Level	0.000
Binder*Polymer type	0.844

Tukey's confidence tests showed that no significant difference between linear SBS and radial SBS exists as indicated by the p-value of 0.58. The Tukey's test also showed that there are no significant differences between Elvaloy AM and Elvaloy 4170 (p-value = 0.11).

Additionally, an ANOVA test was performed to investigate the effect of filler type on fatigue performance. The results showed that fatigue life is not significantly affected by filler type.

<u>Work Planned Next Quarter</u>

Work in the next quarter will continue preparing the draft report.

Work Element F2b: Mastic Testing Protocol (TAMU)

<u>Work Done This Quarter</u>

This work element is completed and the reader is referred to work element M1c.

Work Element F2c: Mixture Testing Protocol (TAMU)

<u>Work Done This Quarter</u>

Two technical papers were accepted for publication in academic journals:

- "Microstructure-Based Inherent Anisotropy of Asphalt Mixtures" has been accepted for publication in the ASCE *Journal of Materials in Civil Engineering*; and
- "Anisotropic Viscoelastic Properties of Undamaged Asphalt Mixtures" has been accepted for publication in the ASCE *Journal of Transportation Engineering*.

Additional laboratory tests were conducted in this quarter on 16 asphalt mixture samples according to the mixture testing protocols proposed in last quarter. In addition, a mechanistic model based on fracture mechanics was proposed to characterize the viscoelastic fracture properties of asphalt mixtures under a compressive load. Details of the achievements made in this quarter are summarized as follows:

1) Laboratory Verification of Mixture Testing Protocols

In previous quarters, an experimental protocol was developed that included three tests: 1) a nondestructive compressive creep test to obtain the creep compliance and relaxation modulus of undamaged asphalt mixtures; 2) a nondestructive compressive dynamic modulus test to obtain the dynamic modulus and phase angle of undamaged asphalt mixtures; and 3) a destructive compressive dynamic modulus test to obtain the dynamic modulus and phase angle of damaged asphalt mixtures. The total strain measured in the destructive dynamic modulus test was decomposed into elastic strain, viscoelastic strain, plastic strain, viscoplastic strain and viscofracture strain by employing the pseudo strain concept and the extended elastic-viscoelastic correspondence principle.

To verify the proposed testing protocols and the strain decomposition method, the aforementioned tests are conducted on 16 lab-mixed-lab-compacted (LMLC) asphalt mixture specimens that have the following variables:

- Two types of asphalt binder: labeled by AAM and AAD in the Strategic Highway Research Program (SHRP) Materials Reference Library (MRL);
- Two air void contents: 4% and 7% (variation within ±0.5%); and
- Two aging conditions: unaged and continuous 6-month 60 °C aged asphalt mixtures.

Two replicate specimens are made for each combination of the asphalt binder, air void content and aging condition.

1.1) Testing Results of the Undamaged Asphalt Mixtures

The undamaged properties of the 16 asphalt mixtures are obtained by conducting the nondestructive creep tests and nondestructive dynamic modulus tests in compression. Testing results are analyzed using the linear viscoelastic theory, in which the creep compliance and relaxation modulus are modeled with the Prony series model and the dynamic modulus ($|E^*|$) and phase angle (δ) of the undamaged asphalt mixtures are found to remain constant for each sample. The Young's modulus (E_Y) represents the instantaneous (elastic) response of a material and E_Y can be calculated using $E_Y = E(0) = 1/D(0)$, where $E(0)$ is the instantaneous relaxation modulus and $D(0)$ is the instantaneous creep compliance. Figure F2c.1 presents the measured Young's moduli, dynamic moduli and phase angles for the 16 undamaged asphalt mixture specimens that vary in the binder type, air void content and aging condition.

As can be observed in figure F2c.1, both Young's modulus and dynamic modulus increase as the asphalt mixtures become stiffer due to aging or less air void content. The phase angle decreases as the asphalt mixture is aged which is reasonable because the asphalt mixture behaves more elastically when it is aged. No significant correlation is found between the phase angle and the air void content. However, aging reduces the phase angle more in the samples with the higher air void content which have more air available to oxidize the binder in the mix. All of the findings comply with the common understanding of the viscoelastic properties of asphalt mixtures. The measured Young's modulus, dynamic modulus and phase angle of the undamaged asphalt mixtures will be used in the calculation of the pseudo strain and the strain decomposition in the destructive dynamic modulus tests.

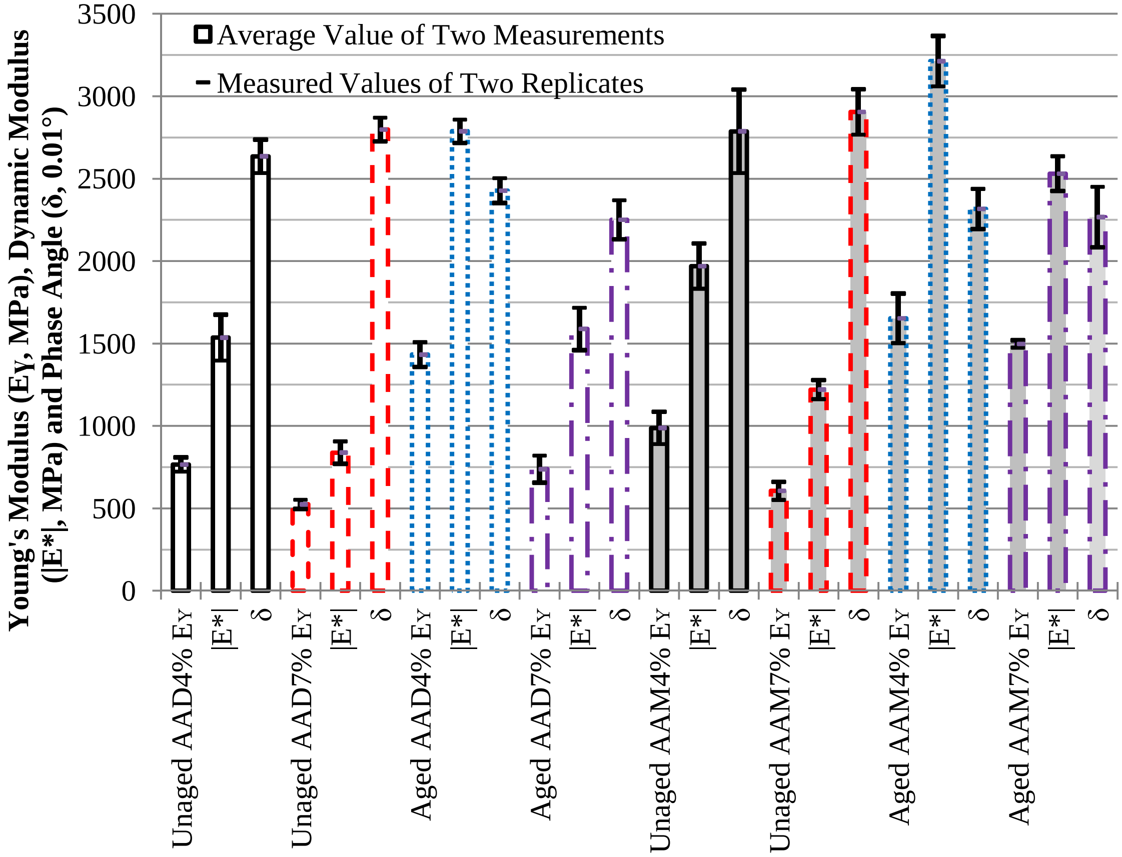


Figure F2c.1. Young's modulus, dynamic modulus and phase angle for different asphalt mixtures at 40°C.

1.2) Testing Results of the Damaged Asphalt Mixtures

The same undamaged asphalt mixtures are later subjected to destructive dynamic modulus tests, in which the dynamic modulus ($\left|E_N^*\right|$) and phase angle (φ_N) of the damaged asphalt mixtures are found to vary with load cycles. All of the 16 samples show similar evolutions of $\left|E_N^*\right|$ and φ_N as follows:

- In the primary stage, $\left|E_N^*\right|$ increases and φ_N decreases due to the closure of the initial air voids under a compressive load;
- In the secondary stage, $\left|E_N^*\right|$ decreases slowly while φ_N remains constant which are the results of material plastic flow under the destructive compressive stress; and
- In the tertiary stage, $\left|E_N^*\right|$ decreases rapidly and φ_N increases, which is because of the opening and propagation of cracks.

The constant phase angle in the secondary stage and the increasing phase angle in the tertiary stage indicate that cracks in the specimen under a compressive load will not develop until the tertiary stage and the growth of cracks is signaled principally by the increase of the phase angle.

The strain decomposition is performed on each of the 16 samples and the total strain measured in the destructive dynamic modulus test is successfully decomposed into the elastic strain, viscoelastic strain, plastic strain, viscoplastic strain and viscofracture strain. The separated viscoplastic strain curve is modeled with the Tseng-Lytton model shown in equation F2c.1 to characterize the permanent deformation of the asphalt mixtures. The separated viscofracture strain curve is modeled with a fracture strain model proposed in equation F2c.2 to characterize the fracture of the asphalt mixtures.

$$\varepsilon^{vp} = \varepsilon_{\infty}^{vp} \exp\left[-\left(\rho/N\right)^{\lambda}\right] \tag{F2c.1}$$

$$\varepsilon^{vf} = \varepsilon_{0}^{vf} \left\{\exp\left[\theta\left\langle N - N_f\right\rangle\right] - 1\right\} \tag{F2c.2}$$

where N_f = flow number that is the starting point of the tertiary stage; $\varepsilon_{\infty}^{vp}$, ρ, λ, ε_0^{vf} and θ = fitting parameters. $\left\langle N - N_f \right\rangle$ is a step function where $\left\langle N - N_f \right\rangle = N - N_f$ if $N - N_f \geq 0$ and $\left\langle N - N_f \right\rangle = 0$ if $N - N_f < 0$.

To compare the crack growth speed of different asphalt mixtures, a parameter $\eta = \theta\varepsilon_0^{vf}$ is chosen as a crack speed index and a higher value of η means faster crack propagation. The crack growth speed indices for the 16 asphalt mixtures are shown in figure F2c.2 which also include the viscoplastic strain at flow number ($\varepsilon^{vp}(N_f)$) that is calculated based on the model in equation F2c.1. The flow number is determined by fitting equation F2c.2 to the viscofracture strain curves. Figure F2c.2 shows that the flow number increases while the viscoplastic strain at the flow number and the crack speed index decrease as the air void content decreases or the asphalt mixtures become aged. This observation indicates that a smaller air void or a stiffer asphalt mixture due to aging can provide the material a better resistance to permanent deformation and to fracture.

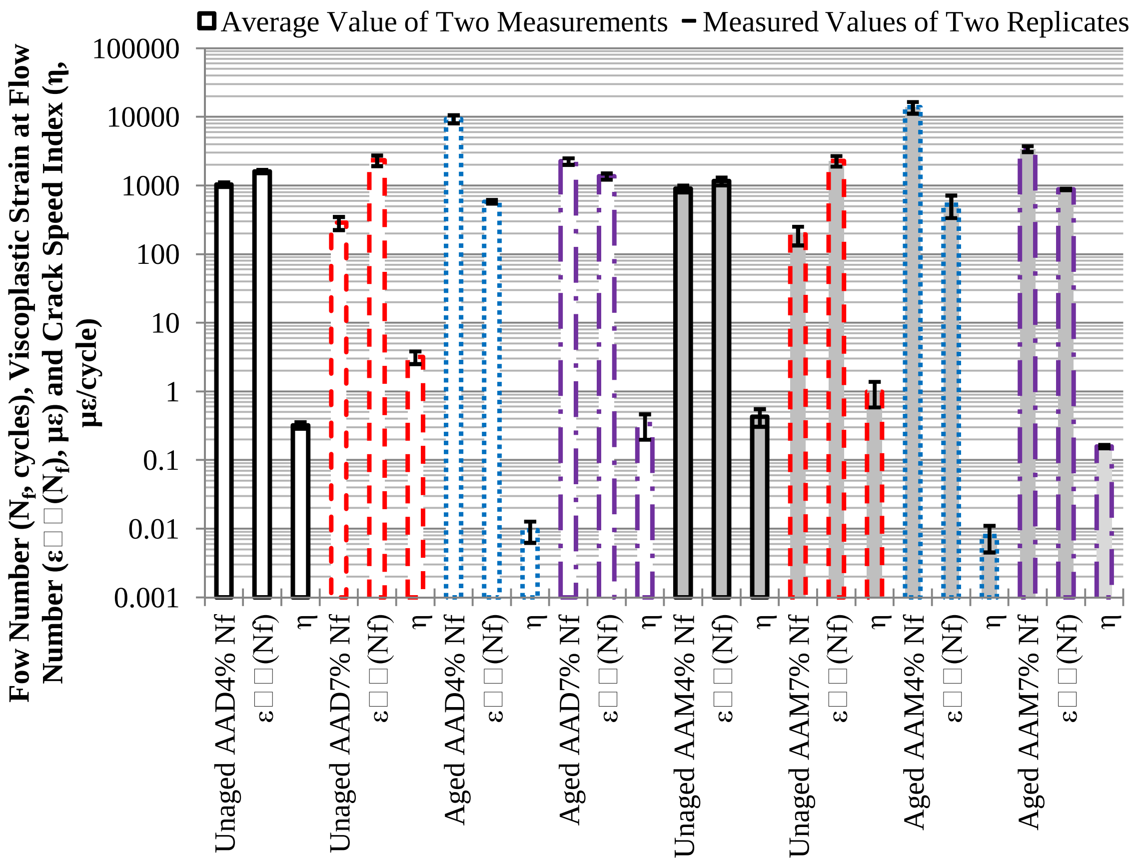


Figure F2c.2. Flow number, viscoplastic strain at flow number and crack speed index for different asphalt mixtures at 40°C.

2) Fracture Mechanistic Analysis of Asphalt Mixture in Compression

In previous quarters, the permanent deformation of the asphalt mixture was characterized by employing the viscoplastic continuum mechanistic model in which the nominal stress was modified by an anisotropic damage density so as to take into account the effect of cracks on the permanent deformation. In this quarter, the damage density is modeled based on a fracture mechanistic method. In a specific direction, the damage density, by definition, equals the ratio of the lost area to the total area of the material. Considering a force balance equation between the apparent (damaged) configuration and the true (undamaged) configuration as in equation F2c.3, the damaged density can be calculated by equation F2c.4.

$$\sigma^A A_0 = \sigma^T \left(A_0 - A_L \right) \tag{F2c.3}$$

$$\xi = \frac{A_L}{A_0} = 1 - \frac{\sigma^A}{\sigma^T} \tag{F2c.4}$$

where ξ = damage density; A_0 = total cross sectional area of the specimen; A_L = lost area due to growth of cracks; σ^A = apparent stress that is controlled during tests; and σ^T = true stress which can be estimated by using a dissipated pseudo strain energy (DPSE) balance equation shown in equation F2c.5:

$$\frac{\pi}{2}\sigma^A\varepsilon^{vf}\sin\left(\varphi_N-\varphi_{II}\right)=\frac{\pi}{2}\frac{\left(\sigma^T-\sigma^A\right)^2}{\left|E^*\right|}\sin\left(\delta-\varphi_{II}\right) \tag{F2c.5}$$

where ε^{vf} = viscofracture strain; φ_N = phase angle of the damaged asphalt mixtures; φ_{II} = the constant phase angle in the secondary stage of the destructive dynamic modulus test; $\left|E^*\right|$ and δ = dynamic modulus and phase angle of the undamaged asphalt mixtures. Solving equation F2c.5 yields the true stress as:

$$\sigma^T=\left[\sigma^A\varepsilon^{vf}\left|E^*\right|\frac{\sin\left(\varphi_N-\varphi_{II}\right)}{\sin\left(\delta-\varphi_{II}\right)}\right]^{\frac{1}{2}}+\sigma^A \tag{F2c.6}$$

Equations F2c.4 and F2c.6 give the expression of damage density:

$$\xi=1-\sigma^A\left\{\left[\sigma^A\varepsilon^{vf}\left|E^*\right|\frac{\sin\left(\varphi_N-\varphi_{II}\right)}{\sin\left(\delta-\varphi_{II}\right)}\right]^{\frac{1}{2}}+\sigma^A\right\}^{-1} \tag{F2c.7}$$

Figure F2c.3 shows an example of the viscoplastic strain and viscofracture strain obtained by performing strain decomposition. Figure F2c.3 also presents the fitted viscofracture strain, true stress and damage density calculated using equation F2c.2, equations F2c.6 and F2c.7, respectively. It is found that the equation F2c.2 fits the measured viscofracture strain very well. In the tertiary stage, the true stress and the damage density increase due to the growth of cracks. According to the viscoplastic theory, an increasing true stress will yield more plastic deformation, which means the growing cracks in the tertiary stage can result in extra permanent deformation even though the asphalt mixture is subjected to a controlled compressive load with a constant amplitude.

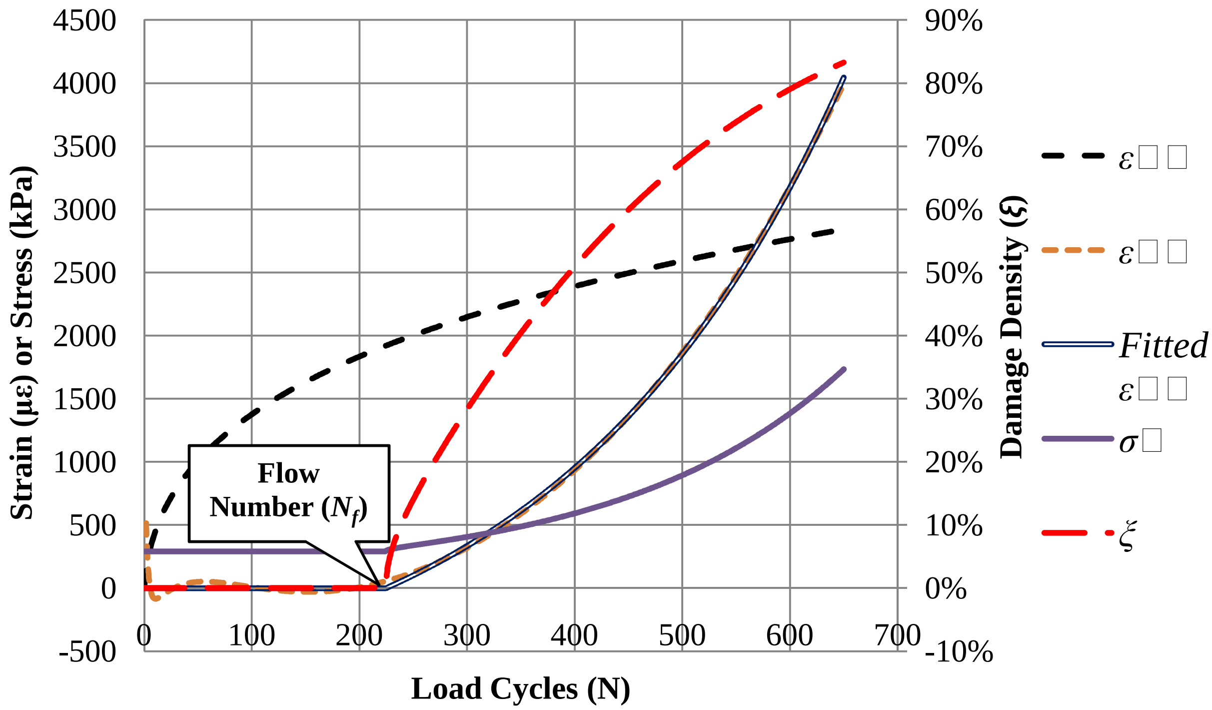


Figure F2c.3. Viscoplastic strain, viscofracture strain, true stress and damage density.

Significant Results

The mixture testing protocols and the strain decomposition method proposed in the last quarter on characterizing the asphalt mixture in compression are verified in this quarter by conducting tests on 16 asphalt mixture specimens that have two binder types, two air void contents and two aging conditions. Results indicate that the proposed testing protocols can obtain consistent and reasonable material properties. The strain decomposition is successfully performed on each asphalt mixture specimen and yields viscoplastic and viscofracture strains that are respectively used in the characterization of permanent deformation and cracking of the asphalt mixture. A fracture mechanistic model is proposed to analyze the growth of the cracks in the tertiary stage, based on which the damage density is obtained to address the effect of the cracks on the permanent deformation during the viscoplastic modeling. Results indicate that the cracks in the tertiary stage can yield an increasing true stress which, in turn, leads to extra plastic deformation when an asphalt mixture is subjected to a controlled compressive load with a constant amplitude.

Significant Problems, Issues and Potential Impact on Progress

None.

Work Planned in Next Quarter

- One-dimensional testing protocols and fracture mechanics analysis need to be extended to the three-dimensional condition. The anisotropic damage density is needed in the anisotropic viscoplastic-fracture analysis; and
- The constant strain rate strength tests will be conducted on more specimens to obtain the yield surface of the asphalt mixtures that vary by binder types, air void contents and aging conditions.

Work Element F2d: Structural Characterization of Micromechanical Properties in Bitumen using Atomic Force Microscopy (TAMU)

Work Done This Quarter

Statistical analysis of the AFM creep presented in previous quarterly reports, and summarized in the year 5 work plan under work element F2d: Structural Characterization of Micromechanical Properties in Bitumen using Atomic Force Microscope (AFM) was performed in order to make inferences about the populations of asphalt phases in which the data were collected. Included in the statistical analysis were relative frequency histograms and q-q plots to test for normality of the data, t-tests and ANOVA f-tests to compare the means of two or more asphalt phases, individual comparisons based on Fisher's LSD to identify specifically where differences occur amongst three or more phases, Matched Pairs analysis to compare means of individual phases (continuous or dispersed) before and after aging, and Contingency analysis of categorical variables for making inferences based on proportions of measurements falling within specified asphalt stiffness ranges.

The relative frequency histograms and q-q plots revealed that some non-normality and outliers were present in most of the data sets, which indicated the need for a more robust statistical method, such as the Wilcoxon/Kruskal Wallis Sum Rank test to verify the results of the more powerful t-tests and f-tests. The t-tests and ANOVA f-tests (accompanied by the Wilcoxon/Kruskal Wallis Sum Rank test) provided at least 95% confidence that differences in phase properties existed in five of the six asphalt binders that were tested. There was a lack of statistical evidence to find a difference between the phase properties of Aged Asphalt AAB. Fisher's LSD analysis revealed with 95% confidence that each of the three phases in Aged Asphalt AAD had distinctively different properties. Matched pairs analysis provided at least 95% confidence that 11 of 12 continuous and dispersed asphalt phases that were studied reveal a decrease in maximum creep deflection (increase in stiffness) due to aging; this finding strongly supports the notion presented by Allen et al. (2011) that observed increases in asphalt stiffness during aging are not only due to the presence of higher percentages of the stiffest phase after aging but also due to increased stiffness of the continuous and dispersed phases due to aging. For Asphalts AAD and ABD, the contingency analysis resulted in rejection of the null hypothesis that asphalt stiffness is independent of both asphalt phase and asphalt age at the $\alpha = 0.0001$ level (99.99% confidence level); however, there was a lack of statistical evidence to reject the null hypothesis for Asphalt AAB.

Significant Problems, Issues and Potential Impact on Progress

None.

Work Planned Next Quarter

Tomography will be carried out as needed for the models development.

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

Work Done This Quarter

The research team tested binders using the linear amplitude sweep (LAS) test and compared results with mixture fatigue results from time sweeps conducted in the indirect tension (IDT) mode. The mixture test results were taken from NCHRP Project 9-45 (Bahia et al. 2011). In NCHRP 9-45, the effect of mineral filler on HMA performance was studied by testing mixtures blended with different fillers. Four binders and two gradations were included. All mixtures were prepared with a binder to filler mass ratio of one, which is within Superpave specifications. All tests were run in the stress controlled mode at 25°C and 10Hz frequency. Failure was taken to be a 45% reduction in dynamic modulus (E*). The results of the mixture tests are provided in figure F2e.1. As shown in figure F2e.1, a wide range of fillers were used. It is evident that both binder type and filler type impacted IDT fatigue results.

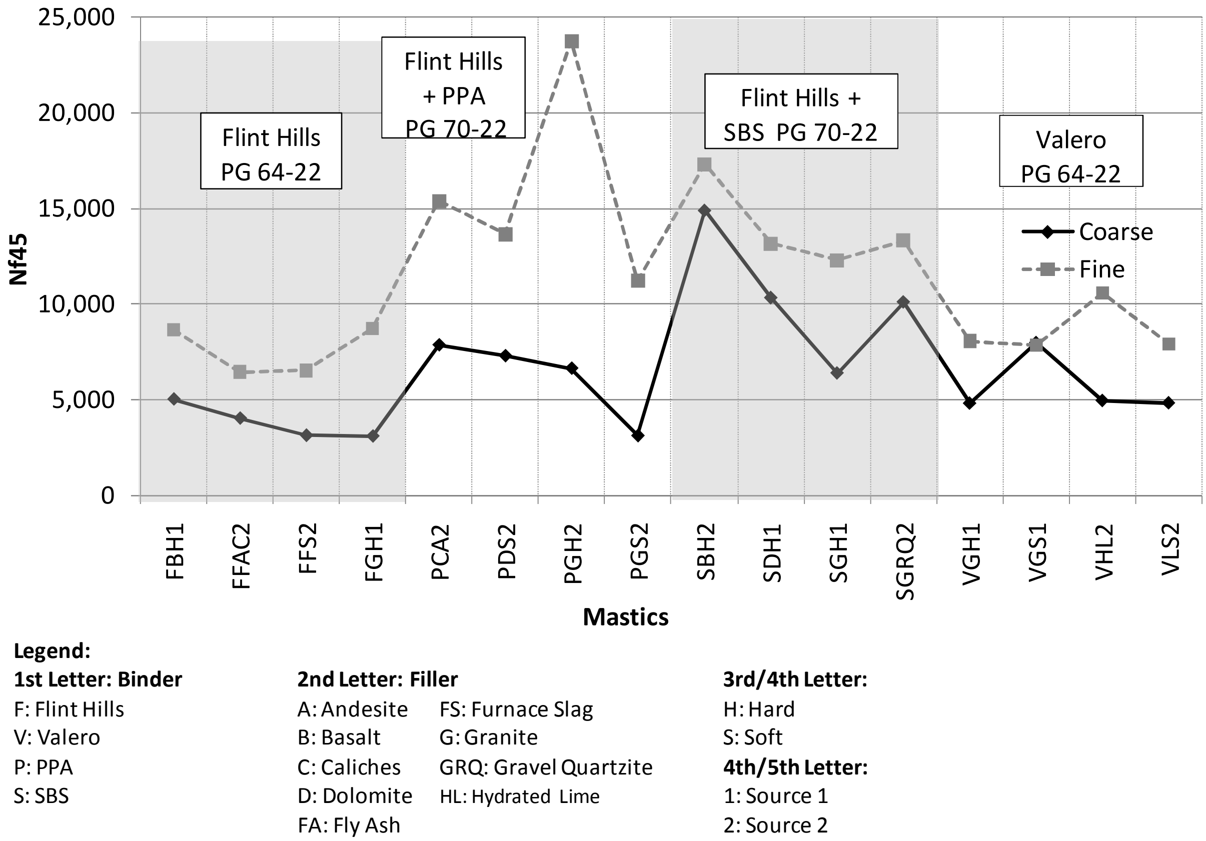


Figure F2e.1. Graph. Mixture IDT fatigue results from NCHRP 9-45 (Bahia et al. 2011).

Additionally, further analysis of mastic LAS results presented last quarter was conducted.

Significant Results

The four binders used in the mixture testing of NCHRP 9-45 were tested using the LAS test at 25°C (i.e. the same temperature as mixture testing). Failure was taken to be a 45% reduction in complex modulus, to be consistent with mixture testing. Viscoelastic continuum damage mechanics (VECD) was used to predict the number of cycles to failure at 2% strain. Binder results were correlated with mixture results as shown in figure F2e.2 below.

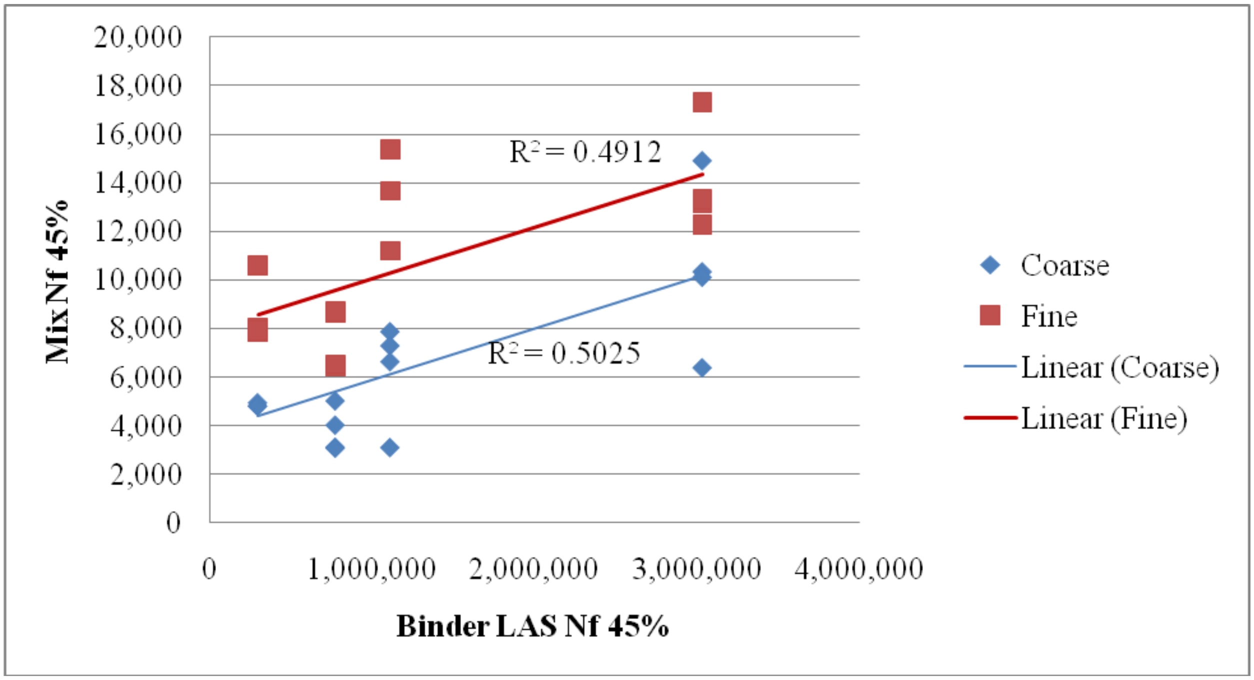


Figure F2e.2. Graph. Correlation between mixture and binder results.

The Flint Hill base binders with PPA and GH2 filler for the fine gradation was not included as it was found to be an outlier. Figure F2e.2 shows that a moderate correlation between binder and mixture results exists. As evident by figure F2e.1, different filler types can lead to vary different results. However, the correlation between binder and mixture results indicates the binder effect is more significant than the filler effect. Thus, a high correlation was not anticipated and therefore, it appears the LAS test is a fair indicator of mixture fatigue performance. It is important to note that the LAS is a strain controlled test while the mixture testing was conducted in stress controlled mode. The research team plans on testing some of the mastics used in the mixture testing using stress-controlled loading to see if the correlation between mixture and LAS results improves.

As presented last quarter, filler volume fraction has a significant impact on binder fatigue while filler type is of less significance. Further analysis of mastic fatigue results demonstrated that increasing filler volume fraction leads to a vertical shift in the fatigue law plot. Thus, results indicate the slope of the fatigue law plot does not change with inclusion of mineral filler. This phenomenon is depicted in figure F2e.3.

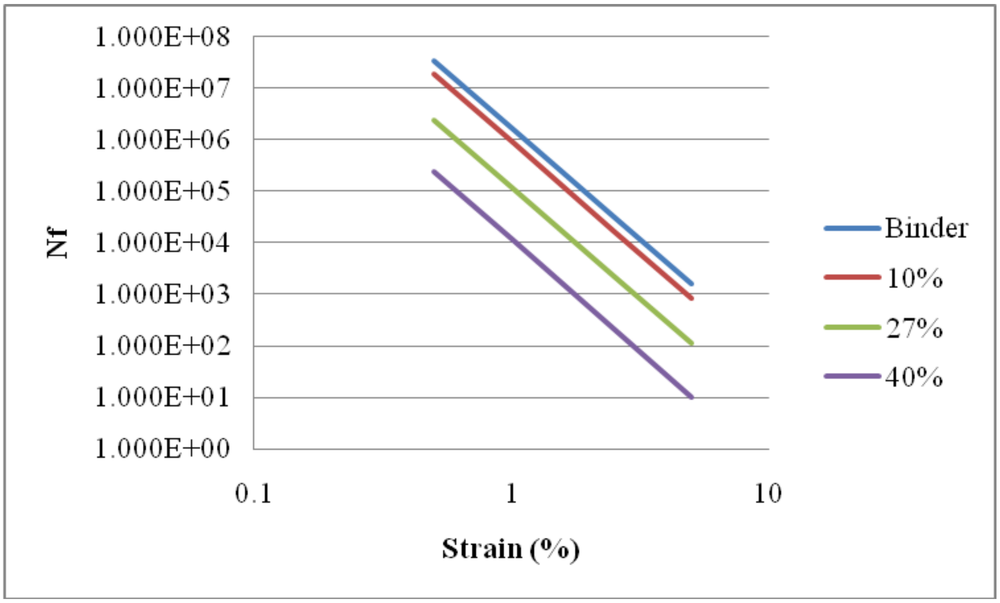


Figure F2e.3. Graph. Effect of filler volume fraction on relationship between number of cycles to failure (Nf) and strain.

Significant Problems, Issues and Potential Impact on Progress

None.

Work Planned Next Quarter

The team will conduct LAS testing of mastics used in mixture IDT fatigue testing and investigate the relation between mastic and mixture fatigue results.

Cited References

Bahia, H.U., A. Faheem, C. Hintz, I. Al-Qadi, G. Reinke, and E. Dukatz. Test Methods and Specification Criteria for Mineral Filler Used in HMA, *NCHRP Draft Final Report*, 201.

CATEGORY F3: MODELING

Work Element F3a: Asphalt Microstructural Model

Work Done This Quarter

Subtask F3a-1. ab initio Theories, Molecular Mechanics/Dynamics and Density Functional Theory Simulations of Asphalt Molecular Structure Interactions (URI)

Previous reports described how asphaltene structures proposed by Mullins (2010) were found to contain bonding patterns that resulted in high internal energies and thus low probabilities of occurring in practice. A manuscript was submitted to and accepted by the journal *Energy & Fuels* that demonstrates via quantum mechanics calculations how these energies can be attributed to Flory's "pentane effect": torsion angles that appear to be locally favorable instead lead to position overlaps for atoms separated by 6 bonds. Asphaltene structures that alleviate most of these effects are being used in subsequent calculations.

Molecular dynamics simulations were conducted of next-generation model asphalts that are representative of SHRP AAA-1, AAK-1, and AAM-1. See subtask F3a-3 below.

Subtask F3a-2. Develop algorithms and methods for directly linking molecular simulation outputs and phase field inputs (URI, VT)

Sub-subtask F3a-2.1. Collect information on available models and numerical methods suitable for phase field modeling (VT-WRI)

Work Done

This sub-subtask was completed in the 1st quarter. Major achievements include a comprehensive literature review, identification of promising theory and identification of corresponding numerical tools.

Significant Problems, Issues and Potential Impact on Progress

None

Work Planned Next Quarter

NA

Sub-subtask F3a-2.2. Phase-field parameter determination (VT-WRI)

Work Done

The work on extracting phase-field parameters from molecular dynamics simulations has started and is still in progress. A literature review has been conducted to look into the methods on computing free energies from the trajectory information from the molecular dynamics simulations.

Significant Problems, Issues and Potential Impact on Progress

None

Work Planned Next Quarter

We will build a connection between molecular dynamics and phase-field simulations. Meanwhile, other methods will also be used to test asphalt binder to determine phase-field parameters for the selected asphalt binders.

Sub-subtask F3a-2.3. Numerical solution of the phase-field equations (VT-WRI)

This sub-subtask focuses on developing numerical algorithms, computer code and methods for visualizing the computational results.

Work Done

A Matlab code has been developed to simulate the 2D phase-field (Cahn-Hilliard) equations. A Fourier spectral method is used to achieve high accuracy in space. For time integration, a second order semi-implicit method is used. This code can calculate the phase separation and mixing in 2D periodic domains.

Significant Problems, Issues and Potential Impact on Progress

None

Work Planned Next Quarter

The flow field will be coupled into the phase-field simulations. In order to model flows with non-periodic boundary conditions, the finite difference method will be used to replace the spectral method.

Sub-subtask F3a-2.4. Application of diffuse interface modeling to asphalt microstructure evolution (VT-WRI)

This sub-subtask includes development of diffuse interface model, modeling the phase distribution due to heating/re-solidification, and modeling of inter-phases diffusion.

Work Done

Primitive results on phase separation and mixing have been obtained.

Significant Problems, Issues and Potential Impact on Progress

None

Work Planned Next Quarter

The parameters in the phase-field model will be associated to the physical properties of the asphalt binder at different temperatures. By linking the phase-field parameters at different temperatures, we aim to simulate microstructure evolution due to heating and re-solification.

Sub-subtask F3a-2.5. Develop phase field models for characterizing asphalt emulsion and phase separation processes (VT-WRI)

This sub-subtask includes formulating bulk and gradient energy theory, modeling of emulsion process, and modeling of phase separation.

Work Done

2D simulations of phase separation have been performed using the Matlab code that we developed in task F3a-2.3.

Significant Problems, Issues and Potential Impact on Progress

None

Work Planned Next Quarter

Currently, the code can only be used for phase separation. The application of this phase-field method on emulsification will be explored in the next quarter.

Sub-subtask F3a-2.6. Phase-field modeling for fatigue cracking and self-healing processes(VT-WRI)

This sub-subtask focuses on the development of mesoscale cracking initiation, propagation and arrest criteria, modeling of self-healing process, and performing experimental verification.

Work Done

No significant achievements for this quarter.

Significant Problems, Issues and Potential Impact on Progress

None

Work Planned Next Quarter

The next quarter will develop a mechanism to link the density change to the cracking process using the phase field theory. Self-healing process will be modeled at the atomistic scale and up scaled to mesoscale.

Subtask F3a-3. Obtain temperature-dependent dynamics results for model asphalts that represent asphalts of different crude oil sources (URI)

Molecular dynamics simulations for different temperatures were continued to sample the dynamics of molecule positions and orientations in the next-generation AAA-1 system. As noted in the prior quarter, the molecule choices have been revised compared to the prior model of AAA-1 (Zhang and Greenfield 2008) to improve agreement with measured molecule size. Molecular dynamics simulations were initiated at the end of the quarter to equilibrate positions and orientations of molecules within models of SHRP asphalts AAK-1 and AAM-1 at a high-temperature (473 K). This temperature is chosen because enough relaxations can occur over time scales that can be obtained during the simulations.

Results for AAA-1 were completed during the quarter. The full set of results was included in the M.S. thesis of graduate student Derek D. Li, who completed his degree during the quarter. Two manuscripts describing the results were still in preparation stages at the end of the quarter. One describes the proposed compositions of the model asphalts and addresses how missing terms in the classical force field were calculated. The other describes the dynamics of molecules within the model asphalts.

Two examples of results are shown below (figure F3a-3.1). First, the rotational relaxation times (left) of molecules chosen to be in the model of SHRP asphalt AAA-1 show two temperature regimes. Above 333 K, all molecules change with temperature in a similar manner. Below 333 K there are larger slowdowns for larger molecules. Second, the single-molecule translational diffusion coefficients of molecules in model AAA-1 indicate the same temperature dependence for different molecules across the full temperature range. The linear behaviors on an Arrhenius plot suggest a similar activation energy for diffusion among all the molecules in the model asphalt. Together, these results suggest that rotation and diffusion occur in a size-independent manner above 333 K.

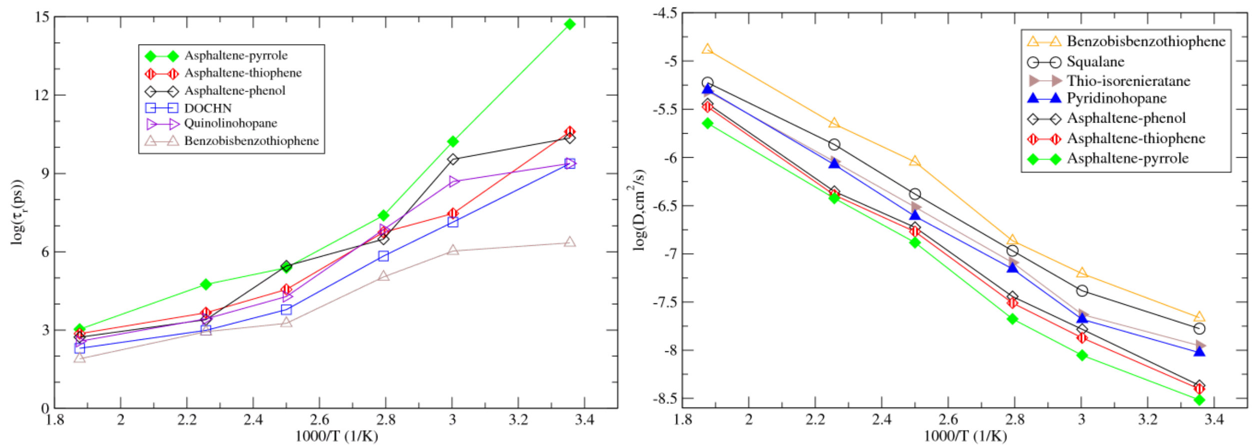


Figure F3a-3.1. Results from molecular dynamics simulations on next-generation model asphalt AAA-1. **(Left)** Rotational relaxation times of different molecules in this model asphalt indicate comparable decreases in rotation rate with decreasing temperature with larger differences appearing below 333 K. **(Right)** Self-diffusion coefficients of different molecules in this model asphalt indicate comparable decreases in translational diffusion rate with decreasing temperature. The common slopes suggest a comparable activation energy for all the molecules.

Significant Problems, Issues and Potential Impact on Progress

The challenges for balancing sulfur content with aromatic vs. aliphatic carbon content, as described in the December 2010 quarterly report, remain. The molecular dynamics simulations for the next-generation AAA-1 system were performed using the model composition with 3.6% sulfur (compared to 5.5% reported from experiments in the literature) and 39.5% aromatic carbon (compared to 28.1% reported from experiments in the literature). Increasing the sulfur concentration further would increase the aromatic carbon content, and vice versa. Similar issues arise in AAK-1 model asphalt. Model AAM-1 asphalt has a proper sulfur level (1%) but has a higher aromatic content than in the true asphalt used in experiments.

Derek Li was awarded a Transportation Fellowship from the New England Transportation Consortium for the spring 2011 semester. Thus the graduate student expenses were smaller than expected for the quarters that ended in March and June 2011.

Work Planned Next Quarter

Data analysis and manuscripts will be completed on a spontaneous wax formation event in a molecular simulation. This work was delayed from the prior quarter in order to focus efforts on conducting and analyzing the AAA-1 molecular simulations. Manuscripts that describe the equilibrium and dynamics properties for the AAA-1 system will be completed and prepared for publication. Molecular simulations will be continued to additional temperatures for the model AAK-1 and AAM-1 bitumen systems.

Cited Reference

Mullins, O. C., 2010, The Modified Yen Model. *Energy Fuels*, 24: 2179-2207.

Subtask F3a-4. Simulate changes in asphalt dynamics after inducing representations of chemical and/or physical changes to a model asphalt (URI)

Nothing to report.

Subtask F3a-5. Molecular mechanics simulations of asphalt-aggregate interfaces (VT)

This subtask focuses on modeling of binder-aggregate compatibility, the interface shear behavior, the interface tensile behavior, and moisture damage using molecular dynamics.

<u>Work Done This Quarter</u>

The methodology has been developed to simulate the asphalt-aggregate interface behavior using MD code LAMMPS. The asphalt binder is modeled using an average molecular structure and aggregates are modeled as a crystal structure. The moisture damage effect is modeled by placing a water molecule between the aggregate and binder molecules.

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

None

<u>Work Planned Next Quarter</u>

The major work in next quarter will focus on applying the methods developed for evaluating the aggregate-binder compatibility, the shear and tensile strength between the aggregate and binder, and assessing the major influencing factors to moisture damage.

Subtask F3a-6. Modeling of fatigue behavior at atomic scale (VT)

This subtask includes atomistic scale exploration of fatigue mechanism, nano pore creation process, modeling of fatigue in coupled physical-mechanical factors, modeling of stiffness reduction at macro scale, and modeling of binder-mastic-mixture fatigue relationship.

<u>Work Done This Quarter</u>

The newly developed fatigue test for binder and mastics is modeled using a Finite Element Method (FEM) with an elastoplastic model. Major components (binder and aggregates) of asphalt mixture are modeled using different constitutive models. The aggregates and fillers are modeled as linear elastic. The asphalt binder is modeled as elasto-plastic. In the mesh generation of asphalt mastic and mixture specimens, 2D x-ray scanned images are used to reconstruct the 3D internal structure. The elements belonging to different components are identified and assigned different material properties. An assumption is made that fatigue damage only happened in asphalt binder but not in aggregates and fillers. The hardening behavior of the asphalt binder at low temperature is described using a combined isotropic/kinematic hardening model developed by Lemaitre and Chaboche in 1990. The model consists of two components: a nonlinear kinematic hardening component, which describes the translation of the yield surface in stress space through the backstress; and an isotropic hardening component, which describes the change of the equivalent stress defining the size of the yield surface as a function of plastic deformation. The elastic modulus of the asphalt binder is measured using direct tension test at a desired temperature. The parameters of the kinematic and isotropic hardening model are determined using the first half cycle data of the fatigue test for asphalt binder. To address the fatigue damage caused by cyclic loading, the stiffness of the asphalt binder decreases during the fatigue process, which is described by a damage model proposed by Darveaux in 2000. The parameter analysis of the model is conducted and calibrated by comparing the fatigue simulation results and fatigue test results. To avoid the extremely high computational cost during the fatigue simulation, direct cyclic analysis is used to obtain the response of the structure after a large number of loadings.

Significant Problems, Issues and Potential Impact on Progress

None

Work Planned Next Quarter

The next quarter will focus on associating the nano pore creation process with fatigue mechanism, and the relationship between the modulus reduction and damage mechanisms in a view using fundamental mechanics.

Subtask F3a-7. Modeling of moisture damage (VT)

This subtask focuses on investigating the moisture damage mechanisms at atomistic scale, void structure and mesoscale damage due to excess pore water pressure, and binder-mastics-mixture moisture damage using a multiscale approach.

Work Done This Quarter

The excess pore water induced damage to asphalt mixture is modeled using a poroelasticity model based on mixture theory formulations implemented on FEM code ABAQUS. Different influencing factors including elasticity modulus, loading magnitude, boundary conditions, permeability and vehicle speeds have been assessed.

Significant Problems, Issues and Potential Impact on Progress

None

Work Planned Next Quarter

The next quarter will focus on the modeling of moisture damage mechanisms at atomistic scale for asphalt binder.

Subtask F3a-8. ab initio Calculations of Asphalt Molecular Structures and Correlation to Experimental Physico-Chemical Properties of SHRP Asphalts (WRI-TUDelft)

Nothing to report.

Work Element F3b: Micromechanics Model

Subtask F3b-1: Model Development (TAMU, NCSU, UNL)

Work Done This Quarter

During this quarter we have extended the model applications for general asphalt concrete microstructure where separate phases exist and the rate-dependent cohesive zone fracture elements are randomly embedded to simulate viscoelastic mixed-mode crack growth. Various parametric analyses of the microstructure model were conducted by varying key model inputs (i.e., fracture properties of matrix phase such as cohesive strength, fracture energy, and rate-dependency parameters; and geometric characteristics of mixture microstructure such as the mixture volumetrics and aggregate angularity, etc.). Model simulation results clearly demonstrated the effect of material-specific properties and geometric characteristics on the overall asphalt mixture performance. Simulation results were quite sensitively influenced by model inputs, which indicate that the microstructure fracture model has been well developed to properly examine material-dependent fracture performance and damage resistance potential of heterogeneous asphalt mixtures.

With all aspects and outcomes from this subtask, we have written a final report. The final report includes all key components including the modeling methodology developed, constitutive model theory, numerical implementation of the model, testing protocols developed, resulting test data, and various model simulations for verification, calibration, validation, and application through the various parametric analyses. The report is currently 65% completed.

Significant Problems, Issues and Potential Impact on Progress

None.

Work Planned Next Quarter

In the next quarter we will finish model validation and a draft version of the final report.

Lattice Micromechanical Model (NCSU)

<u>Work Done in This Quarter</u>

Lattice Micromechanical Model

Work is continuing on characterizing and virtually fabricating air voids. While the characterization has been somewhat complete in the previous quarters, the virtual fabrication procedure is still being developed based on the finding that the air void shape is dependent on the surrounding aggregate structure. Currently, an observation/physics based microstructure generation procedure is being investigated. It is expected that the virtual fabrication procedure will be finalized in the next quarter, along with verification and validation.

Continuum Damage to Fracture

In this quarter, work is focused on developing criterion for the onset of localization. Extensive experimental data is analyzed, and various existing theories are tested to determine a valid criterion. It turned out that many existing methods appear to be inconsistent with the experimental data and research is continuing on devising a modified micro-structure based criterion for the onset of localization.

<u>Significant Results</u>

None

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

None

<u>Work Planned Next Quarter</u>

Lattice Micromechanical Model

- Finalizing the virtual fabrication algorithm for air voids.
- Validation of the resulting algorithm with respect to predicting the stiffness.

Continuum Damage to Fracture

- Further work on devising a criterion for the onset of localization.
- Investigation of nonlocal modeling framework for cyclic loading.

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

Work Done This Quarter

See M4c for details on the progress in the development of the continuum-based moisture-induced damage mode. Also see F1d-8 on the development of the continuum-based micro-damage healing model. We have completed the calibration and validation of the nonlinear viscoelastic and viscoplastic constitutive models in PANDA using the ALF laboratory data from NCState based on compression and tension data under different temperatures.

Significant Results

We have developed a model to account for the softening behavior of asphalt mixtures under repeated loading. This model was proven to be essential for predicting accumulation of permanent deformation.

Significant Problems, Issues and Potential Impact on Progress

The challenge is to develop models for reducing the time for simulating the fatigue and permanent deformation at the structural level of asphalt pavements.

Work Planned Next Quarter

We will work on the simulations of the structural response of the ALF pavements.

Continuum-based Model for Aging

Work Done This Quarter

This task was temporarily suspended in this quarter and resources were diverted to the task on the validation of PANDA against the ALF rutting tests. We expect to resume work on this task as soon as we complete the validation of PANDA against the ALF rutting performance data.

Significant Results

There are no significant results for this quarter.

Significant Problems, Issues and Potential Impact on Progress

Although this task is temporarily suspended, we expect to resume the task in near future as soon we have the aging data from the ARC 2x2 asphalt mixture testing.

Work Planned Next Quarter

We expect to resume work on this task as outlined in the fifth year work plan.

TABLE OF DECISION POINTS AND DELIVERABLES FOR FATIGUE

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
F1a: Cohesive and Adhesive Properties (TAMU)	Draft Report	Draft Report on Cohesive and Adhesive Properties, 508 compliant	11/11	N/A	N/A
	Final Report		6/30/12		
F1b-1: Nonlinear viscoelastic response under cyclic loading (TAMU)	Models and Algorithm	A constitutive model that accounts for the nonlinearity and three -dimensional stress state of the material including a method to obtain model constants for asphalt binders.	3/31/09 6/30/10 12/31/11	3/31/12	It is more efficient and informative if the three different final reports, models and algorithms are consolidated into a single final report. The work at UT Austin that will make up the final report is 60% complete.
	Draft report		12/31/08 12/31/11		
	Final report		6/30/08 3/31/12	6/30/12	
F1b-2: Viscoelastic properties under monotonic loading (TAMU)	Draft Report	Documentation of PANDA Models and Validation Including the Method for Analysis of Viscoelastic Properties	11/11	N/A	N/A
	Final Report (M5, M4c, F1b-1, F1c, F1d-8, F3c, and V3c)		3/12	6/12	N/A
F1c: Aging (Unified Continuum Model for Aging) (TAMU)	Draft Report	Draft Report on the aging modeling	03/12	N/A	N/A
	Final Report (M5, M4c, F1b-1, F1c, F1d-8, F3c, and V3c)		3/31/12	6/30/12	
F1c-2. Experimental Design (TAMU)	Report	Experimental Design Report	1/09	Complete	N/A

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
F1d – 1,2,3,4,5a,5b,8: Healing (TAMU)	Models and Algorithm	A mathematical model for self-healing at the micron scale, partial validation of this model, measurement of properties related to this model, measurement of overall healing as a function of damage and rest period, and micro to nano scale evaluation of properties that influence fracture and self-healing	06/30/11	3/31/12	It is more efficient and informative if the different final reports, models and algorithms are consolidated into a single final report. The final report is based on two theses: the thesis from Texas A&M University is complete and work for the thesis from UT Austin is 70% complete.
	Draft report		06/30/10 06/30/11 12/31/11		
F1d-6: Evaluate relationship between healing and endurance limit of asphalt binders (UWM)	Draft Report	Report summarizing major findings for evaluation of healing of binders by means of cyclic testing with rest periods	12/11	N/A	N/A
	Final Report	Final report in 508 format on healing characterization of binders and its relation to fatigue performance	1/12	6/12	Final report submission date moved back to allow at least 6 months between draft and final report submission.
F1d-8: Coordinate Form of Healing Parameter with Micromechanics and Continuum Damage Models (TAMU)	Draft Report (M5, M4c, F1b-1, F1c, F1d-8, F3c, and V3c)	Draft Report on the self-healing modeling	12/11		
	Final Report (M5, M4c, F1b-1, F1c, F1d-8, F3c, and V3c)	Report on the self-healing modeling	3/12	6/12	

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
F2a-5: Analyze data and propose mechanisms (UWM)	Draft Report	Report summarizing major findings for the effect of modification on asphalt binder performance at high and intermediate temperatures.	10/11	N/A	N/A
	Final Report	Report in 508 format summarizing major findings for the effect of modification on asphalt binder performance at high and intermediate temperatures	1/12	4/12	Final report submission date moved back to allow at least 6 months between draft and final report submission.
F2d: Structural Characterization of Micromechanical Properties in Bitumen using Atomic Force Microscopy (TAMU)	Protocol for Measuring Viscoelastic Properties Using AFM	Protocol for preparing samples and taking measurements in AASHTO format – Protocol development complete, AASHTO format planned for 5/30/11	7/31/10	N/A	N/A
	Evaluation of Impact of Aging and Moisture Conditioning	Complete	12/15/10	N/A	N/A
	Final Research Report		2/28/12	N/A	N/A
F2e-2: Selection of Testing Protocols (UWM)	Draft Report	Report on the development and implementation of the Binder Yield Energy (BYET) test and the Linear Amplitude Sweep Test (LAS)	4/09	Complete	N/A
	Final Report		7/09		
	Draft Report		4/10		
	Final Report		7/10		
F2e-4: Verification of Surrogate Fatigue Test (UWM)	Draft Report	Correspond to reports in F2e-2	10/10	Complete	N/A
	Final Report		1/11		
F2e-6: Recommendations for Use in Unified Fatigue Damage Model (UWM)	Draft Report	Report summarizing major findings for each subtask. The report includes: evaluation of correlations between binder and mixture fatigue performance, comparison between binder fatigue testing procedures, verification/validation of LAS test	11/11	N/A	N/A
	Final Report	Final report in 508 format on the development and implementation of the Linear Amplitude Sweep (LAS) Test. It includes the latest AASHTO standard.	1/12	5/12	Final report submission date moved back to allow at least 6 months between draft and final report submission.

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
F3b-1: Micromechanics Model Development (Fatigue) (UNL)	Models and Algorithm	Cohesive zone fracture modeling of asphalt mixtures considering inelasticity, nonlinearity, rate-dependent fracture, and mixture microstructure: modeling methodology, constitutive theory, testing protocols, test data, model simulation/calibration/validation, user element (UEL) codes in ABAQUS, and user-friendly manuals. Multiscale modeling of asphaltic mixtures and pavements: modeling methodology, constitutive theory, and parametric analyses of the model.	3/31/11	No change	N/A
	Draft report		06/30/11	9/30/11	A little more time is necessary for model validation with lab testing.
	Final report		12/31/11	No change	N/A
F3c: Development of Unified Continuum Model (TAMU)	PANDA Workshop	Workshop on PANDA Models and Validation Results	8/11	N/A	N/A
	Draft Report	Documentation of PANDA Models and Validation	11/11	N/A	N/A
	Final Report		3/12	6/30/12	N/A
	UMAT Material	PANDA Implemented in Abaqus	3/12	N/A	N/A

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

LEGEND

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

Work planned
Work completed
Parallel topic

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

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[x]	Indicates completion of deliverable x

Work planned

Work completed

Parallel topic

PROGRAM AREA: ENGINEERED MATERIALS

CATEGORY E1: MODELING

Work element E1a: Analytical and Micro-mechanics Models for Mechanical Behavior of Mixtures (TAMU)

Work Done This Quarter

In this quarter, two technical papers have been completed and submitted to the ASCE *Journal of Materials in Civil Engineering*: "Complex Stiffness Gradient Estimation of Field-Aged Asphalt Concrete Layers Using Direct Tension Test" and "Characterization of Asphalt Mixtures Using Controlled-Strain Repeated Direct Tension Test".

Additional investigation is conducted in this quarter on:

- Characterizing of healing properties of asphalt mixtures;
- Testing fracture properties of field cores using the Overlay Tester; and
- Evaluating fracture properties of fine asphalt mixtures (FAM).

1. Healing Properties of Asphalt Mixtures

In previous quarters, the internal stress was measured using the revised creep and recovery test and was simulated using a mathematical model in order to study the healing properties of asphalt mixtures. The simulated internal stress was used to characterize the recovery properties of both undamaged and damaged asphalt mixtures. The recovery properties of undamaged asphalt mixtures remained the same with an increase of loading levels, but the recovery properties of damaged asphalt mixtures were different due to the healing process. This difference is studied in detail in this quarter to determine the driving force for the healing process and the material properties required to conduct the mechanistic analysis on the healing process.

Recovery of asphalt mixtures occurs at any loading level after removing the load, while healing only occurs after cracking damage is generated in the material. When the asphalt mixture is not damaged, there is only a recovery process in which the material recovers its deformation and the internal stress relaxes. The internal stress is the driving force of the recovery process. It has been proven that in the recovery process of the asphalt mixture, the stress-strain relationship characterized by the recovery modulus does not change. When the asphalt mixture is damaged, there are two processes: recovery and healing in the material. As mentioned in previous quarterly reports, these processes are driven by internal stress and interfacial force of attraction in a damaged asphalt mixture. The internal stress drives the recovery of the bulk material, and the interfacial force of attraction acts on the adjacent separated crack surfaces and tends to draw the surfaces together until complete contact exists.

Previously, the interfacial force of attraction was regarded to be the only driving force of the healing process (Schapery 1989). Whether it is the only force driving the healing process is examined by the energy redistribution around the crack caused by the action of the force associated with this process. Since healing is a counter process to cracking, the energy redistribution in the healing process is counter to that in the cracking process. The energy redistribution in the cracking process has been documented in previous quarterly reports. The energy redistributed around the crack as a result of crack propagation involves the recoverable pseudo strain energy (RPSE) released in the intact material above and below the crack and the RPSE restored on the newly created crack surfaces. Therefore, the RPSE redistributed around the crack as a result of healing are the RPSE restored in the intact material above and below the crack and the RPSE released from closure of crack surfaces. The RPSE released from the closure of crack surfaces equals the surface energy, which is the work done by the interfacial force of attraction. The RPSE restored in the intact material above and below the crack is the work done by the internal stress in the intact material. In fact, two forces are involved in the healing process: the interfacial force of attraction and the internal stress in the intact material. Both of them contribute to the energy interchange and drive the growth of the contact area of the crack surfaces.

As one of the driving forces for the healing process, the internal stress in the intact material is different from that measured from the revised creep and recovery test. The measured internal stress is assumed to be uniformly distributed over the entire cross section of the asphalt mixture specimen. However, the internal stress can only act on the intact material to drive the recovery of the intact material. Therefore, the internal stress carried by the intact material is the true internal stress, and the measured internal stress is called apparent internal stress. In both undamaged and damaged asphalt mixture, the recovery process always refers to a process in which the true internal stress drives the deformation of the intact material. The true internal stress cannot be observed nor measured, but can be inferred from the apparent internal stress. In order to obtain the true internal stress and healing properties through the experimental measurement, both apparent and true material properties of undamaged and damaged asphalt mixture are needed from the nondestructive and destructive tests, respectively.

The apparent material properties refer to the material properties of the entire asphalt mixture specimen measured from the test. The apparent material properties that are used to characterize the healing properties include the apparent creep compliance, apparent relaxation modulus and apparent recovery modulus. The apparent creep compliance is measured in the creep phase of the nondestructive revised creep and recovery test, and is modeled using the following function:

$$D(t) = D_0 + D_1\left(1 - e^{-\frac{t}{\tau}}\right) \tag{E1a.1}$$

where $D(t)$ is the creep compliance; D_0 is the instantaneous creep compliance; D_1 is the creep compliance coefficient; and τ is the retardation time. The apparent relaxation modulus is obtained by applying the Laplace transform to the apparent creep compliance, which has an expression as follows:

$$E(t) = E_\infty + E_1 e^{-\frac{t}{\kappa}} \tag{E1a.2}$$

where E_∞ is the long term relaxation modulus, calculated using:

$$E_\infty = \frac{1}{D_0 + D_1} \tag{E1a.3}$$

E_1 is the relaxation modulus coefficient, calculated using:

$$E_1 = \frac{D_1}{D_0\left(D_0 + D_1\right)} \tag{E1a.4}$$

κ is the relaxation time, calculated using:

$$\kappa = \frac{D_0 \tau}{D_0 + D_1}$$

The apparent recovery modulus is measured from the recovery phase of the destructive revised creep and recovery test. The true material properties refer to the material properties of the intact material of the asphalt mixture specimen. The true material properties of an undamaged asphalt mixture include the true creep compliance and the true relaxation modulus. The true creep compliance is obtained through the dissipated strain energy (DSE) balance equation, which states that the apparent DSE within the entire asphalt mixture specimen equals the true DSE within the intact material.

$$\mathrm{DSE}^A = \mathrm{DSE}^T \tag{E1a.5}$$

where DSE^A is the apparent DSE calculated using the apparent material properties; and DSE^T is the true DSE determined by the true material properties. The true relaxation modulus is then obtained by applying the Laplace transform to the true creep compliance. The true recovery modulus is obtained from the recovery phase of the nondestructive revised creep and recovery test. A plot of the apparent/true creep compliance and apparent /true relaxation modulus and a plot of the apparent/true recovery modulus are given in figures E1a.1 and E1a.2, respectively.

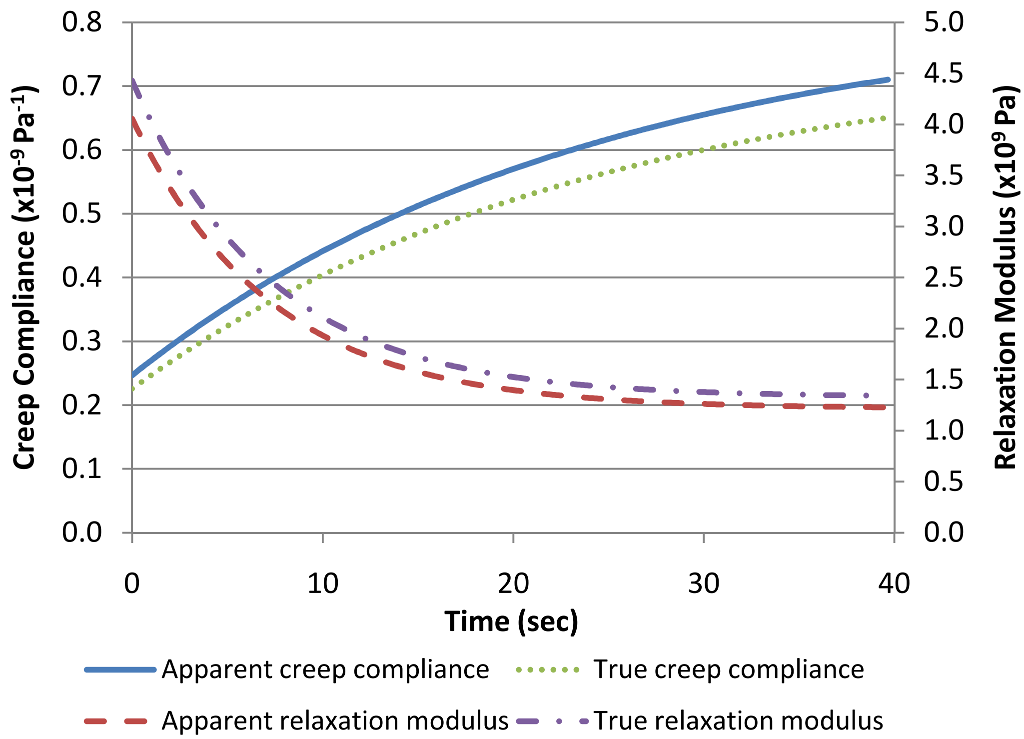


Figure E1a.1. Apparent and true material properties of undamaged asphalt mixtures.

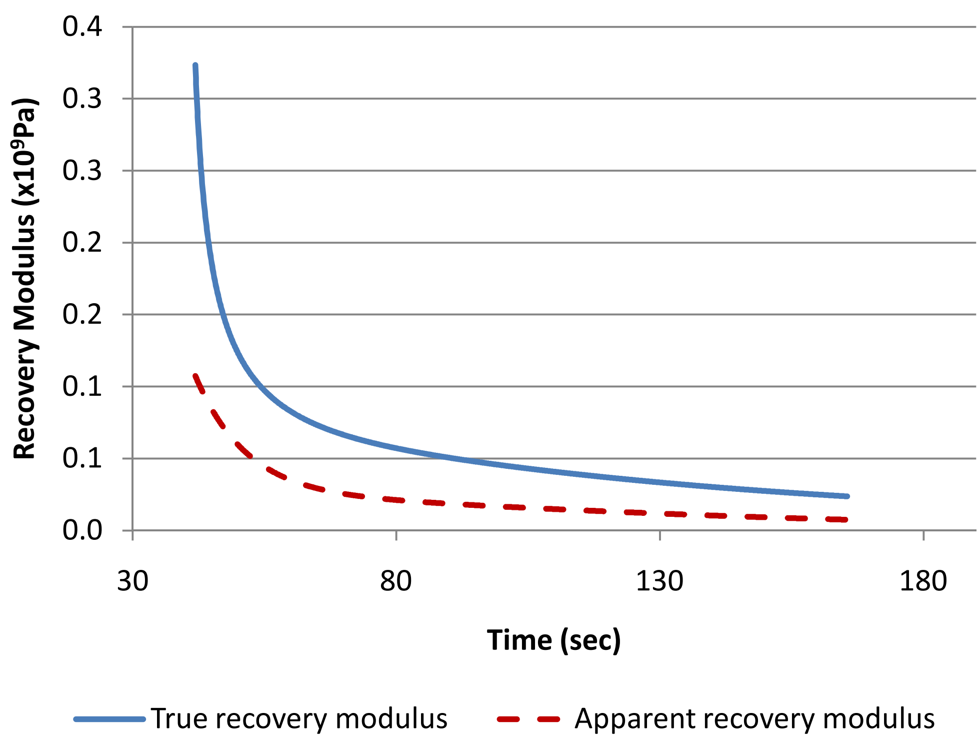


Figure E1a.2. Apparent and true recovery modulus.

2. Fracture Properties in Field Cores Using the Overlay Tester

Following the successful completion of the stiffness gradient determination in field-aged specimens in previous quarters, fracture properties of laboratory-compacted specimens are investigated in this quarter using the Overlay Tester (OT). The OT machine was designed primarily for testing asphalt overlays, but since then it has been used to evaluate the fatigue cracking susceptibility of asphalt mixtures. The sample that is tested has a standard 6-inch diameter. The OT machine consists of fixed and moving plates as shown in figure E1a.3. A specimen is glued to the plates and a triangular displacement pattern with time is applied to the moving part with a specific frequency to mimic the tensile repeating strains in the bottom of the asphalt layer, which has been previously identified as a cause for fatigue cracking. The repeated tensile loading causes a crack to grow. Measurements of the load and opening as they vary with time allow the growth of the crack to be monitored without needing to actually measure the crack length.

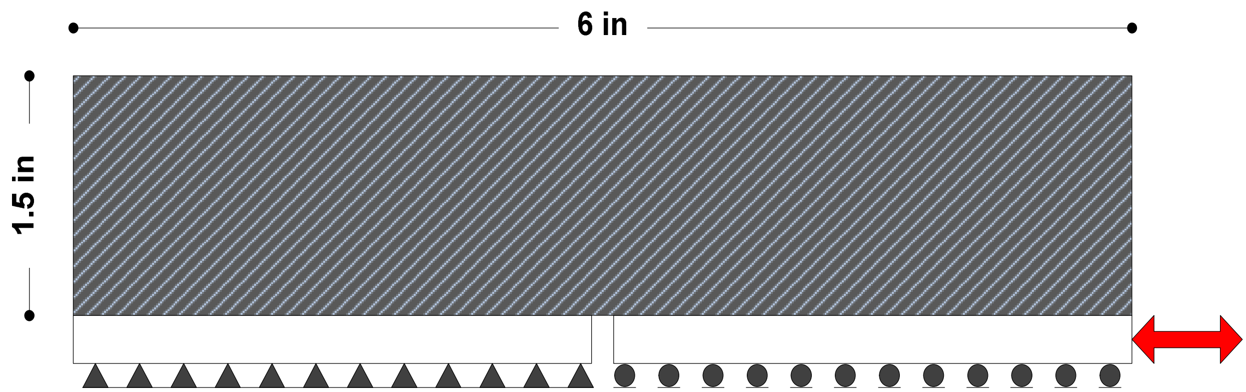


Figure E1a.3. Overlay tester setup and boundary conditions of the finite element model.

This crack monitoring requires an understanding of the stress and strain distribution over the tip of the crack as the crack grows. The laboratory OT test was simulated in ABAQUS, a finite element (FE) analysis program. The boundary conditions used in the model are shown in figure E1a.3. The model simulates both the undamaged condition as well as cracks with different sizes. The material was assumed to be elastic with a Poisson's ratio of 0.3 which is a common value used for modeling asphalt mixtures. Since the test is displacement controlled, the strain profiles above the tip of the crack remain the same regardless of the magnitude of the elastic modulus.

Figure E1a.4 shows the principal stress distribution in the deformed model of the specimen with a loading displacement of 0.025 inches when the crack length is 0.625 inches.

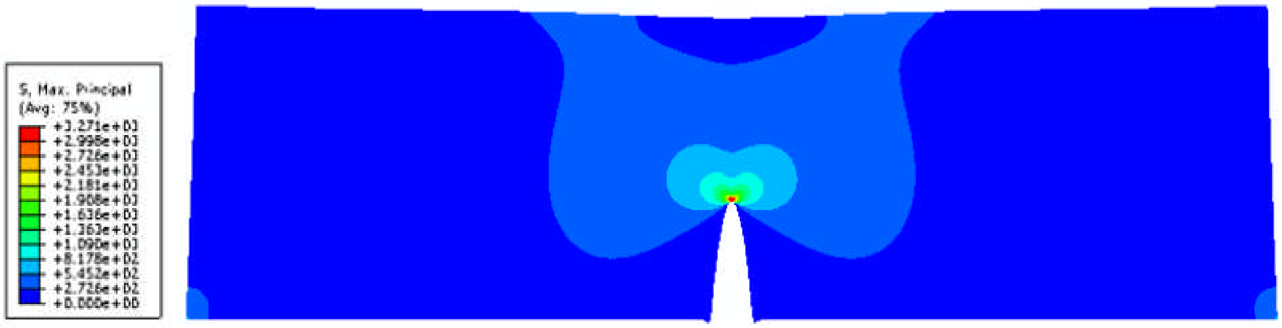


Figure E1a.4. Principal stress distribution in deformed specimen with loading displacement of 0.025 inches and crack length of 0.625 inches.

The computed strain profiles for four different crack lengths are shown in figure E1a.5. As can be seen in figure E1a.5, when the crack advances, the area under the strain profiles throughout the depth of the sample decreases.

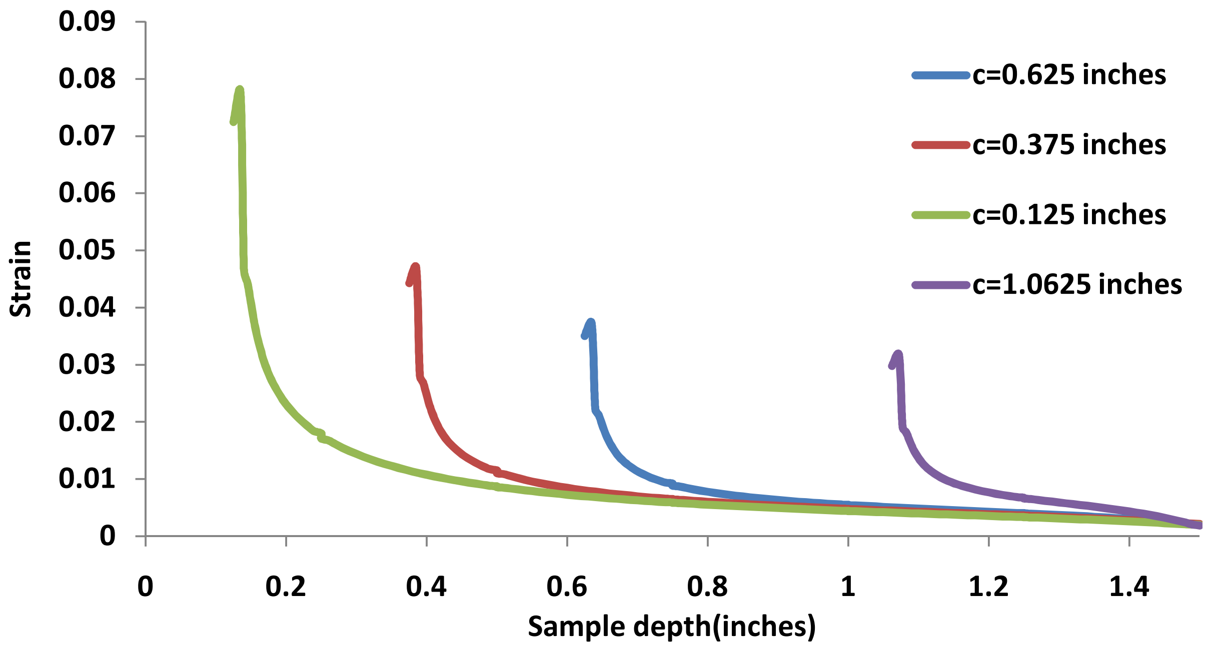


Figure E1a.5. Strain profiles above crack tip when crack size is 0.125, 0375, 0.625 and 1.0625 inches, respectively.

As the test setup shows, the crack in the OT test is a Mode I tensile crack .The crack growth rate is controlled by the size of the stress intensity factor, K_{I} which is defined as:

$$K_{\mathrm{I}} = \sigma\sqrt{\pi C}(FL^{-\frac{3}{2}}) \qquad \text{(E1a.6)}$$

where σ = stress and C = the half crack length. Figure E1a.6 shows that the stress intensity factor for Mode I reduces significantly as the crack advances through the specimen depth.

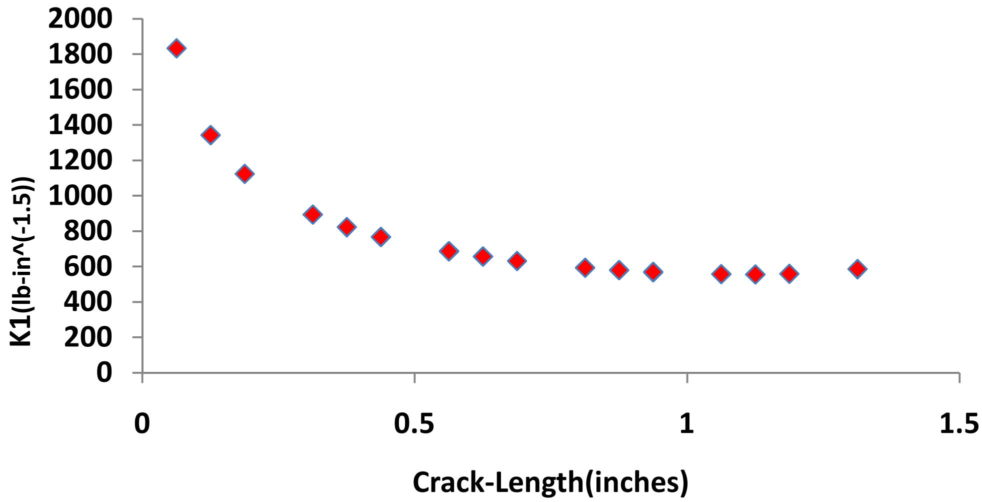


Figure E1a.6. The stress intensity factor versus crack length.

The same trend can be seen in figure E1a.7 for the J-integral (strain energy release rate) which is related to the fracture toughness under Mode I loading at the tip of the crack (Yoda, 1980).

$$J_{\mathrm{I}} = K_{\mathrm{I}}^2(\frac{1-\nu^2}{E})(FL^{-1}) \qquad \text{(E1a.7)}$$

where K_{I}, ν and E are the fracture toughness, Poisson's ratio and Young's modulus, respectively.

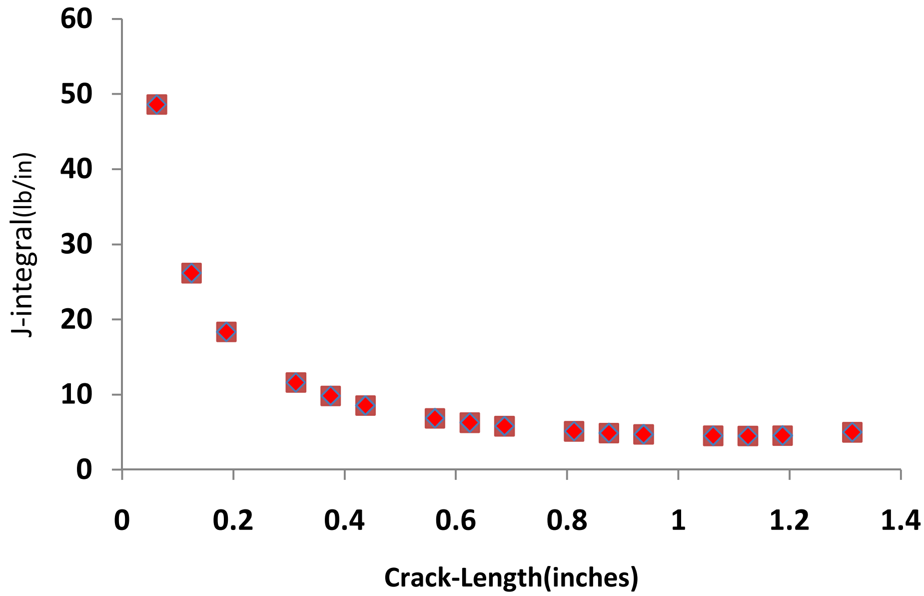


Figure E1a.7. J-integral versus crack length.

After the strain distribution inside the specimen during the test is established using the FE model, the Correspondence Principle is used to derive the equations needed to determine the viscoelastic force. First, the undamaged properties of the specimen are determined by applying the very small displacement of 0.002 inches to the specimen with the loading pattern depicted in figure E1a.8.

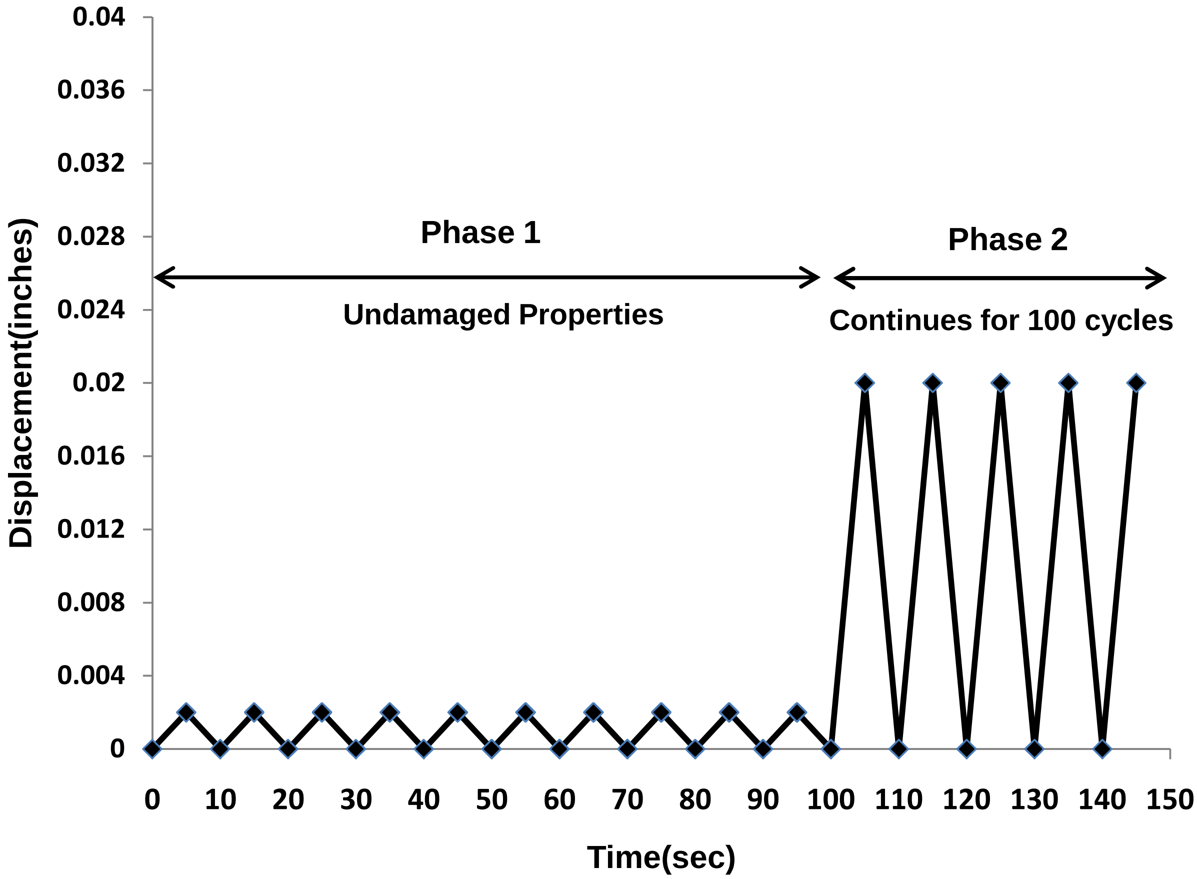


Figure E1a.8. OT test loading pattern.

The undamaged properties E_1 and m, which are the coefficients in the relaxation modulus form shown in equation E1a.8, are calculated using equation E1a.9. Linear regression analysis is used to find E_1 and m from the first load cycle. Equation E1a.9 is derived by solving the Convolution Integral in the undamaged state.

$$E(t) = E_1 t^{-m} \tag{E1a.8}$$

$$P_{LVE}(t) = \frac{2bE_1 t^{2-m}}{t_1^2 (2-m)(1-m)} \varepsilon(c=0) \tag{E1a.9}$$

In equation E1a.9, $P_{LVE}(t)$ is the measured load in the undamaged material at time t , t_1 is the stretching time in each cycle, b is the specimen width and $\varepsilon(c=0)$ is the area under the strain profile when there is no crack in the specimen.

The next step is to calculate the crack length in each load cycle. To achieve this goal, the Convolution Integral for the case with crack length C is written and solved. Equations E1a.10 and E1a.11 show the measured maximum force calculated in times 0< t< t_1 and t_1 <t<2 t_1 for each cycle.

$$\max .P_{LVE}(z=c)=\frac{E_1 b t^{1-m}}{(1-m)t_1}\varepsilon(c) \qquad 0<t<t_1 \qquad \text{(E1a.10)}$$

$$\max .P_{LVE}(z=c)=b\varepsilon(c)\frac{E_1 t^{1-m}}{(1-m)t_1}-2b\varepsilon(c)\frac{E_1(t-t_1)^{1-m}}{(1-m)t_1} \qquad t_1<t<2t_1 \qquad \text{(E1a.11)}$$

where $\max .P_{LVE}(z=c)$ is the measured maximum viscoelastic force within the specified time interval, b is the width of specimen, and $\varepsilon(c)$ is the area under strain profile above the crack. This area under the strain profile is calculated with the FE model and is shown in figure E1a.9.
In order to find the actual crack growth in each cycle, the healing of the crack when the displacement is forced back to zero must be considered. The high magnitude of the compressive force in each cycle is responsible for the healing that occurs in a very short time. As can be seen in figure E1a.9, the value of $\varepsilon(c)$ decreases as the crack grows. Healing actually reduces the crack size and as a result the area under the strain profile above the tip of the crack increases. In order to include the healing effect, the areas under the strain profiles in tension and compression are summed for each cycle. The resultant $\varepsilon(c)$ is applied to the $\varepsilon(c)$ curve shown in figure E1a.9 to find the corresponding crack length.

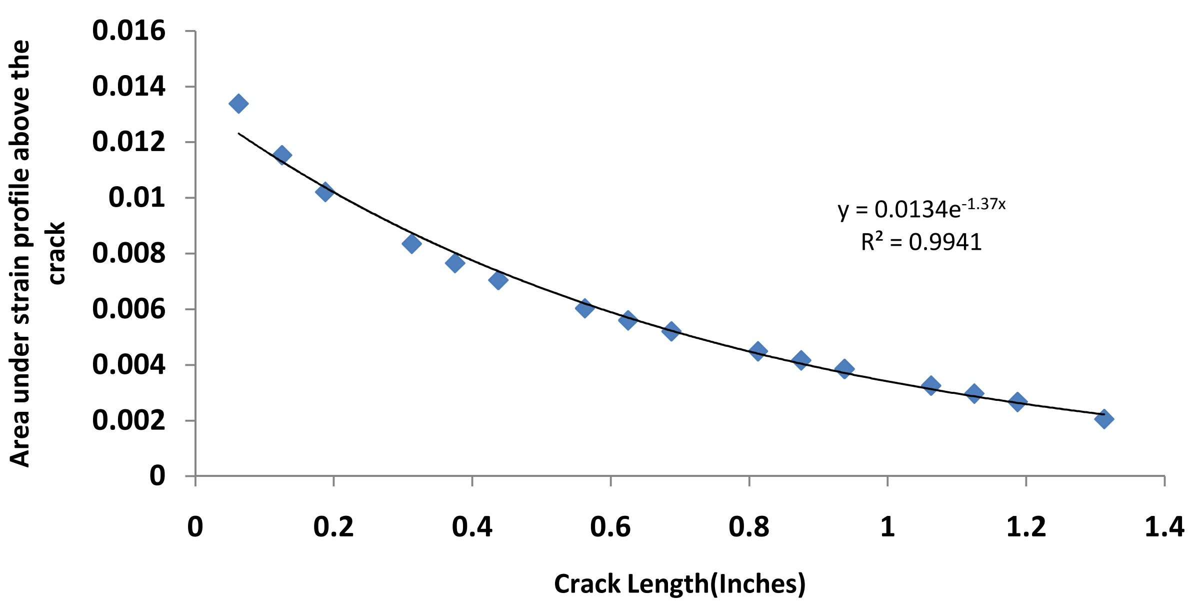


Figure E1a.9. The crack length versus the integration of strain profile above the crack.

Figure E1a.10 shows the calculated crack growth for a specimen of which the values of E_1 and m are 47544 psi and 0.351, respectively.

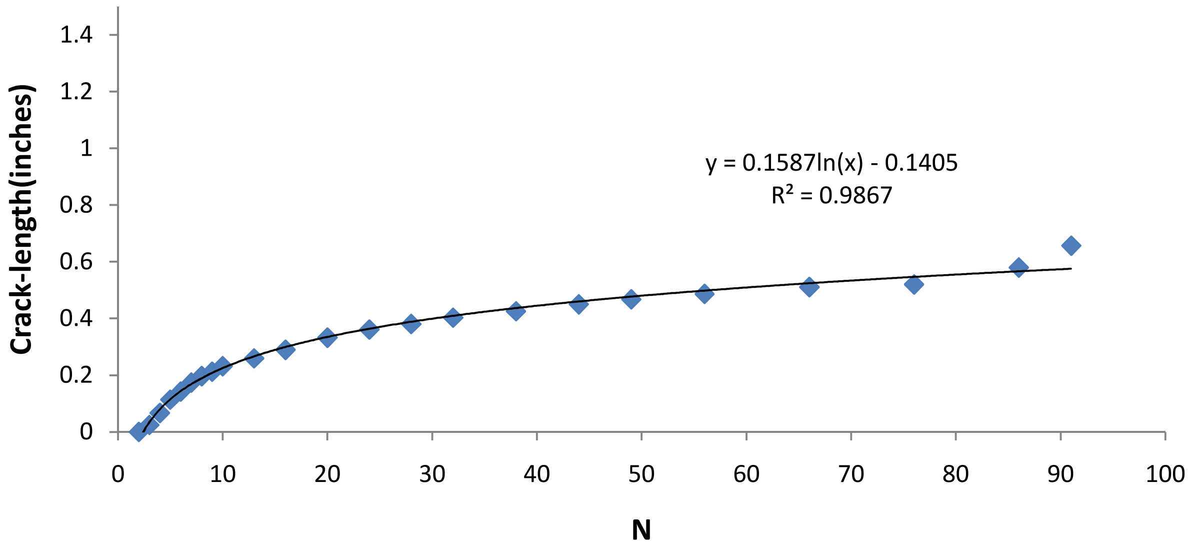


Figure E1a.10. The calculated crack growth curve for a sample specimen.

3. Moisture Susceptibility of Fine Asphalt Mixtures

In this quarter, a model is established to predict the relative humidity (RH) gradients. It is commonly agreed that water vapor diffusion is the major factor contributing to the moisture damage in pavement. However, it is not clear how the moisture builds up within the asphalt mixture layer. A suction model is established to illustrate the wetting up of the HMA layer due to RH increase in pavement. As listed in table E1a.1, three locations with air RH 10% for west Texas, 50% for central Texas and 74% for east Texas are selected for analysis. Since Thornthwaite Index (TI) can be used to predict the suction profiles in the soil, the base PF, which is the suction of the soil material beneath the asphalt surface layer, is determined by in-situ TI measurements in these locations. The water vapor diffusion coefficient for asphalt mixture is obtained from the graph between air voids and measured vapor diffusion coefficients in the literature (Kassem et al, 2006). The published coefficient of vapor transfer from the pavement into the air is 0.254 cm^{-1} and the pF of the asphalt mixture as compacted is an oven dry pF of 7, as listed in table E1a.1.

Table E1a.1. Inputs for pavement HMA layer suction prediction model.

Locations	West Texas	Central Texas	East Texas
Average Air RH %	10	50	74
Base (PF)	4.0	3.6	3.2
Water Diffusivity (cm^2/sec)			5.00E-06
Coefficient of Vapor Transfer (cm^{-1})			0.254
Initial Asphalt Mixture (Oven Dry) PF			7.0

$$u(x,t) = u_d + \frac{4}{\pi}(u_d - u_0)\left\{\sum_{n=1}^{\infty}\frac{(-1)^n}{(2n-1)} * e^{-(2n-1)\frac{\pi^2\alpha t}{4d^2}} * cos\left[\frac{(2n-1)\pi\sqrt{\alpha}\,x}{2d}\right]\right\}$$
$$-(u_d - u_0) * e^{(h*x+h^2\alpha t)} * erfc(\frac{x}{2\sqrt{\alpha t}} + h\sqrt{\alpha t}) \qquad \text{(E1a.12)}$$

$$PF = \log_{10}\left[-\left(\frac{RT}{mg}\ln\left(\frac{RH}{100}\right)\right)\right] \qquad \text{(E1a.13)}$$

$$erfc(x) = \frac{2}{\sqrt{\pi}}\int_x^{\infty} e^{-t^2}\,dt \qquad \text{(E1a.14)}$$

where u_d = base PF; u_0 =initial asphalt mixture PF; α = water vapor diffusivity of an asphalt mixture; x = depth of the HMA layer; t = service time of HMA; and h = film coefficient of vapor transfer.

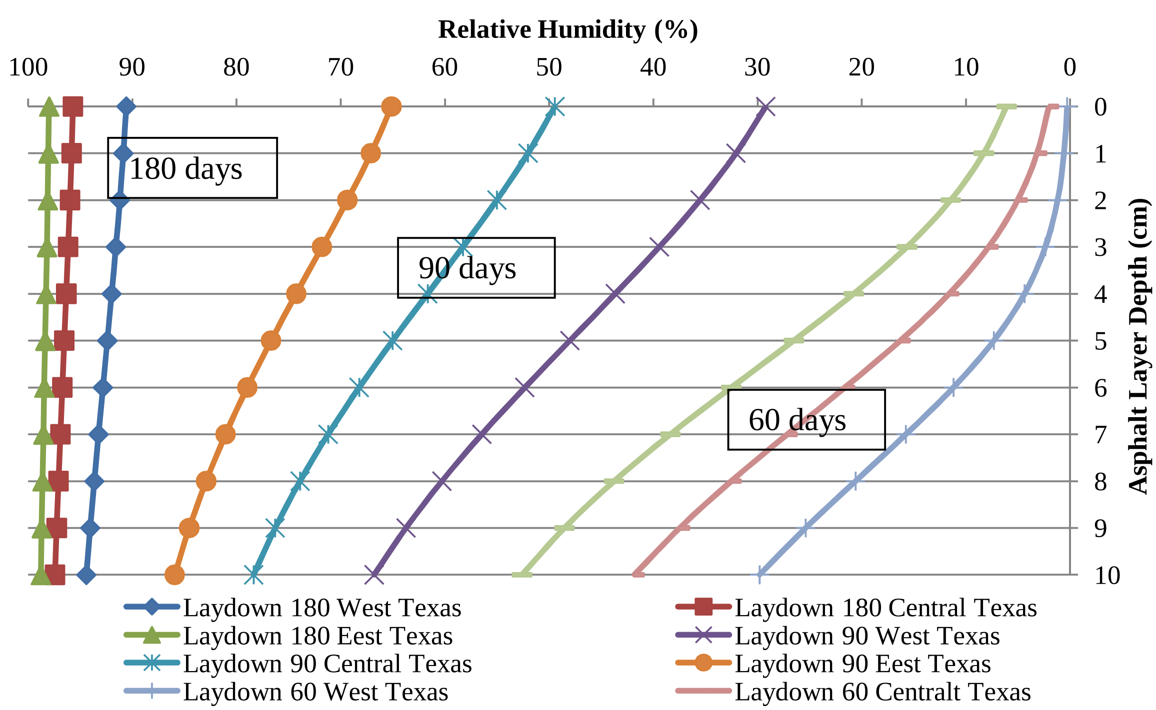


Figure E1a.11. HMA layer relative humidity modeling.

As illustrated in figure E1a.11, with the service time increases, the asphalt mixture gradually wets up due to the moisture movement from the base to the surface layer. The relative humidity is greater with depth below the surface of the pavement. The relativity humidity in the HMA layer reaches a relatively stable state 180 days after placement, and it does not significantly fluctuate as the air humidity changes. Moisture driven by humidity gradients builds up in the asphalt mixture and ultimately damages the mixture.

Fine asphalt mixture (FAM) specimens with the AAM binder that are conditioned at 100% RH have been tested using the controlled-stress repeated direct tension (RDT) test. The crack growth of each specimen has been evaluated using the developed fatigue crack model, and the analysis results are illustrated in figure E1a.12.

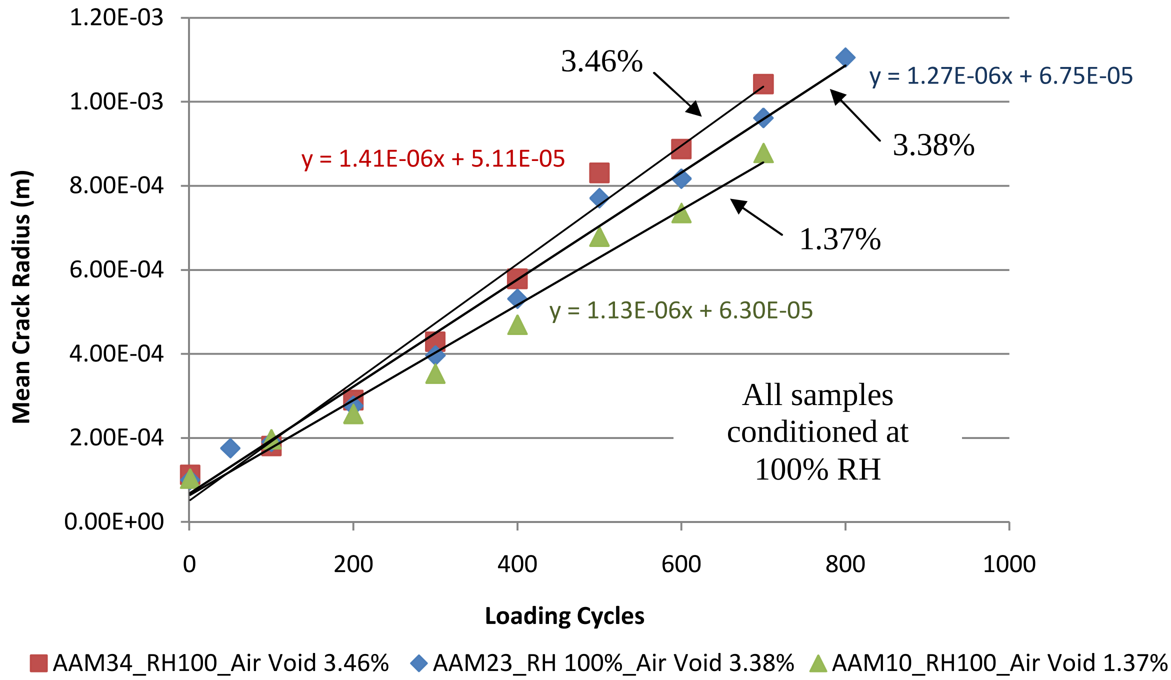


Figure E1a.12. Crack growth rate for specimens conditioned at same RH.

With repeated tensile loading, the mean crack radius increases linearly with increasing load cycles. The crack growth varies from specimen to specimen depending on the level of initial air voids. As shown in figure E1a.12, all samples are conditioned at 100% RH and the crack growth rate increases with increasing air voids. Similar tests on samples with the same air voids but conditioned at different levels of RH show that crack growth rates increase with the level of relative humidity.

<u>Significant Results</u>

The driving forces of the healing process in the damaged asphalt mixture are determined to be the true internal stress and the interfacial force of attraction. The true internal stress is the internal stress in the intact material in an asphalt mixture specimen. It not only drives the recovery of the bulk material, but also contributes to the closure of the crack surfaces. The true internal stress helps to construct the energy balance equation for the healing process, which is further used to determine the crack closure rate of a damaged asphalt mixture specimen. In order to construct the energy balance equation for the healing process, certain material properties of an asphalt mixture are required, including the apparent/true creep compliance, apparent/true relaxation modulus, and apparent/true recovery modulus. The apparent material properties are measured from the test, while the true material properties associated with the healing process are inferred from the apparent measurement in the test.

The new OT analysis methods' results give very consistent crack growth and Pseudo-work release rates. The crack growth patterns match crack length observations in the OT test.

The fatigue crack growth rates of FAM AAM specimens conditioned at 100% relative humidity increased with the level of air voids.

Significant Problems, Issues and Potential Impact on Progress

The measured creep compliance of an asphalt mixture specimen has to be simulated using a mathematical model. It is crucial to select an appropriate model since it influences the accuracy of the relaxation modulus, which is obtained by applying the Laplace transform to the simulated creep compliance. The relaxation modulus will be used in the calculation of the dissipated pseudo strain energy (DPSE) that quantifies the cracking damage in the creep phase and the recovery pseudo strain energy (RPSE) that is used to determine the crack closure rate in the recovery phase of the revised creep and recovery test.

Work Planned Next Quarter

In order to characterize the healing properties of an asphalt mixture, the damage density of crack growth in the creep phase of the revised creep and recovery test must be determined first. This is because the damage density at the end of the creep phase is the starting point of the healing process. The extent of healing that an asphalt mixture specimen can have depends on the amount of the cracking damage that is generated under the destructive loading. The first step in determining the damage density of the crack growth has been discussed above, and the following steps are planned to be studied in the next quarter, including: 1) calculate the pseudo strain and reference modulus; 2) determine the true creep strain and true creep stress of damaged asphalt mixtures from the destructive test; 3) determine the damage density and average crack size and the number of cracks from the destructive test.

Currently, the actual crack growth in the OT test can be calculated. The next step will be the application of the Pseudo displacement principle to find the A and n, Paris' law's fracture parameters, as well as B and m values for healing properties. Subsequently, the same approach will be applied to the field cores with the different stiffness gradients. This method will allow us to determine the fracture and healing properties of both lab-compacted samples as well as cores taken from aged asphalt layers in the field.

Further investigation will be conducted on AAD specimens conditioned at 25% and 75% relative humidity, and additional analysis will be performed on the AAM specimens in the next quarter.

Cited References

Kassem, E.A., et al., 2006, Measurements of Moisture Suction and Diffusion Coefficient in Hot Mix Asphalt and their Relationships to Moisture Damage. *Transportation Research Record: Journal of the Transportation Research Board*, 1970, 45-54.

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

Yoda, M., 1980, The J-integral fracture toughness for Mode II. *International Journal of Fracture*, 16 (4), 175-178.

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

Subtask E1b-1: Rutting of Asphalt Binders

Work Done This Quarter

The Multiple Stress Creep and Recovery (MSCR) testing of modified binder mastics was completed this quarter. Three modified binders (styrene-butadiene-styrene (SBS), CBE (plastomer-modified) and ground tire rubber (GTR)) were used. Limestone and granite fillers were used to make the mastics. Testing temperatures included 46, 58 and 70°C, and stress levels of 100 and 3,200 Pa.

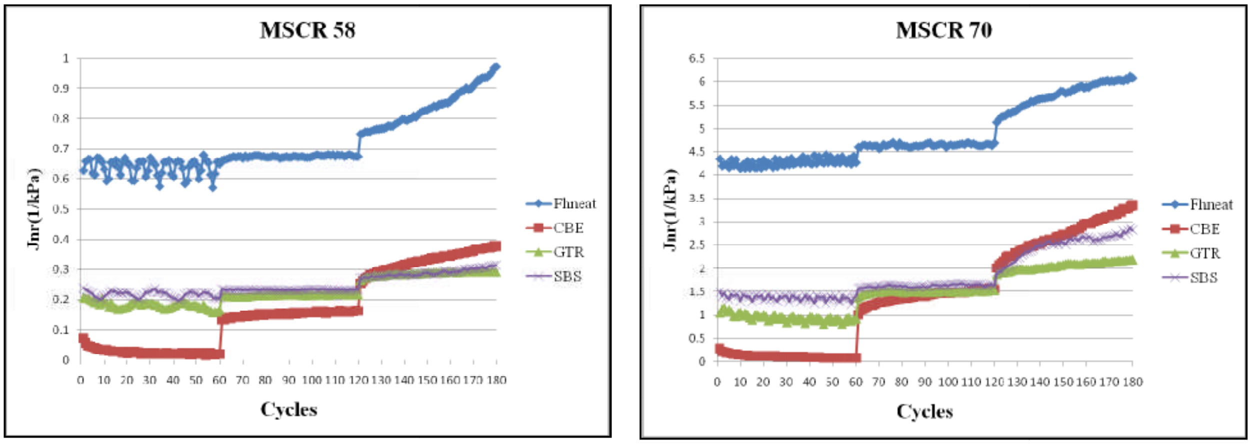
Study of the variability of MSCR results continued this quarter with conducting a modified MSCR test with 30 and 60 cycles of stress creep and recovery at three stress levels of 100, 3,200 and 10,000 Pa. The purpose of this study was to explore the effect of number of cycles and stress levels on the MSCR results. Binder and mastic modeling was also continued in this quarter.

Significant Results

The results of MSCR on mastics indicated that for both types of filler, J_{nr} values of mastics are about 50 % of the binders. Also, limestone mastics exhibit smaller values of J_{nr} in comparison to the granite ones. Percent recovery values of mastics are similar to those of the corresponding binders. The above observations were true for mastics made of both neat and modified binders. The results show that the ranking of different mastics is the same as that of the binders.

As reported in the last quarterly report, MSCR data for the binders revealed that some fluctuations can be observed in the J_{nr} and %R values from the first to the last cycles at each stress level. Further analysis conducted in this quarter led the team to the conclusion that calculating the J_{nr} and %R by taking the average of the last five cycles at each stress level reduces the variability of the results.

Figure E1b-1.1 shows the plots of J_{nr} values at 58 and 70°C for different binders at two different temperatures for 60 cycles, at each stress level.



(a) 60 Cycles per each stress level at 58C (b) 60 Cycles per each stress level at 70C

Figure E1b-1.1. Summary of extended MSCR testing.

Preliminary analyses of the results indicate that increasing the number of cycles does not yield significant reduction of fluctuations of the response at the lowest stress level. Furthermore, figure E1b-1.1 (a) shows that the increased number of cycles at higher stress levels can cause a change in the ranking of the binders as the number of cycles exceeds 30 at 3,200 Pa and the onset of the testing at 10,000 Pa. The results, however, continues to show that the reduction of J_{nr} values for all 3 types of modifiers remains very significant as compared to the neat asphalt. In other words, all three modifiers improve resistance to binder rutting significantly regardless of the stress level or the stress sensitivity. Further work in this regard on both binders and mastics is underway and will be finalized in the next quarter.

The other activity in this quarter was completion of the binder and mastic modeling based on the model proposed for RCR data in the 2008 Q3 report. The nonlinear constitutive relationship was extended to develop a model in order to describe the behavior of binders and mastics in MSCR tests. Since MSCR test involves multiple steps of loading, the Heaviside step function was used to describe the pattern of MSCR loading. The equations for the first stress level can be summarized as follows:

Loading Phase:

$$\gamma(t) = (n-1)\gamma_p(1) + \gamma_p(t-10(n-1)) + \sum_{i=0}^{n-1}\gamma_r(t-10i) - \sum_{i=0}^{n-2}\gamma_r(t-(10i+1))$$

Unloading Phase:

$$\gamma(t) = (n)\gamma_p(1) + \sum_{i=0}^{n-1}\gamma_r(t-10i) - \sum_{i=0}^{n-1}\gamma_r(t-(10i+1))$$

n = Cycle Number

The binder model was also applied for different temperatures, stress levels and an increased number of cycles successfully. In this process, Excel Solver was used to fit the model to the observed results. Also, the model was further modified to simultaneously fit the equations instead of using Solver, causing a small reduction in goodness of fit. Further applications of the model will be investigated in the next quarter.

The imaging software was modified this quarter to capture new microstructure features including aggregate contact length and contact orientation. Furthermore, the software was improved to capture the contact branches, which refer to the mixture aggregate skeleton, that is the main contributor to the mixture load bearing capacity.

Two mixes were designed based on the Bailey's method concept, one mix designed to have good aggregate packing, while the other had poor packing. The latter was compacted at two different compaction efforts (600 and 300 kPa). The lab samples produced for these mixes where cut and image analysis of the cut sections were used for verification of the aforementioned added software microstructure features.

Significant Problems, Issues and Potential Impact on Progress

None.

Work Planned Next Quarter

Work for next quarter will focus on the following tasks:

- Further study on the effect of number of cycles using the results of RCR and MSCR testing.
- Investigate the relationship between binder and mastic, in terms of rutting performance.
- Correlate the binder and mastic MSCR results and mixture rutting performance.
- Use the new features in the improved image analysis software to characterize the microstructure of real mixes with rutting performance data.
- Start working on the draft final report.

Presentations and Publications

A paper entitled "Evaluation of Using the MSCR Test for Modified Binders' Specification" was submitted to the 56th Annual Conference of Canadian Technical Asphalt Association, November 2011.

Subtask E1b-2: Feasibility of Determining Rheological and Fracture Properties of Asphalt Binders and Mastics using Simple Indentation Tests

Work Done This Quarter

In this quarter a temperature control system for the indentation test was developed to enable testing at varying temperatures. A water bath attached to a standard cooling chiller was added to the indentation system as shown in figure E1b-2.1.

The creep compliance and the non-recoverable compliance (J_{nr}) obtained from Indentation and Dynamic Shear Rheometer (DSR) tests were compared this quarter. The deflection measurements used to estimate the creep compliance and J_{nr} were obtained at constant temperature using the new system and correcting for size effects.

Figure E1b-2.1. Photograph. Modified temperature controlled indentation/penetration test.

Significant Results

Six binders of different grades were tested at 25°C using the indentation device and the DSR at 100 Pa and 3200 Pa stress levels. The creep and recovery procedure in the DSR was the same as in the indentation test: 3 minutes of loading and 12 minutes of recovery. The creep compliance and J_{nr} obtained in the DSR and in indentation tests are presented in tables E1b-2.1 and E1b-2.2, respectively. Furthermore, the percent recovery (%R) obtained from both test methods are presented in table E1b-2.3.

As reported in previous quarterly reports, theoretical solutions for creep compliance in indentation boundary value problems assume that the sample size is infinite. Therefore, correction factors to account for boundary effects are needed when using these solutions. Generally, the effect of the finite sample size depends on the stiffness of the material and the substrate that supports the testing sample. The effect of finite size samples has been extensively investigated for elastic and elasto-plastic materials but not for viscoelastic materials such as asphalt binders. Walters (1965) argued that the stress pattern despite being distorted due to the proximity of the boundary would remain geometrically similar for any given ratio of the thickness, *t*, of the sample and the radius of contact, *a*. The author proposed correction curves based on the size of the sample and the radius of contact for the case of a rigid spherical indenter in elastic materials. Based on his work and finite element simulations, the research team developed similar correction curves for viscoelastic materials. Table E1b-2.2 shows the creep compliance after taking into account size effects.

Table E1b-2.1.Creep compliance and J_{nr} from DSR creep tests.

		DSR @ 100 Pa		**DSR @ 3200 Pa**	
Binder ID	**Binder Type**	**J(180s)**	**J_{nr}**	**J(180s)**	**J_{nr}**
1	**Nustar-64-22+3.5%CBE**	1.11E-04	6.50E-05	1.32E-06	9.00E-07
2	**Nustar-64-22+3.5%CBE_AS**	8.91E-05	5.04E-05	9.75E-07	6.04E-07
3	**Nustar-85-15+3.5%AC9_AS**	1.52E-04	9.55E-05	1.51E-06	9.80E-07
4	**Nustar-85-15+2.5%CBE**	1.27E-04	7.51E-05	1.24E-06	7.66E-07
5	**Nustar-76-22**	1.77E-04	8.50E-05	1.44E-06	7.14E-07
6	**Nustar-64-22**	5.67E-04	5.01E-04	5.67E-08	1.77E-11

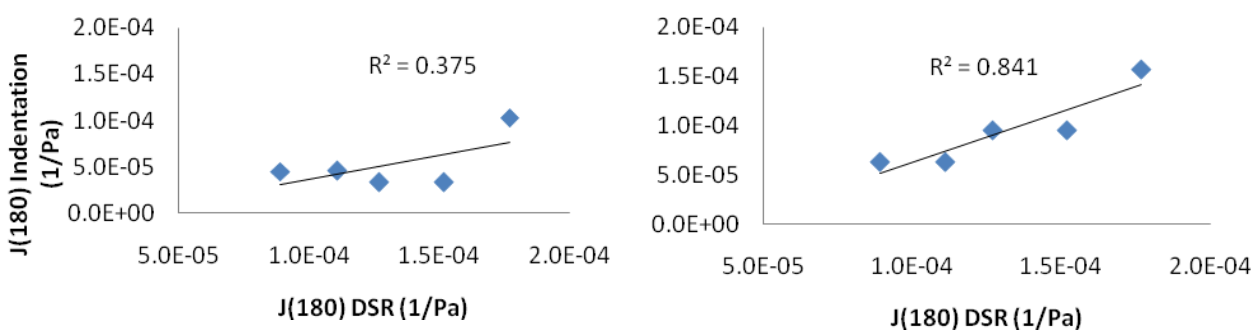
Table E1b-2.2. Creep compliance and non-recoverable compliance (J_{nr}) obtained from Indentation before and after size effect correction.

		Before Correction		**After Correction**	
Binder ID	**Binder Type**	**J(180s)**	**J_{nr}**	**J(180s)**	**J_{nr}**
1	**Nustar-64-22+3.5%CBE**	4.54E-05	2.47E-05	6.34E-05	3.23E-05
2	**Nustar-64-22+3.5%CBE_AS**	4.52E-05	2.74E-05	6.30E-05	3.63E-05
3	**Nustar-85-15+3.5%AC9_AS**	3.34E-05	3.78E-05	9.52E-05	5.27E-05
4	**Nustar-85-15+2.5%CBE**	3.34E-05	3.27E-05	9.52E-05	4.57E-05
5	**Nustar-76-22**	1.03E-04	5.20E-05	1.57E-04	5.35E-05
6	**Nustar-64-22**	9.64E-04	7.86E-04	1.79E-03	1.44E-03

Table E1b-2.3. Percent of recovery obtained from DSR and Indentation.

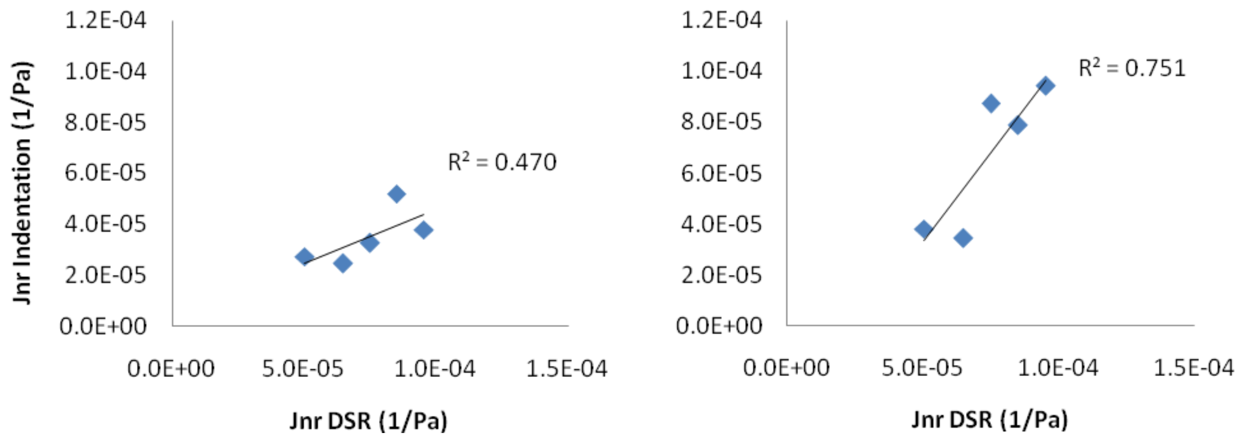
	% Recovery		
	DSR @100 Pa	**DSR @ 3200 Pa**	**Indentation**
Nustar-64-22+3.5%CBE	11.65	8.00	18.47
Nustar-64-22+3.5%CBE_AS	41.36	31.81	39.31
Nustar-85-15+3.5%AC9_AS	36.98	35.15	43.21
Nustar-85-15+2.5%CBE	43.49	38.06	46.76
Nustar-76-22	40.86	38.09	46.61
Nustar-64-22	51.80	50.58	49.63

The creep compliance at 180 sec (end of loading step) measured from Indentation and DSR tests are compared in figure E1b-2.2. The creep compliance from indentation tests were corrected for size effects. It can be seen that the correlation significantly improves after taking into account boundary effects. Note that DSR results at 100 Pa were used for this comparison, as the stress levels during indentation test are close to this level rather than the 3200 Pa case. Correlations between J_{nr} obtained from DSR and Indentation test also improved after accounting for finite size effects as indicated in figure E1b-2.3. Furthermore, it was observed that the ranking of binders in terms of % Recovery from DSR and Indentation tests is very similar (figure E1b-2.4).



(a) Before size effect corrections. (b) After size effect corrections.

Figure E1b-2.2. Graph. Correlation of J(180) from DSR and Indentation Test.



(a) Before size effect corrections. (b) After size effect corrections.

Figure E1b-2.3. Graph. Correlation of J_{nr} from DSR and Indentation Test.

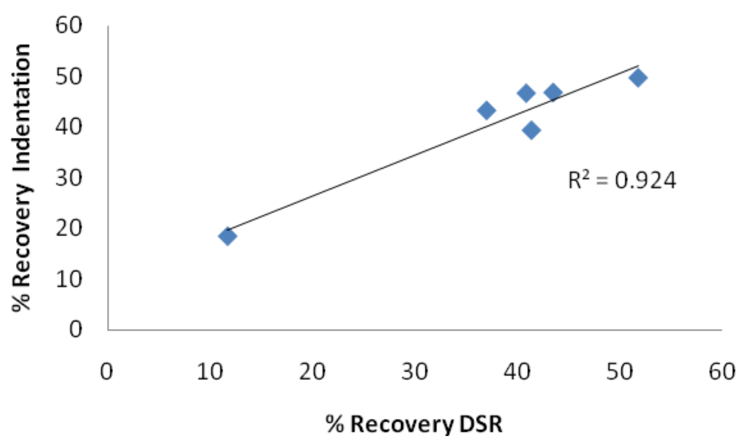


Figure E1b-2.4. Graph. Correlation of % Recovery from DSR and Indentation Test.

Work Planned Next Quarter

Efforts will focus on writing a consolidated report for work element E1b: “Binder Damage Resistance Characterization” following 508 format requirements. This report will include experimental results and analysis obtained during the development of the indentation system for rheological characterization of asphalt binders.

Cited References

Walters, N. E., 1965, The indentation of thin rubber sheets by spherical indentation. *British Journal of Applied Physics*, 16, 557-563.

Work Element E1c: Warm and Cold Mixes

Subtask E1c-1: Warm Mixes (UWM)

Work Done This Quarter

The evaluation of asphalt binder workability continued this quarter, including work on the Asphalt Lubricity tests and simplified methods for estimating mixing and compaction temperatures for modified binders. The experiment to further develop the Asphalt Lubricity Test procedure included using five testing speeds, two levels of normal force and three temperatures. A modified and neat binder from the same source was used. The experimental plan is 25% complete. The literature review conducted identified methodologies for evaluating the lubricating properties of Newtonian and non-Newtonian fluids. These methods will be evaluated using the data collected from the Asphalt Lubricity test pending completion of the experimental plan. A simplified method for defining mixing and compaction temperatures of modified asphalt based on viscosity at low shear rates was developed for evaluation of the impacts of WMA additives on the production temperatures of modified binders.

Efforts related to the evaluation of the effects of WMA additives and reduced aging temperatures on asphalt binder focused on the evaluation of appropriate binder aging methods. Similar materials aged at three temperatures in the RTFO and TFOT were compared to separate the effects of viscosity and oxidation on binder aging. To isolate the effects of oxidation and reduce testing time, a thin film binder aging method is currently under development.

Collaborative efforts continued with the University of Nevada-Reno on moisture damage testing. Mixture performance testing was begun this quarter. Bitumen bond strength testing at UW Madison remains 50% complete; aggregate plates from Reno have been prepared and testing will commence next quarter. The research team was informed by WisDOT that there are a significant number of WMA projects planned for the 2011 construction season and that they are willing to partner with the research team. To date, no specific projects have been identified, but it is expected there will be projects for the fall of 2011. The progress of this task is conditional upon WisDOT collaboration.

Significant Results

The Asphalt Lubricity test demonstrates repeatable measurements of torque and normal force for a single sample across most levels of normal forces and most speeds. As testing speed increased above 50 RPM, it was generally observed that the consistency of the measured torque values and the ability of the machine to control normal force decreased. Inconsistency between replicates was observed for the values of coefficient of friction; however, all test results showed similar trends with changing normal force or testing speed. The machine and testing apparatus are currently under evaluation to identify the source of variability between testing results.

Preliminary evaluation of the applicability of the Low Shear Viscosity (LSV) method developed based on the procedure proposed in the NCHRP 459 report indicated that the procedure was successful in identifying the presence of WMA additives. The procedure was sensitive to concentration, with increasing concentration leading to higher temperature reductions. The 2% Rediset additive resulted in reductions of 9°C and 5°C for mixing and compaction temperatures, respectively. Temperature reductions based on LSV will be compared to recommended temperatures from the NCHRP 9-43 mix design method to determine the contribution of viscosity to overall temperature reduction. Data collected will be analyzed using this method for more WMA additive types and concentrations.

Comparison of continuous grading results for RTFO and TFOT materials aged at 105°C, 120°C, and 163°C indicated that the increase in viscosity due to decreasing temperatures in the RTFO significantly influenced the asphalt binder susceptibility to aging. For the RTFO aged materials the range in continuous grade between high and low aging temperatures was approximately 5°C. Conversely, the range for TFOT was 2.5°C. As a result, a new thin film oven aging method is under development. In an effort to reduce testing time by reducing film thickness, the method uses 33% of the material used in the current TFOT procedure.

Asphalt mixture workability studies have indicated that reducing the temperature by 30°C did not significantly affect the volumetric properties of the mix. Furthermore, certain combinations of WMA additive/concentration produced a lubricating effect in the mix that caused it to become too dense for a given level of compactive effort. As a result, a conventional mix design that meets volumetric criteria may have the potential to fail volumetric criteria due to the presence of a WMA additive. A methodology to integrate this consideration into the mix design process by adjusting asphalt content and/or compaction effort is currently under development.

Significant Problems, Issues and Potential Impact on Progress

Asphalt lubricity testing has been delayed due to a lack of repeatability between samples. Necessary adjustments to the machine are currently underway to resolve this issue. To date, testing has been delayed two weeks.

The decision was made to combine the draft reports promised in the Yr. 5 work plan into one report. The report will summarize work by UW Madison and University of Nevada Reno. The scope of the report and deadline for submittal is currently being developed by the research team.

Work Planned Next Quarter

Lubricity Testing
The experiment to establish the repeatability and the sensitivity to testing parameters will be conducted. A final procedure will be developed and the experiment to evaluate the effect of WMA additive type and concentration will commence.

Development of Mixing and Compaction Guidelines for WMA
Comparison of the LSV and Phase Angle methods shall be used to determine appropriate mixing and compaction temperatures for modified binders with WMA additives. Testing temperatures will be applied to lubricity, viscosity, and mixture workability testing. Mixture workability testing will be completed for two gradations, two aggregate types, and a minimum of two WMA

additives used with conventional PG 64-22 and SBS modified PG 76-22 binders. The work is currently 25% complete. In accordance with the NCHRP 9-43 mix design procedure, aggregate coating, mix design volumetrics, and compactability will be evaluated.

Impacts of Reduced Aging on Performance
The thin film oven aging method will be developed and implemented to evaluate the impact of reduced oxidation on the performance of the binder at high and intermediate temperatures. Specifically, testing will include use of the MSCR at high temperatures and the Linear Amplitude Sweep Test at intermediate test temperatures. Mixture testing will start at the end of the quarter.

Moisture Damage
Complete BBS testing matrix and coordination with Reno to discuss results of mixture testing.

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

<u>Work Done This Quarter</u>

The research team began to collaborate with Heritage Research Group (HRG), a private sector company with extensive field experience in cold mix applications. HRG will provide UW Madison with aggregate material and emulsions for use in the laboratory along with a current job mix formula (JMF) pertaining to an adequately performing field section. At the conclusion of the collaboration, UW will provide HRG with performance test data for their current JMF along with data and suggestions for alternative gradations, moisture levels, and emulsion contents. There is also potential for field validation of the suggested alternative JMFs during the current construction season.

The experimental plan calls for a blend of two aggregate stockpiles, one crushed limestone and the other natural sand, and the use of one emulsion type. The initial aggregate blend and emulsion grade were specified by HRG as acceptable for use in this application. The specified aggregate gradation was evaluated according to the Bailey Method (Vavrik et al., 2002) for gradation selection, which is formulated for hot mix asphalt applications. It is hypothesized that the Bailey Method recommendations formulated for SMA and coarse graded mixes may be applied to cold mix gradations.

Initial coating tests of the selected gradation were performed according to ASTM D 7229, Standard Test Method for Preparation and Determination of Bulk Specific Gravity of Dense Graded Cold Mix Asphalt Specimens by Means of the Superpave Gyratory Compactor (ASTM, 2008). Based on the degree of coating noted for trial aggregate moisture contents, three trial emulsion contents were selected for compaction. The aggregate moisture contents tested were 3%, 3.5%, and 4% by dry weight of the aggregate blend. The trial emulsion contents were selected to achieve 5%, 5.5%, 6%, and 6.5% residual asphalt binder content; selected based on standard dense graded HMA and SMA mix guidelines (the corresponding emulsion contents were 8.1%, 8.8%, and 9.5%, respectively). From the coating test results, 3% aggregate moisture was selected and compacted at each of the former residual asphalt binder contents. The samples will be used for density and volumetric information coupled with the gradation analysis provided by the Bailey Method in order to begin specifying appropriate compaction, curing and gradation requirements for cold mix asphalt.

Significant Findings

The trial gradation supplied by HRG was evaluated based on the Bailey Method with the results shown in table E1c-2.1. The Bailey Method identifies certain sieve sizes as critical to the formation of air voids in the mixture, and provides recommended ranges for optimum pavement performance of three ratios, the coarse aggregate ratio (CA), the fine aggregate coarse ratio (FA_c), and the fine aggregate fine ratio (FA_f). The CA, FA_c, and FA_f ratios are calculated based on the trial gradation nominal maximum aggregate size (NMAS) and percent passing information and are representative of proportions of aggregate percent passing at certain sieves to others.

Table E1c-2.1. Analysis of trial gradation using the Bailey Method.

NMAS	19 mm		
	CA Ratio	FA_C Ratio	FA_f Ratio
Recommended by Bailey Method	0.60 - 0.75	0.35 - 0.50	0.35 - 0.50
Calculated from trial gradation	0.64	0.50	0.19

It is important to note that the recommended aggregate ratios are suggested as starting points for coarse graded HMA mixtures; they have been shown to provide mixtures with volumetric characteristics similar to those found in adequately performing pavements. The Bailey Method also provides relationships between the above ratios and volumetric properties, namely VMA. For example, when the CA ratio increases, the VMA increases. Conversely, when the FA ratios are increased, the VMA will *decrease*. It is noted that changing the FA_C ratio has the most significant impact on mixture VMA, followed by the CA ratio.

Coating tests were completed using the trial gradation provided by HRG according to ASTM D 7229, Section 7.2. Three trial aggregate moisture contents were selected for evaluation based on industry suggestions. The aggregate moisture content was calculated as a percent of the total dry aggregate weight. ASTM D 7229 also provides a recommendation for trial initial emulsion content (IEC). Based on the IEC and coating results, three additional emulsion contents were selected for analysis. Samples were mixed in a mechanical mixer for two minutes and spread onto a table for visual inspection. Degree of aggregate coating was evaluated based on visual analysis of the coarse particle coating, fine particle coating, and presence of 'clumping' of asphalt particles. The results of the coating test indicated premix aggregate moisture content of 3% was sufficient for coating. The 5.0% residual asphalt content mix did not provide adequate coating and will not be considered in the optimum emulsion content analysis. Samples will be compacted at 3% moisture with residual asphalt contents of 5.5%, 6.0% and 6.5% according to the compaction and curing procedure outlined in ASTM D 7229.

The selected emulsion content – aggregate moisture content combinations were compacted in the gyratory compactor according to ASTM D 7229. Samples were compacted at 600 kPa and 33 gyrations in a modified Superpave gyratory mold; the mold allows water to drain from the specimen during compaction as seen in figure E1c-2.1 along with a compacted sample. It was noted that the aggregate locking point, defined as the point where the sample height remains constant for three or more gyrations, was found to be in the range of 27-30 gyrations for compacted mixes.

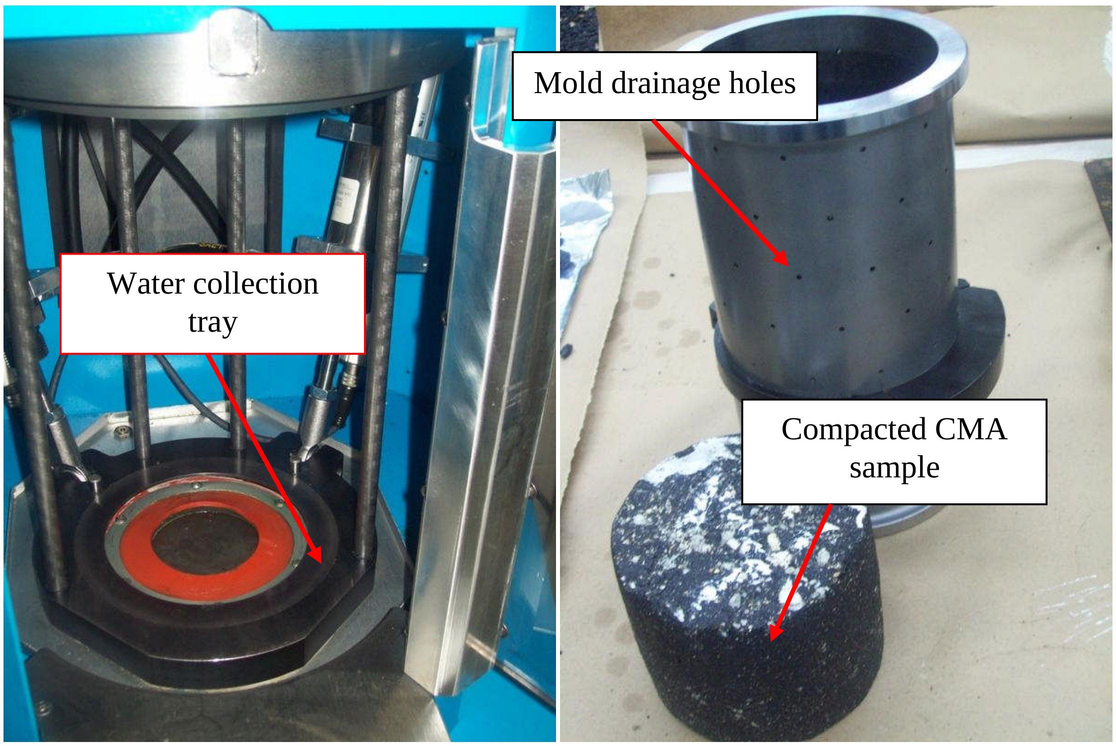


Figure E1c-2.1. Photograph. Modified gyratory mold and apparatus with compacted CMA sample.

Mass (moisture) loss was also recorded for the samples during compaction and during curing. In addition to water forced from the sample during compaction, it is established that cold mixes experience a 'curing' interval in which sample moisture evaporates/escapes over time, allowing an increase in voids in the mixture along with increased mixture stability over time. The typical full 'curing' time for a cold mix is commonly reported as 72 hours at 60°C. At the time of this reporting, mass loss through 48 hours was the only parameter measured for the samples. It was found that the relative cumulative mass loss and highest initial compaction relative mass loss was highest for the 5.5% residual asphalt content, followed by the 6.0% residual asphalt content and 6.5% residual asphalt content mixes, respectively. It should be noted that the percent loss is relative the total sample mass; a loss of 20 grams will represent a larger relative mass loss for the 5.5% residual asphalt content compared to the 6.0% and 6.5% residual asphalt content since aggregate mass is constant between all three emulsion contents.

Significant Problems, Issues and Potential Impact on Progress

The laboratory sieve shaker was out of service for a significant portion of this quarter, limiting the amount of aggregate material that could be processed for this project. The sieve is now operational and not expected to cause further delays. Unexpected weather and scheduling conflicts caused approximately two weeks of delay in receiving the aggregate and suggested JMFs for the project. The UW lab now has enough aggregate and emulsion material for at least one more quarter of work before the need for replenishing.

Work Planned Next Quarter

The following work is planned for next quarter:

- *Density and Curing.* Determination of volumetric and curing properties of the aforementioned cold mix specimens in order to begin drafting appropriate design considerations for cold mix applications. After the gradation as suggested by HRG is evaluated, alternative gradations will also be evaluated based on volumetric – gradation relationships provided by the Bailey Method.
- *Mechanical Testing.* The research team will evaluate potential mechanical tests of cold mixes and apply them to trial lab samples. Suggested at this time is flow number testing (rutting), permeability testing, and moisture susceptibility (via indirect tension).
- *Emulsion Type and Grade*. The research team will evaluate the effect of modified and alternative emulsions on cold mixes using the above procedures. Potential areas of research will be emulsion set rate, grade, and polymer modification.

Cited References

ASTM D 7229 Standard Test Method for Preparation and Determination of Bulk Specific Gravity of Dense Graded Cold Mix Asphalt Specimens by Means of the Superpave Gyratory Compactor. American Society for Testing and Materials, 2008.

Vavrik, W., G. Huber, W. Pine, S Carpenter, and R. Bailey, 2002, *Bailey Method for Gradation Selection in HMA Mixture Design*. Transportation Research Board, Transportation Research Circular Number E-C044, October 2002.

CATEGORY E2: DESIGN GUIDANCE

Work element E2a: Comparison of Modification Techniques (UWM)

Work Done This Quarter

This quarter the four binders received from Universitat Politecnica de Catalunya (UPC)-Spain were tested for glass transition temperature (T_g). Mixture testing conducted at UPC was used to investigate the relationship between binder and mixture performance in terms of fatigue and thermal cracking. Binder fatigue performance was measured from the linear amplitude sweep test (LAS) while the EBADE (Pérez Jiménez 2011) test was used for the mixtures. The performance at low temperature was measured using the Single Edge Notched Beam test (SENB) and the FENIX (Pérez Jiménez 2010) test for binders and mixtures respectively.

<u>Significant Results</u>

An example of the calculated glass transition temperature for the Spanish binders using a dilatometric device is shown in figure E2a.1.

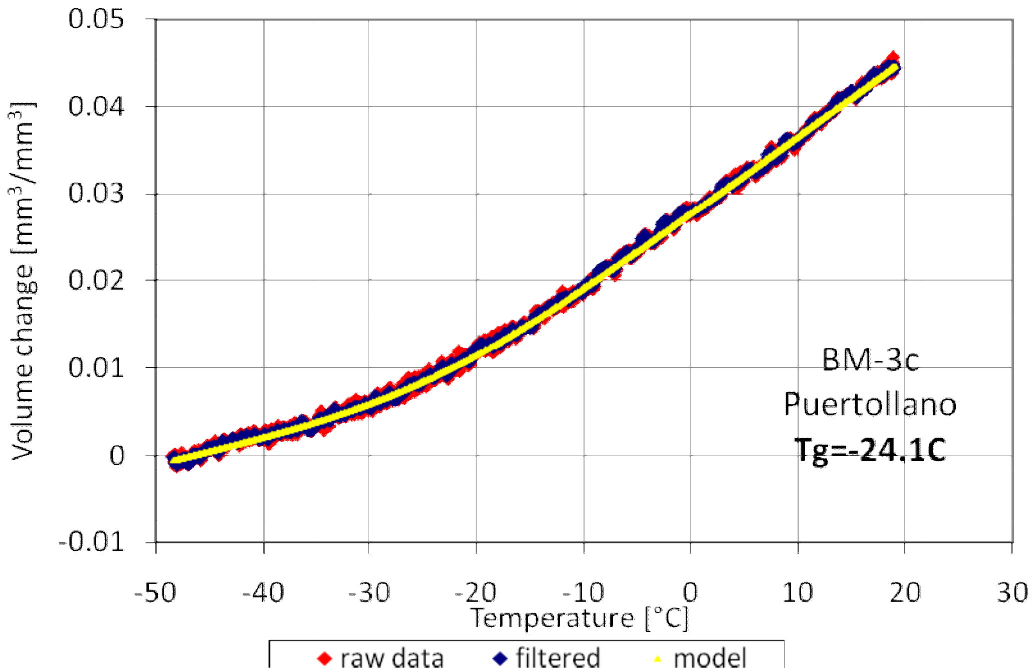


Figure E2a.1. Graph. Glass transition temperature for BM-3c- Puertollano binder.

The correlation between binder and mixture fracture energy is shown in figure E2a.2. The correlation was calculated using fracture energies at all temperatures. The fairly good correlation observed between the mixture and binder testing indicates the importance of fracture response of the binder to the overall low temperature cracking performance of the mixture. Figure E2a.2 suggests that approximately 70% of the variation of the fracture energy of the mixture can be explained by the binder fracture properties.

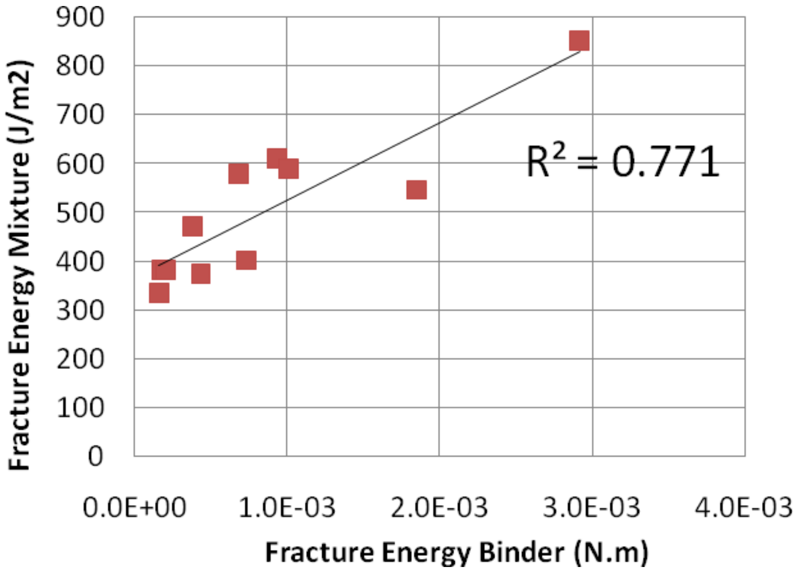


Figure E2a.2.Graph. Correlation between binder and mixture fracture energy.

Figure E2a.3 shows the displacement at maximum load in SENB and FENIX testing as an indication of the ductility of the binders and mixtures. There are two distinctive linear trends in figure E2a.3. The points corresponding to tests conducted at 5 and -5°C fall in a different line in comparison to the tests conducted at -15°C. These two different trends can be explained by the glass transition behavior of the binders which by average is around -15°C. Note that the glass transition temperatures for the selected binders are between -12.6 and -24.1°C. As with fracture energy, there is a fairly good correlation between the displacements at fracture from the binder and mixture.

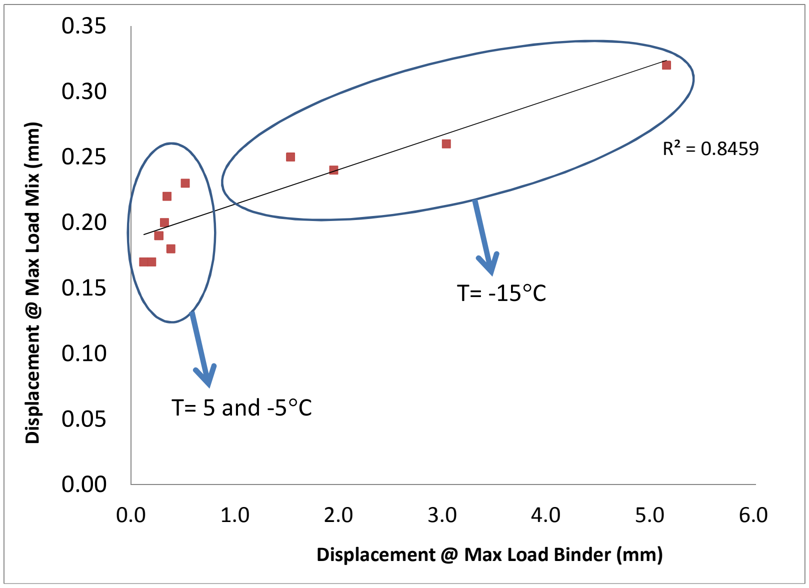


Figure E2a.3. Graph. Displacement at maximum load in mixture and binder in low temperature cracking testing.

The normalized stress vs. strain response of the binder and mixture to accelerated fatigue loading is very similar (figure E2a.4). The stresses and strains were normalized by their respective maximum values. Significant reduction in the stress happened at about the same normalized strain in the binder and mixture. It can be seen that the mixture has remaining strength after reaching peak stress, probably due to the aggregate structure.

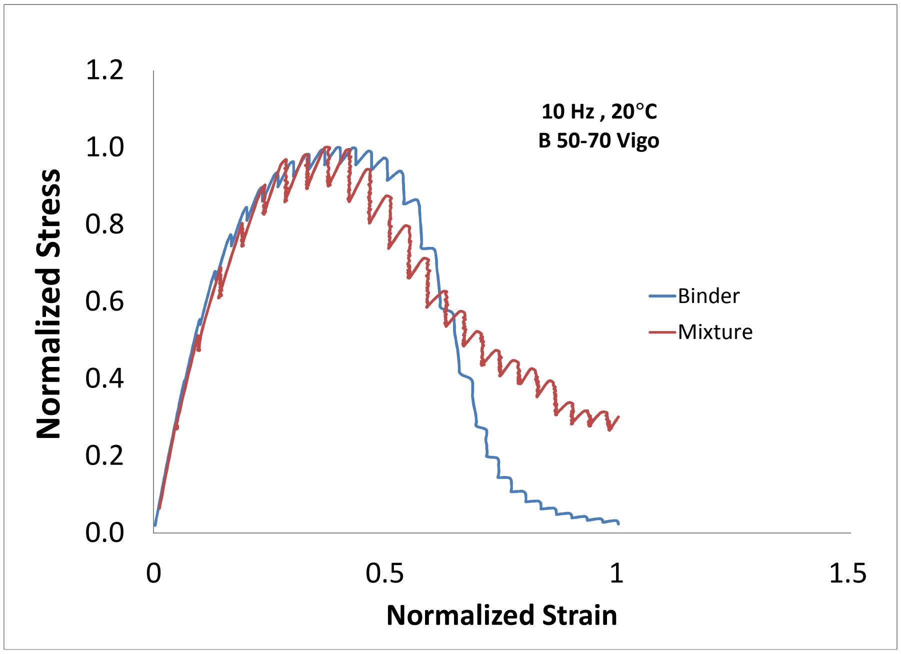


Figure E2a.4. Graph. Mixture (EBADE) and binder (LAS) normalized stress-strain response to accelerated fatigue.

Significant Problems, Issues and Potential Impact on Progress

The research team is planning to spend most of the remaining resources associated with this work element on the analysis of testing results and development of cost index for each modification type. Therefore, the test matrix previously proposed for the Bitumen Bond Strength (BBS) test and Glass Transition measurements will be eliminated from the planned work, or only limited testing will be included.

Work Planned Next Quarter

Work for next quarter will focus on developing a model to estimate the level of modification needed to meet a specific performance criteria and the costing index associated with modification. Also, efforts will be directed in preparing the draft final report.

Cited References

Pérez Jiménez, Félix.,et. al., “Effect of thermal stresses on fatigue behavior of bituminous mixtures,” TRB 2011.

Pérez Jiménez, Félix.,et. al., “Fenix Test: Development of a new test procedure for evaluating cracking resistance in bituminous mixtures,” TRB 2010.

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

Work Done This Quarter

This work element is a joint project between University of Nevada, Reno and University of Wisconsin–Madison. Work done during this quarter focused on the development, refinement, and validation of a DSR based testing procedure to estimate blended binder viscosity (workability) at high temperatures. The results can be used to predict the change in mixing and compacting temperatures due to the addition of RAP materials. The work included three major tasks:

- Develop a DSR based test method that estimates the change in fresh binder viscosity due to RAP binder replacement congruent with the proposed mortar testing procedure.
- Validate the above procedure externally against the RV and internally using artificial RAP materials (similar to what was done for the low, intermediate, and high temperature continuous grading procedure presented in 2010 quarterly reports).
- Application of the proposed procedure to a simple test matrix to determine the sensitivity of the test method to RAP and fresh binder source.

Recommendations were submitted to the RAP ETG on the characterization of RAP aggregate specific gravity. The recommendations are to be considered by the RAP ETG for incorporation in AASHTO M323 procedure.

The subtask E2d-3, “Develop a Mix Design Procedure,” was completed. The data analysis was conducted for the mixing temperature records, grades of the recovered binders, volumetric properties and mechanical properties using the dynamic modulus. The work is currently being finalized to provide recommendations for the most appropriate laboratory mixing procedure for HMA mixtures with RAP.

Under subtask E2b-4, the effective PG in the RAP binder was evaluated for the plant-produced mixtures from the Manitoba PTH8 sections. The following methodologies we assessed:

- Grading of recovered asphalt binder
- Blending chart process
- Mortar analysis process
- Backcalculation process using Hirsch model
- Backcalculation process using modified Huet-Sayegh model

Significant Results

Preliminary workability testing in the DSR included the Steady Shear Flow (SSF) method proposed in NCHRP Report 648 Mixing and Compaction Temperatures of Asphalt Binders in Hot Mix Asphalt and a rotation controlled shear test. The SSF method was suitable for the fresh binder materials but was found to be unsuitable for the mortars. The viscosity of the mortar material was shown to *increase* as the shear stress increased, without reaching a plateau, in opposition to the fresh binder behavior. Due to these results, a rotation based procedure was proposed; a binder or mortar sample was subjected to a constant rotation and viscosity was measured with time. This procedure was later abandoned as testing at multiple temperatures resulted in multiple revolutions of the plate (very high strain), sometimes shearing or damaging the sample beyond a reasonable point. It was agreed that oscillation testing using 2% total strain would be better suited for this application.

The testing procedure was finalized as measuring the complex viscosity (η^*) of the fresh binder, RRAP mortar, and SRAP mortar at four consecutive temperatures, 76 °C, 94 °C, 115 °C, and 135 °C. The samples are tested with parallel plate geometry using 10 rad/sec (0.20 1/sec shear rate) oscillation controlled at 2% strain and a 1 mm test gap. It was hypothesized that the complex viscosity would be equivalent to the dynamic viscosity in the RV if the same shear rate conditions were applied to both test methods. The complex viscosity of the fresh binder sources in the DSR was compared against the rotational viscosity measured in the RV at 76°C and 94°C, and was found to be within 2 Pa-sec of each other for all fresh binder sources and temperatures tested. Testing at higher temperatures was not possible because the low shear rate caused unreasonably low torque values in the RV, resulting in machine measurement error.

The research hypothesis of the current work is in line with the proposed continuous grading procedure developed for low, intermediate and high temperatures. The relative difference in viscosity measurements between the RRAP (no RAP binder) mortar and the SRAP (RAP binder present) mortars can be attributed solely to the RAP binder in the SRAP mortar, as the total mortar asphalt content and gradation is held constant. For all of the RAP source – fresh binder combinations tested thus far, as well as all of the binder replacement values tested, the ratio of SRAP viscosity to RRAP viscosity follows a linear trend with test temperature. The relationship is as expected; the ratio of mortar viscosities decreases with increasing temperature. It should be noted that the fresh binders tested were unmodified. The ratio of viscosities at a given temperature is applied to the fresh binder via simple multiplication at that temperature to provide an estimate of the blended binder viscosity. Applying the ratio at all test temperatures results in an estimated blended binder viscosity – temperature profile.

The DSR procedure was verified using artificial RAP materials prepared in a similar fashion as presented in previous reports. Two artificial RAP materials were produced and each combined with a single fresh binder, for a total of two verification cases. Each verification case was blended at 10%, 20%, and 25% RAP binder replacement values to demonstrate the ability of the procedure to isolate RAP binder properties even at low binder replacements. The procedure viscosity estimates were compared against physical blended binders representing the fully blended RAP binder – fresh binder combination. The procedure was found to be capable of estimating the blended binder viscosity within a 10% difference for nearly all temperatures and binder replacement values tested. It should be noted that the largest difference between the estimated and measured binder viscosity values occurred at the lowest test temperature- binder replacement combinations, as expected.

The estimated blended binder viscosity- temperature profile is plotted according to ASTM D 2493 – Viscosity Temperature Charts for Asphalts (ASTM 2009). The appropriate viscosity ranges for mixing and compacting temperatures are applied and the corresponding temperature is obtained. Repeating this process for each binder replacement value tested allows for an estimation of the effect of RAP binder replacement on the mixing and compaction temperatures for the blended binder. An example with typical result is shown in table E2b.1. Note that increasing the RAP binder replacement results in an increase in mixing and compaction temperatures, as expected.

Table E2b.1. Effect of RAP on mixing and compaction temperatures of HMA
(Fresh Binder: PG 58-28. RAP Source: Manitoba, Canada).

	Mixing Temp. Range† [C]		**Compaction Temp. Range‡ [C]**	
Binder Replacement	**High**	**Low**	**High**	**Low**
Original Binder [0%]	148	142	136	131
10%	150	144	138	133
20%	152	146	140	135

†Mixing temperature range corresponding to a binder viscosity of 0.17 ± 0.02 Pa – sec.
‡ Compaction temperature range corresponding to a binder viscosity of 0.28 ± 0.03 Pa – sec

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

Fatigue equipment at UNR was facing some problems and needed to be fixed. This delayed the testing for the Manitoba mixtures.

<u>Work Planned Next Quarter</u>

Work will continue on a simple test matrix that has been proposed for the above workability testing. In addition, the effect of warm mix additives on high percentages of RAP will be explored. Modified binders will also be considered in the analysis.

Significant work with the SENB fracture testing is planned for next quarter; first will be a variability analysis using the mortar materials followed by the development of a testing matrix to assess the sensitivity of the SENB test to RAP and fresh binder source. It is expected that a proposed analysis procedure for RAP in the SENB will be developed by next quarter.

The proposed mortar method for high temperature continuous grading will be re-visited in an effort to revise the testing procedure to provide more reasonable estimates of blended binder continuous grade at high temperature.

A paper will be drafted for publication in the Transportation Research Record and presentation at the Transportation Research Board annual meeting that highlights significant research findings to date for the E2b work element.

A paper will be drafted for publication in the Transportation Research Record and presentation at the Transportation Research Board annual meeting that highlights significant research findings to date for the evaluation of effective PG in high RAP mixtures from Manitoba.

A paper will be drafted for publication in the Journal of Association of Asphalt Paving Technologists and presentation at the AAPT annual meeting that highlights the recommendations for the characterization of RAP aggregate specific gravity.

Fatigue testing of the Manitoba PTH8 mixtures will resume as soon as the fatigue equipment is fixed.

Cited References

ASTM D 2493 – Viscosity Temperature Charts for Asphalts. American Society for Testing and Materials, 2009.

Subtask E2b-2: Compatibility of RAP and Virgin Binders

Work Done this Quarter

Work in this subtask has ramped up in the past quarter. A large suite of blends were made as shown in table E2b-2.1 below using RAP binders extracted using 2 different extraction solvents. RTFO aged asphalts BI-0001 and BI-0002 from the ARC core asphalts were selected for the results to provide blending data from 2 very different binders. RAP binders from three different sources (South Carolina, California, and Iowa) were extracted using either toluene/ethanol (85/15) or cyclohexane. Cyclohexane is being used as an alternative because it has solubility parameters similar to that of asphalt, unlike the toluene/ethanol mixture. The hypothesis is that by extracting with an asphalt-like solvent, an approximation can be made for the binder that actually blends from any given RAP source.

Included in the table below are materials/samples from the Manitoba comparative performance site that have already been subjected to Asphaltene Determinator (AD) and rheological (DSR) analysis. These samples are included in the matrix to help tie the laboratory effort to field performance. This earlier work indicated that the use of cyclohexane extracted RAP asphalt, rather than the exhaustive toluene/ethanol extraction, may provide an approximation of the RAP fraction that is actually mixing with a virgin binder. In general, the cyclohexane extracted RAP binders are softer than analogous samples from toluene-ethanol extractions. Additionally, the AD results indicate less asphaltene content in the cyclohexane extracted binders, in particular in the toluene soluble fraction. This supports the theory that RAP and virgin binder do not mix completely and that the RAP asphalt that blends is most likely lower in asphaltene and/or highly polar resin material that is both stiff and irreversibly adsorbed to an aggregate surface.

Automated Flocculation Titrimetry, or compatibility testing, is nearly complete on the entire sample set shown below. This data will be used to compare the differences in compatibility of the virgin and extracted RAP binders with the binders blended at different levels of RAP. It is expected that the compatibility of most virgin-RAP binder blends will decrease in comparison to the virgin binder, resulting in an expected stiffening of the asphalt. In some cases, however, virgin binder has been shown to soften when blended with RAP (NCHRP 9-12). Compatibility testing on a suite of asphalt binders used in the NCHRP 9-12 project will also be performed here in the coming weeks to determine whether AFT and compatibility can be used as an indicator for the changes in physical properties that are observed in these blends. The binders from NCHRP 9-12 were obtained from Dr. McDaniel at the North Central Superpave Center recently and have been submitted for analysis by AFT as well as AD.

Significant Results

None.

Significant Problems, Issues and Potential Impact on Progress

None.

Work Planned Next Quarter

AFT for this sample set will be completed in the upcoming quarter. In addition, Asphaltene Determinator (AD) analysis will also be completed next quarter. Rheological analysis will begin in the next several weeks; however, the full sample set may not be completed next quarter due to a backlog of samples awaiting DSR. SARA analysis may be performed on samples depending on need after obtaining data from the other methods.

Analysis of the NCHRP 9-12 samples will begin next quarter as well. It is hoped that most of these samples will be completed in the upcoming quarter as well.

Table E2b-2.1. Sample matrix for RAP compatibility study. Testing completed on blends is indicated by an ‘x’ in the box under the associated analytical method.

Asphalt	RAP %	Extract solvent	AFT	AD	SARA	DSR
SC RAP	100%	Toluene/EtOH	x	x		x
		Cyclohexane				
IA RAP	100%	Toluene/EtOH	x			
		Cyclohexane				
CA RAP	100%	Toluene/EtOH	x	x		x
		Cyclohexane				
PTH8 RAP	100%	Toluene/EtOH		x		x
		Cyclohexane		x		x

Asphalt	RAP %	Extract solvent	AFT	AD	SARA	DSR
BI-0001	none	Toluene/EtOH	x			
	15% SC	Toluene/EtOH	x			
		Cyclohexane	x			
	50% SC	Toluene/EtOH	x			
		Cyclohexane	x			
	15% IA	Toluene/EtOH	x			
		Cyclohexane	x			
	50% IA	Toluene/EtOH	x			
		Cyclohexane	x			
	15% CA	Toluene/EtOH	x			
		Cyclohexane	x			
	50% CA	Toluene/EtOH	x			
		Cyclohexane	x			

Asphalt	RAP %	Extract solvent	AFT	AD	SARA	DSR
BI-0002	none	Toluene/EtOH	x			
	15% SC	Toluene/EtOH	x			
		Cyclohexane	x			
	50% SC	Toluene/EtOH	x			
		Cyclohexane	x			
	15% IA	Toluene/EtOH	x			
		Cyclohexane	x			
	50% IA	Toluene/EtOH	x			
		Cyclohexane	x			
	15% CA	Toluene/EtOH				
		Cyclohexane	x			
	50% CA	Toluene/EtOH				
		Cyclohexane	x			

Asphalt	RAP %	Extract solvent	AFT	AD	SARA	DSR
Manitoba	none	Toluene/EtOH		x		x
150/200		Cyclohexane		x		x
	15% PTH8	Toluene/EtOH		x		x
		Cyclohexane		x		x
	50% PTH8	Toluene/EtOH		x		x
		Cyclohexane		x		x
Manitoba	none	neat/RTFO		x		x
200/300	50% PTH8	Toluene/EtOH		x		x
		Cyclohexane		x		x

Work element E2c: Critically Designed HMA Mixtures (UNR)

Work Done This Quarter

The write-ups for the figures and tables captions of the subtask E2c.1 report were completed and the report entitled: "Repeated Load Permanent Deformation Triaxial Testing Conditions of Asphalt Mixtures" was submitted to FHWA for review.

Work continued to evaluate the applicability of the recommended deviator and confining stresses for the flow number test. As part of the FHWA FN task group, materials from FLDOT, NCDOT, TxDOT, Wisconsin, NCAT, Granite (West California), New Jersey, and Indiana have been received. In this quarter, mix designs for New Jersey, Indiana, and Granite (West California) have been verified. Figure E2c.1 shows the blend gradations of the mixtures that have been verified including the mixtures that were evaluated in the previous quarter. The figure shows that the mixtures cover a wide range of gradations. The dynamic modulus of the verified mixtures has been conducted at 7, 4 and 2% air void content.

For each aggregate source an extensive evaluation is been conducted using the Aggregate Imaging System (AIMS). Results are being analyzed in order to characterize the aggregates and determine their influence on the asphalt mixture permanent deformation performance. In addition, Flow Number testing is been conducted for FLDOT and NCDOT for braking and non-braking conditions.

The work on converting the pulse duration in time domain for a given pavement response into frequency domain continued to be investigated using the Fast Fourier Transformation (FFT). The concept of predominant frequency(ies), f_p, to predict all components of the pavement responses was verified for different pavement structures and conditions. In this quarter, two additional pavement structures with Cement Treated Base (CTB) were evaluated. The frequencies for the asphalt sub-layers as proposed by the MEPDG procedure were determined and are being compared to the predominant frequencies determined by the FFT analysis. Partial results were presented at the 2011 AFD80 committee annual meeting held in Washington, D.C.

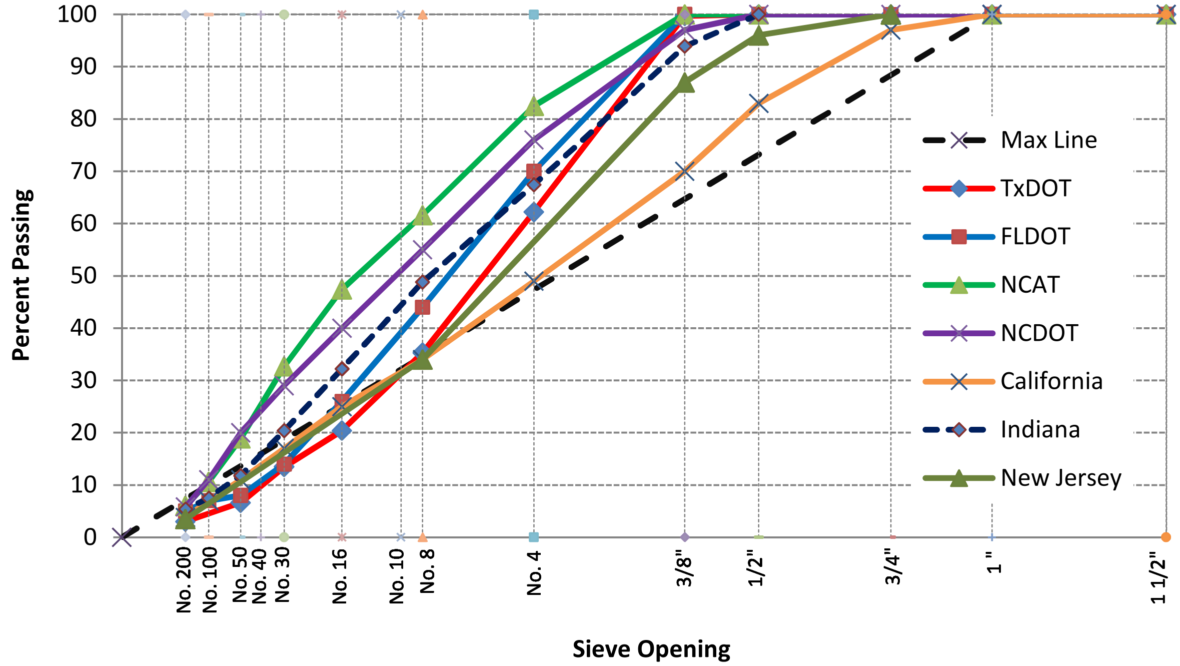


Figure E2c.1. Blend gradations.

Significant Results

The dynamic modulus of the InDOT and Granite (West California) mixes are shown in figures E2c.2 to E2c.3, respectively. Typical AIMS results for FLDOT aggregate source are shown in figures E2c.4 and E2c.5.

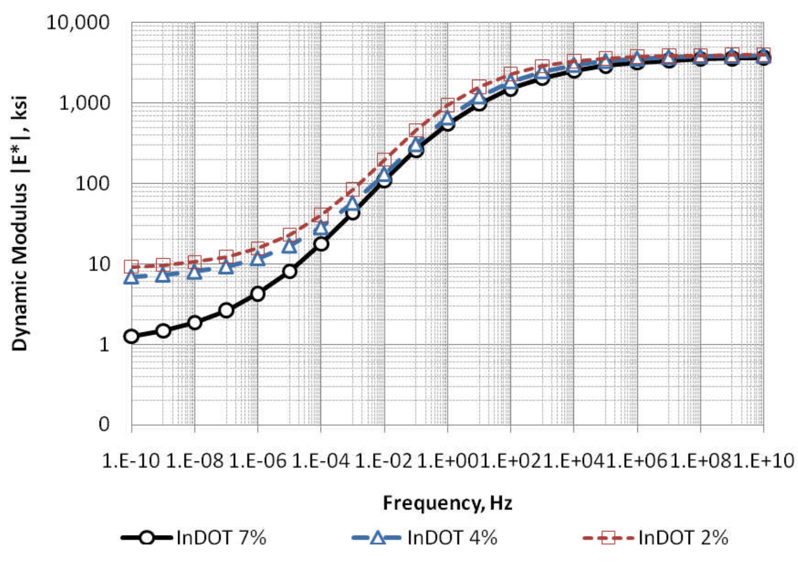


Figure E2c.2. Dynamic modulus at 20°C for InDOT.

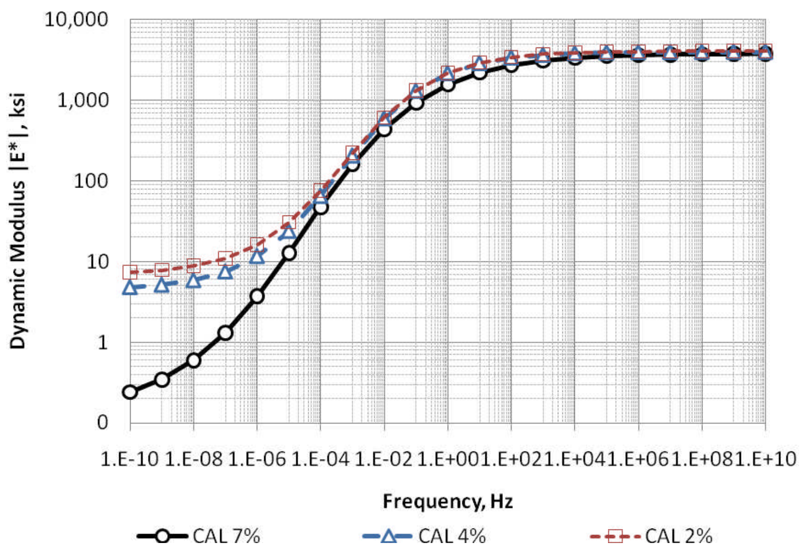


Figure E2c.3. Dynamic modulus at 20°C for Granite (West California).

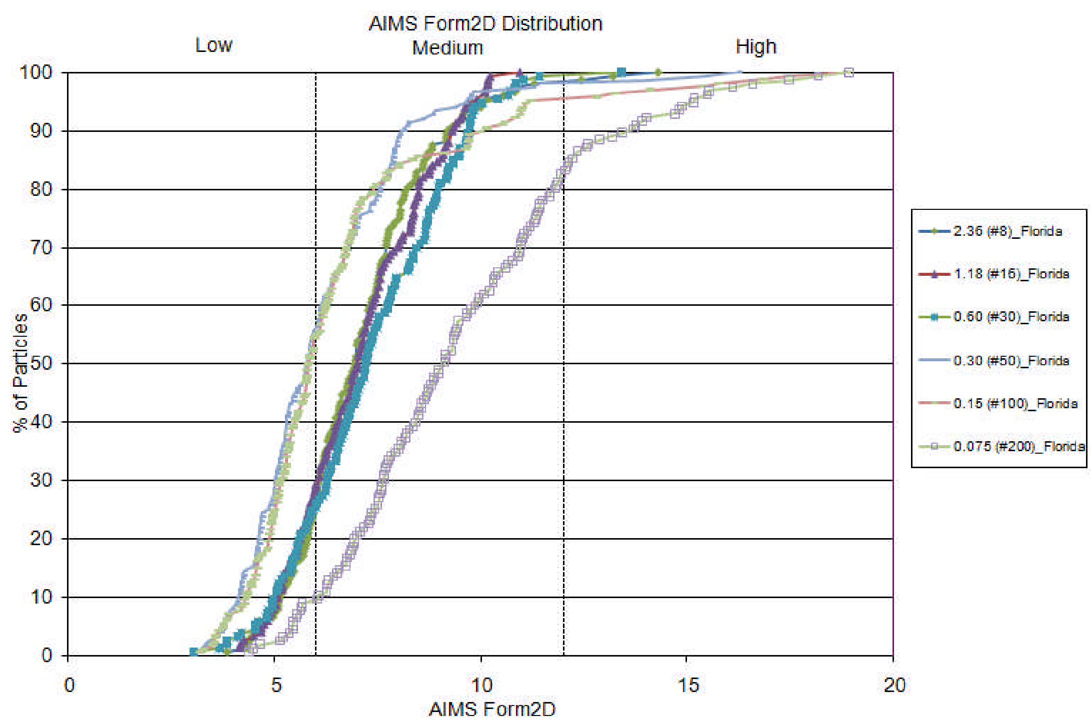


Figure E2c.4. Aggregate form for FLDOT aggregate source.

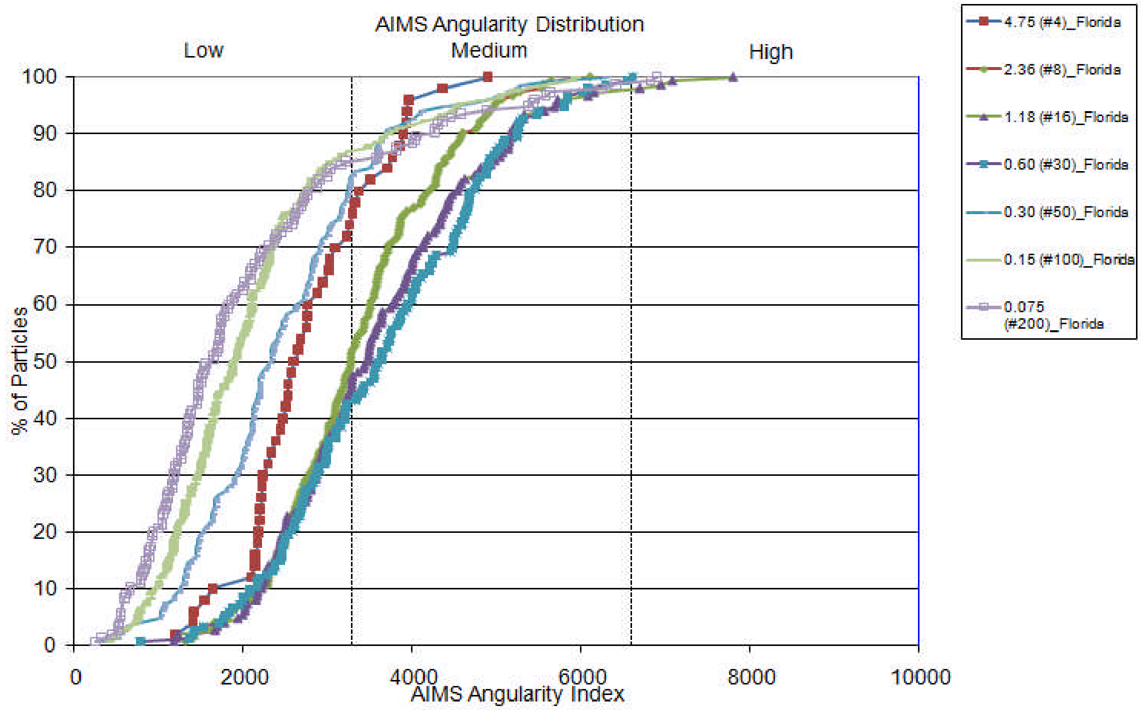


Figure E2c.5. Aggregate angularity for FLDOT aggregate source.

Significant Problems, Issues and Potential Impact on Progress

None

Work Planned for Next Quarter

Continue the evaluation of the various mixtures according to the Flow Number Task Force experimental plan.

Respond to the review comments for the report once received.

Continue the work on the evaluation of the predominant frequencies.

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

Work Done This Quarter

This work element is a joint project between University of Nevada Reno and University of Wisconsin–Madison. Under subtask E2d.1.a, Pavement temperature profiles were further investigated by looking at the five number summary for sections at pavement depths or 12.5 mm and 25 mm. Box plots showing the maximum, minimum, median, and first (Q1) and third quartile (Q3) hourly cooling rates for each section were prepared. Figure E2d.1 shows an example of the five number summary and box plot prepared for hourly cooling rates for sections at a pavement depth of 12.5 mm. This was conducted to investigate all temperature rates and not just maximum hourly cooling and warming rates.

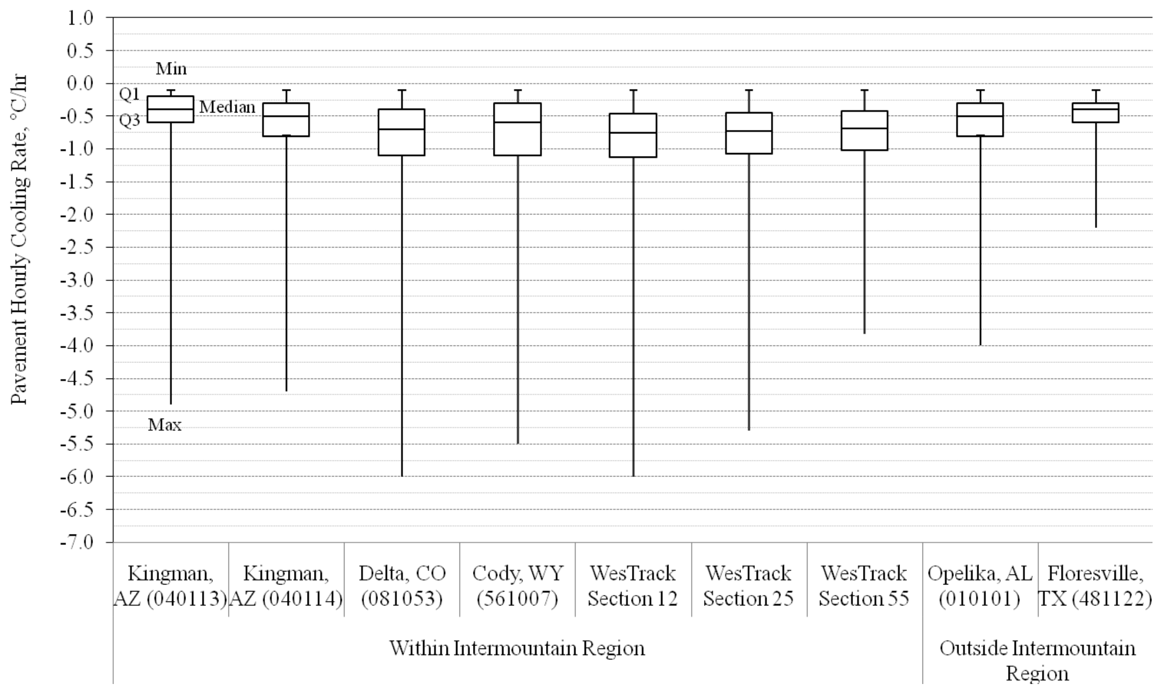


Figure E2d.1. Box plots of all sections at a sensor depth of approximately 12.5 mm using hourly cooling rate data from pavement temperatures of 10°C or colder categorized by region.

The aging of binders under Subtask E2d-3.a has been completed. Most carbonyl measurements have been received from Texas A&M University and hardening susceptibility and reaction kinetics have been prepared for three binders (PG 64-22, PG64-28 polymer modified, and PG64-22+3%SBS).

The TSRST experiment at UNR is ongoing. Particularly, the effect of cooling rate on low-temperature characteristics of cylindrical asphalt mixtures is still under investigation. However, a few refinements of the TSRST test and equipment are currently being investigated which has caused some delay in this research effort. The effect of thermal cycling on the stress build up of asphalt mixtures was also investigated. Tests were designed and performed using the Asphalt Thermal Cracking Analyzer (ATCA). These efforts investigate thermal fatigue as well as the differences in thermal-volumetric response during heating and cooling of asphalt mixtures.

Under subtasks E2d.3.b and E2d.3.c, all of the E*-compression testing and extraction and recovery testing has been completed. Following that process, nearly 60% of the Carbonyl Area (CA) measurements have been completed for this subtask. Further samples are in the process of being tested. Progress continues with the determination of the low shear viscosity (LSV) and binder master curve measurements, with nearly 40% of that testing has been completed from this subtask. The Thermal Stressed Restrained Specimen Test (TSRST) specimens are aged and prepared for testing. A few samples have been tested, as the final testing procedure is being finalized under work element E2d-3.

In this quarter the research team at UW Madison focused their efforts to identify and minimized sources of variability in the Single Edged Notched Beam (SENB) test procedure. The repeatability of the results was significantly improved and an AASHTO draft standard was developed. The following issues were identified as the possible main causes of variability in the SENB:

- Damage to the sample notch during the de-molding process.
- Improper alignment of the loading shaft and the sample notch during loading.
- Variation in load calibration constants from test to test.

Although these factors varied in their relative effect on variability, all were deemed important. The following preventive actions were implemented in the SENB draft AASHTO standard:

- Adding alignment pins to the aluminum mold setup (figure E2d.2) to prevent the movement of the mold end pieces relative to the notch position, which could potentially result in off center or angled notches on the sample beam.
- Recording the load calibration factor generated for every replicate and scaling all the results for a set of replicates to an average consistent calibration factor. This action is deemed a temporary solution. Efforts are being made to modify the test software to correct this issue.
- Specific control of the de-molding process to ensure minimal stress application to notch.
- Refrigeration of samples before de-molding to prevent excessive deformation during handling.

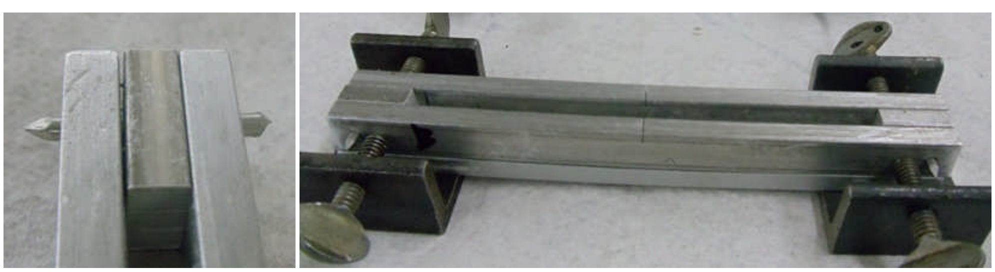


Figure E2d.2. Modified SENB mold system with alignment pins.

Under subtask E2d-4, a numerical procedure was developed to determine the relaxation modulus (E_R) from the stress-build curve as measured by the TSRST test using either closed-form solution or Laplace transformation. Additionally, the master curve of relaxation modulus was determined by considering a sigmoidal function.

Significant Results

Under subtask E2d.1.a, approximately 75% of the hourly cooling rates have a magnitude of less than 1.0°C/hour. Maximum hourly cooling rate values for all sections were greater than 2.2°C/hour. This shows that there is a significant portion of hourly cooling rates that are significantly less than the maximum hourly cooling rates. This further explains the existence of the two hourly cooling rates (an initial high cooling rate followed by a longer period lower cooling rate) during a cooling period.

A significant finding was that when looking at the inter-quartile range (Q3-Q1), the average values for hourly cooling rates were much less than hourly warming rates. At a sensor depth of 12.5 mm, the average inter-quartile range value for hourly cooling rates for sections within the intermountain region and outside the region were 0.6 and 0.4, respectively. On the other hand, at the same sensor depth, the average inter-quartile range value for hourly warming rates for sections within the intermountain region and outside the intermountain region are 2.8 and 2.1, respectively. This implies that hourly warming rates cover a greater range during a warming cycle compared to a cooling cycle.

Significant progress has been made in the E*-Tension testing procedure. The software and hardware upgrades have been installed. The testing protocol has been established and validation testing is taking place prior to the actual experimental matrix samples. Initial results from the E*-Tension testing procedure have been completed with master curves being produced similar to those found in figure E2d.3.

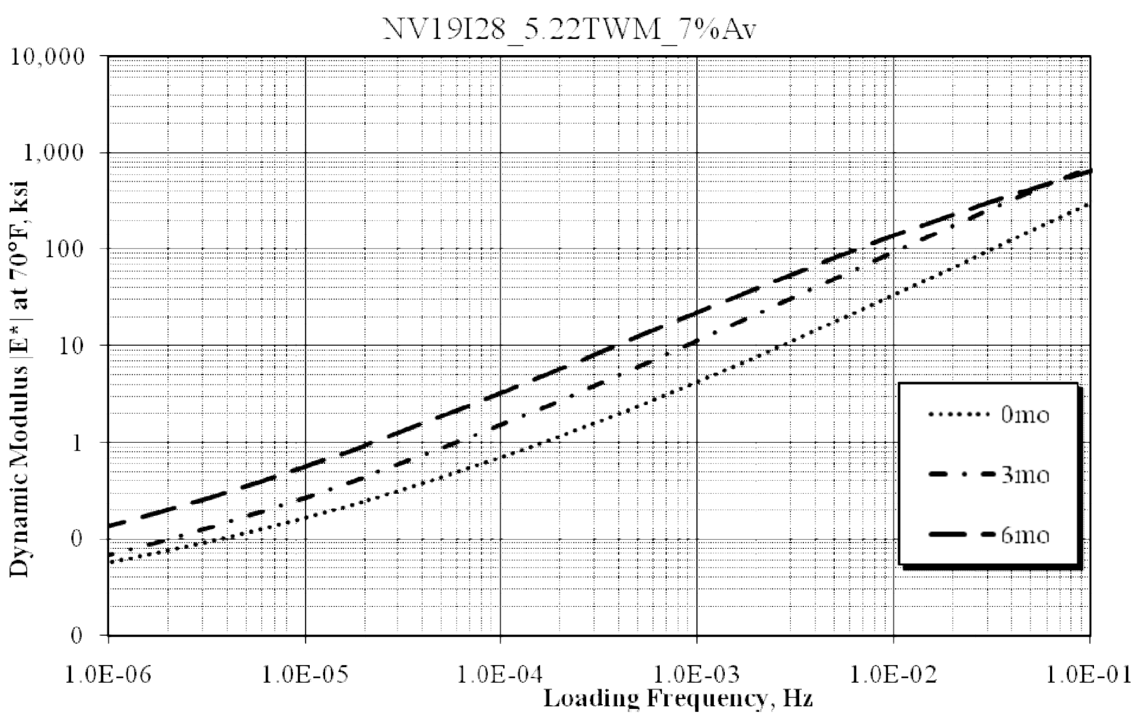


Figure E2d.3. Dynamic modulus tensile creep.

The research team at UNR had a two-day meeting with Dr. Charles Glover from Texas A&M and discussed the temperature and oxidation models and how to incorporate them into the viscoelastic finite element tool (VE2D).

Figure E2d.4 shows an example of SENB replicates after implementing aforementioned improvements to reduce variability. Test results showed the effectiveness of the mold alignment pins in limiting variability in fracture deflection, as well as the effect of the calibration factor correction in minimizing variability in the fracture load. Results of test sets ran after these changes show highly repeatable replicates with COV of fracture load and deformation generally under 10%.

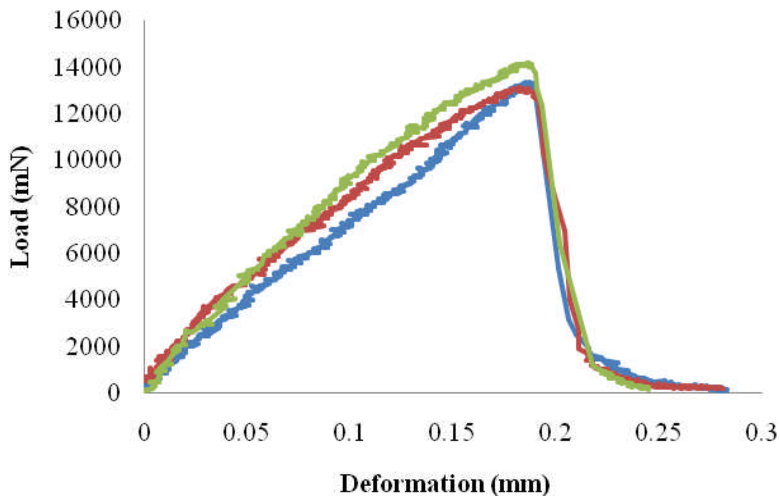


Figure E2d.4. Results of SENB replicates after procedure improvement.

The thermal cycling tests were carried out on mixtures with neat and modified binders from the MnROAD sections. Samples were heated and cooled between 30°C and a lower temperature limit, usually -25°C. The stress and strain curves were measured and compared from cycle to cycle. Figure E2d.5 shows the stress buildup curves for the MnROAD Cell 20 sample. The sample was cycled between 30 and -20°C three times (Cycles #2, 3 and 4), before decreasing the lower limit to -30°C(Cycle #5), and then to -35°C (Cycle #6). The trend in the stress buildup shows a very sudden drop in thermal stress when the sample was cooled toward -25°C in the fourth cycle, while subsequent cycles failed to buildup significant stress. Visual inspection of the sample after cyclic testing showed no visible crack or failure in the sample, thus it was concluded that significant damage had occurred during the first four cycles, leading to an internal structural failure in the sample. The failure cannot be observed visually.

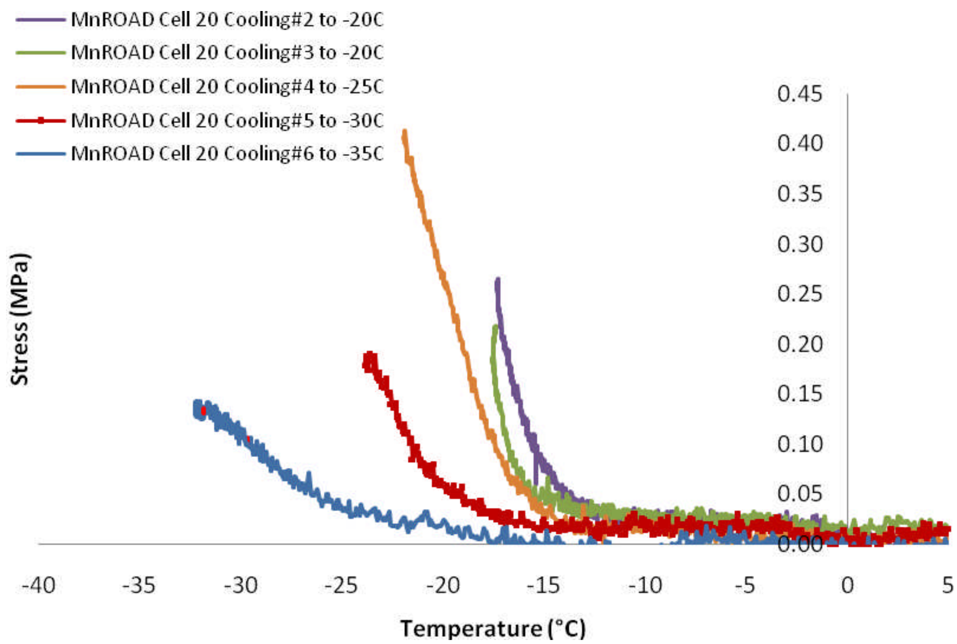


Figure E2d.5. Stress buildup curves under thermal cycling for MnROAD Cell 20.

The thermal strain was also monitored throughout the cyclic tests. The samples tested showed no significant difference between the strain curves from cycle to cycle (figure E2d.6), although heating and cooling curves in each cycle are slightly different as indicated in figure E2d.7. Previous testing has shown that the cooling and heating curves will deviate more significantly when cooling to temperatures well below the glass transition temperatures. In the present tests, in which thermal stress and strain are being measured simultaneously in restrained and unrestrained samples, cycling to such low temperatures was not possible without causing failure in the restrained beam due to excessive thermal stress buildup.

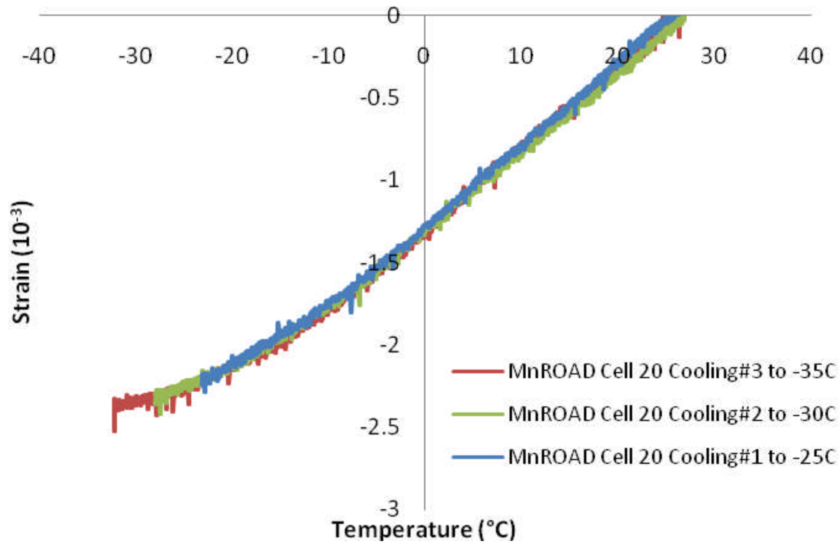


Figure E2d.6. Graph. Thermal strain in MnROAD Cell 20 in the cooling cycles.

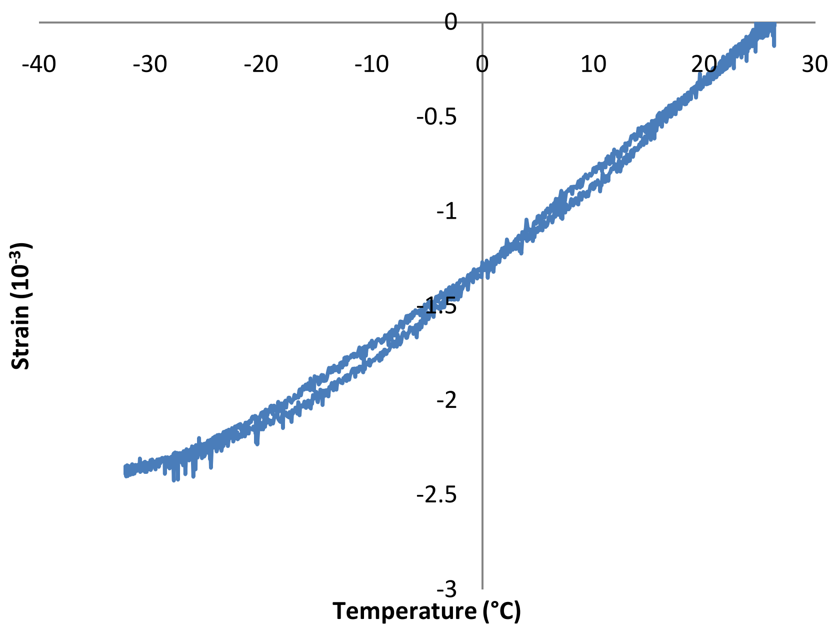


Figure.E2d.7. Thermal strain for MnROAD Cell 20 sample during one cooling and heating cycle.

Significant Problems, Issues and Potential Impact on Progress

Major maintenance activities required on the TSRST equipment has slowed the progress on the development and production testing of those samples.

Work Planned Next Quarter

Continue the experiment to evaluate the aging characteristics (oxidation and hardening kinetics) of asphalt binders when aged in forced convection (horizontal airflow) ovens.

Continue to evaluate the effect of cooling rate on TSRST results using the proposed cylindrical test geometry.

The AASHTO draft standards on the measurement of the binder glass transition temperature, as well as the use of the Asphalt Thermal Cracking Analyzer (ATCA) to measure mixture glass transition will be completed. Tests will also continue on the effect of thermal cycling on thermal stress buildup and volumetric properties of mixtures.

In the coming quarter focus will shift from testing toward critical analysis of the data gathered during previous quarters. The team will focus their efforts in summarizing findings of this work element in a consolidated report following 508 format requirements.

Under subtasks E2d.3.b and E2d.3.c, the main focus early in the next quarter will be to continue to increase the amount of completed testing and begin the analysis of the results. With all of the extraction/recovery testing completed, significant progress in the measurements of carbonyl, low shear viscosity, and binder master curves to be completed under this subtask. With the final validation for E*-tension protocol finalized, significant progress on the production testing should follow. The development of the binder master curves and LSV measurements are expected to proceed with little difficulty just as in the previous quarter. Arrangements have been made to obtain a second DSR for this subtask specifically, so the rate of completion for the binder tests is expected to nearly double. Testing on the TSRST samples are also expected to get underway as the exact testing conditions are determined.

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

Work Done This Quarter

Hirsch Model Refinements

Laboratory work continued this quarter on the experiments to refine the Hirsch model. Three experiments were planned to improve the Hirsch model: (1) curing time experiment, (2) limiting modulus experiment, (3) stress dependency experiment. Each of these experiments addresses a specific aspect of the Hirsch model and dynamic modulus testing. The curing time experiment addresses whether specimen aging significantly affects measured dynamic modulus values. The limiting modulus experiment address whether the limiting minimum modulus is a HMA is significantly affected by the modulus of the aggregate used in the mixture. Finally, the stress dependency experiment address the effect of stress level on the limiting minimum modulus of HMA.

The soft limestone from Florida was procured from the National Institute of Standards and Technology (NIST). NIST is using this aggregate in a flow number experiment that is being conducted for the Mixtures and Construction Expert Task Group. Specimen fabrication and testing is approximately 50 percent complete.

Resistivity Model Refinements

The objective of this work is to refine the rutting model developed in NCHRP Projects 9-25 and 9-31 to better address modified binders by using data from the multiple stress creep recovery tests to characterize the binders. A final experimental design for the resistivity model refinements was developed based on the aggregates selected for the Hirsch model refinement. It includes nine binders with high temperature grade ranging from PG 58 to PG 82. Five of the binders are polymer modified, one is air blown, and three are neat. Eighteen mixtures will be tested. A total of 34 binder/mixture/temperature combinations will be used in the testing.

Binder characterization for all of the binder except the polymer modified PG 82-22 was completed last quarter. No additional work was completed on this experiment this quarter.

Fatigue Model Refinements

Further work on continuum damage fatigue modeling was performed this quarter. During the past quarter two draft papers were completed on fatigue analysis:

"Modeling Fatigue Damage Functions for Hot Mix Asphalt," by Donald W. Christensen, Jr. and Ramon F. Bonaquist (and potentially additional authors from the FHWA).

Abstract: The purpose of this paper is to present a series of equations for predicting the fatigue damage functions for hot-mix asphalt (HMA) mixes from modulus values, shift factor values and the relationship between modulus and phase angle. These equations have been developed using data gathered during uniaxial fatigue testing on a wide range of HMA mixes. Although the equations are empirical in nature, they have been developed within the context of continuum damage theory and represent a significant improvement in accuracy and robustness compared to similar existing equations. The equations have significant utility in the fatigue testing of HMA mixes and in pavement design and analysis.

"Analysis of FHWA ALF Fatigue Data Using a Continuum Damage Approach," by Donald W. Christensen, Jr. and Ramon Bonaquist.

Abstract: The purpose of this paper is to present an analysis of the Federal Highway Administration's ALF 1 and ALF 2 fatigue experiments. The approach used involved application of continuum damage principles and layered elastic analysis to calculate reduced loading cycles and damage ratios at the observed point of initial surface cracking. These data were then used in combination with HMA pavement properties to develop statistical equations for predicting loading cycles to initial surface cracking. The approach discussed is potentially useful for improving current HMA design methods, and for the design and analysis of low volume roads where more rigorous testing and analysis may not be appropriate. Another advantage of the proposed method is that it can be used in the analysis of existing data on the fatigue behavior of HMA pavements. Additional research is needed to expand the data set used in this analysis before it can be used for design purposes.

These papers will be submitted to the Association of Asphalt Paving Technologists (AAPT) for potential publication in 2012.

Work was begun to compare fatigue predictions made using the method in the first paper with fatigue damage functions measured at the FHWA, with the intention of including this work to the paper and adding one or authors from the FHWA. Basic sensitivity analyses were performed using the top-down fatigue cracking equation developed in the second paper, although the equation is quite simple and the analysis straightforward.

<u>Work Planned Next Quarter</u>

Laboratory work will proceed for the Hirsch model, resistivity model, and continuum damage fatigue model refinements. Analysis of the data from these experiments will proceed concurrently with the laboratory testing.

Work will continue analyzing FHWA fatigue data and comparing the results with those of the predictive equations. If appropriate, FHWA fatigue data will be included in the paper on fatigue damage functions and co-authors added to reflect the added content. Both papers described above will be reviewed, edited and submitted for publication.

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

The laboratory experiments in this Work Element are behind schedule. Materials have been procured and laboratory work proceeding. These experiments will be completed during 2011.

TABLE OF DECISION POINTS AND DELIVERABLES FOR ENGINEERED MATERIALS

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
E1a- Model and Algorithm (TAMU)	Model and Algorithm	The model and algorithm for testing and analysis of damaged asphalt mixtures in tension		09/01/11	
E1a- Continuum Damage Permanent Deformation Analysis for Asphalt Mixtures (TAMU)	Final Report	Ph.D. dissertation at TAMU that describes the viscoplastic mechanism for permanent deformation of the asphalt mixtures and provides the testing protocols and analysis methods to acquire the input parameters of the PANDA program.	12/31/2010	12/31/2011	Time is needed to make the product compatible with the PANDA program
E1a- Develop a RDT DMA Testing Protocol (TAMU)	Technology Transfer	This new testing protocol is stress controlled repeated tension testing method and will be used to replace the previous torsional DMA testing method	08/15/2010	02/15/2011	New DMA Machine Arrive Late
E1a- Standardize Testing Procedure for Specifications (TAMU)	AASHTO Specification	Develop a Standard Specification to use as a comparative test to evaluate fracture properties, healing and moisture damage of FAM	4/30/11	09/30/2011	Expanded scope
E1a- Develop a New DMA Testing Protocol for Compression (TAMU)	AASHTO Specification	Develop a Standardized testing method to use as a comparative test to evaluate compressive properties of FAM		09/15/2011	
E1b1-5: Standard Testing Procedure and Recommendation for Specifications (UWM)	Draft Report	Report on final conclusions and proposed procedures and specifications	7/11	10/11	Draft report will be consolidated with other E1b subtasks.
	Final Report		1/12	4/12	Final report submission date moved back to allow at least 6 months between draft and final report submission.
E1b-2i. Literature review (UWM)	Draft Report	Review of previous work on indentation and closed formed solution to the indentation problem.	7/09	Complete	N/A
E1b-2iii. Preliminary testing and correlation of results (UWM)	Draft Report	The use of indentation test for characterization of asphalt binders.	1/10	Complete	N/A

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
E1b-2iv. Feasibility of using indentation tests for fracture and rheological properties (UWM)	Draft Report	Report on Finite element simulations of the indentation test and correlations with DSR results.	1/11	10/11	Postponed due to significant delays in receiving the modified test setup from the machine shop.
	Final Report		4/11	4/12	
E1c-1ii. Effects of Warm Mix Additives on Mixture Workability and Stability (UWM)	Draft Report	Report of reviewed relevant literature and studies (to be combined with final report)	10/08	Complete	N/A
	Final Report		1/09		N/A
	Draft Report	Impacts of WMA Additives on Asphalt Binder Performance and Mixture Workability	4/11	10/11	Delay in standardizing of testing procedures
	Final Report		1/12	4/12	Final report submission date moved back to allow at least 6 months between draft and final report submission
E1c-1v. Field Evaluation of Mix Design Procedures and Performance Recommendations (UWM)	Draft Report	Report on WMA Field Evaluation of Mix Design Procedures and Performance	10/11	N/A	Conditional upon DOT collaboration
	Final Report		1/12	4/12	Final report submission date moved back to allow at least 6 months between draft and final report submission.
E1c-2: Improvement of Emulsions' Characterization and Mixture Design for Cold Bitumen Applications (UWM)	Practice	Mix design method for cold-in-place recycling (CIR) that is consistent with the Superpave technology and that can be used to define the optimum combination of moisture content and emulsion content.	12/11	N/A	N/A
	Practice	Mix design method for cold mix asphalt (CMA) that is consistent with the Superpave technology and that can be used to define the optimum combination of moisture content and emulsion content.	03/12	N/A	N/A

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
E1c-2i: Review of Literature and Standards (UWM)	Draft Report	Review of Literature and Standards that will be combined with the final draft reports (to be combined with E1c-2vii and E1c-2ix final reports)	7/08	Complete	N/A
	Final Report		10/08		
	Draft Report		4/09		
	Draft Report		7/09		
	Draft Report		1/10		
E1c-2iii: Identify Tests and Develop Experimental Plan (UWM)	Draft Report	Reports outlining the required tests and experimental plan for the study (to be combined with E1c-2vii and E1c-2ix final reports)	4/09	Complete	N/A
	Draft Report		10/09		N/A
E1c-2v. Conduct Testing Plan (UWM)	Draft Report	Report on the results and analysis of tests run in accordance to test plan (to be combined with E1c-2vii and E1c-2ix final reports)	10/09	Complete	N/A
E1c-2vii. Validate Guidelines (UWM)	Draft Report	Draft report of the performance and Rheological and Bond Properties of Emulsions (to be combined with E1c-2vii final report)	7/09	9/11	Data compilation and testing is complete. Analysis and interpretation continues.
	Final Report	Final report of the performance and Rheological and Bond Properties of Emulsions	4/11	4/12	Final report submission date moved back to allow at least 6 months between draft and final report submission.
E1c-2ix. Develop CMA Performance Guidelines (UWM)	Draft Report	Draft and final report of the performance guidelines of Cold Mix asphalt pavements	10/11	N/A	N/A
	Final Report		1/12	4/12	Final report submission date moved back to allow at least 6 months between draft and final report submission.

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
E2a-4: Write asphalt modification guideline/report on modifier impact over binder properties (UWM)	Draft Report	Report summarizing effect of modification on low, intermediate, and high temperature performance of asphalt binders. It includes guidelines for modification and cost index for different modification types	10/11	N/A	N/A
	Final Report	Report in 508 format that addresses comments/concerns from Draft Report	1/12	4/12	Final report submission date moved back to allow at least 6 months between draft and final report submission.
E2b-1: Develop a System to Evaluate the Properties of RAP Materials (UNR with UWM input)	Draft Report	Report on Test Method to Quantify the Effect of RAP and RAS on Blended Binder Properties without Binder Extraction (To be combined with E2b1-b draft and final reports) (UWM input)	4/09	Complete	N/A
	Final Report		4/09		N/A
	Practice	Recommend the most effective methods for extracting RAP aggregates based on their impact on the various properties of the RAP aggregates and the volumetric calculations for the Superpave mix design.	12/10	Complete	Additional testing and verifications were required for some of the reported data
	Draft report	Report on the developed testing and analysis procedure system to estimate the RAP binder properties from binder and mortar testing including fracture results.	10/11	N/A	N/A
	Final report		04/12	N/A	N/A
E2b-1.b: Develop a System to Evaluate the Properties of the RAP Binder (UWM)	Draft Report	Report on the developed testing and analysis procedure system to estimate the RAP binder properties from binder and mortar testing including fracture results.	10/11	N/A	N/A
	Final Report		1/12	4/12	Final report submission date moved back to allow at least 6 months between draft and final report submission.
E2b-3: Develop a Mix Design Procedure (UNR)	Draft report	Report summarizing the laboratory mixing experiment.	02/12	N/A	N/A
	Final report		08/12	N/A	N/A

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
E2b-4: Impact of RAP Materials on Performance of Mixtures And E2b-5: Field Trials (UNR)	Draft report	Report summarizing the laboratory and field performance of field mixtures.	02/12	N/A	N/A
	Final report		08/12	N/A	N/A
E2c-2: Conduct Mixtures Evaluations (UNR)	Draft report	Approach to identify critical conditions of HMA mixtures	09/11	N/A	N/A
	Final report		03/12	N/A	N/A
E2c-3: Develop a Simple Test (UNR)	Draft report	Report summarizing the evaluation of mixtures from the Flow Number Task Force group.	11/11	N/A	N/A
	Final report		05/12	N/A	N/A
E2c-4: Develop Standard Test Procedure (UNR)	Practice	Recommended practice to identify the critical condition of an HMA mix at the mix design stage to avoid accelerated rutting failures of HMA pavements.	12/11	N/A	N/A
E2c-5: Evaluate the Impact of Mix Characteristics (UNR)	Draft report	Report summarizing the impact of mixture characteristics on the critical condition of the HMA mixes	02/12	N/A	N/A
	Final report		08/12	N/A	N/A
E2d-2: Identify the Causes of the Thermal Cracking (UNR)	Draft report	Report summarizes the testing and findings for materials from LTPP sections.	12/11	N/A	N/A
	Final report		06/12	N/A	N/A
E2d-3: Identify an Evaluation and Testing System (UNR with UWM input)	Draft report	Low Temperature Cracking Characterization of Asphalt Binders by Means of the Single-Edge Notch Bending (SENB) Test (UWM input)	04/11	10/11	Working with partners at UNR to consolidate one report on low temperature cracking
	Final report		10/11	4/12	Final report submission date moved back to allow at least 6 months between draft and final report submission.

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
E2d-4: Modeling and validation of the Developed System (UNR with UWM input)	Draft report	Thermal cracking characterization of mixtures by means of the unified Tg-TSRST device. (UWM input)	10/11	N/A	N/A
	Final report		04/12	4/12	Final report submission date moved back to allow at least 6 months between draft and final report submission.
	Model	Model that can effectively simulate the long-term properties of HMA mixtures in the intermountain region and assess the impact of such properties on the resistance of HMA mixtures to thermal cracking.	03/12	N/A	N/A
E2d-5: Develop a Standard (UNR with UWM input)	Draft standard	Draft standards for the use of the SENB, binder Tg and the Tg-TSRST device. (UWM input)	10/11	N/A	N/A
	Final standard		01/12	4/12	Final report submission date moved back to allow at least 6 months between draft and final report submission.
	Draft standard	Draft standard for the use of the TSRST with cylindrical specimens compacted using the SGC.	03/11	09/11	Delayed due to issues with specimens breaking at the edge.
	Final standard		01/12	N/A	N/A

Engineered Materials Year 5

	Year 5 (4/2011-3/2012)												Team
	4	5	6	7	8	9	10	11	12	1	2	3	
(1) High Performance Asphalt Materials													
E1a: Analytical and Micro-mechanics Models for Mechanical behavior of mixtures													TAMU
E1a-1: Analytical Micromechanical Models of Binder Properties						JP			D,JP			F	
E1a-2: Analytical Micromechanical Models of Modified Mastic Systems						JP			D		SW, M&A	F	
E1a-3: Analytical Models of Mechanical Properties of Asphalt Mixtures			P(2)			JP			D,JP		SW, M&A	F	
E1a-4: Analytical Model of Asphalt Mixture Response and Damage									D		SW, M&A	F	
E1b: Binder Damage Resistance Characterization													UWM
E1b-1: Rutting of Asphalt Binders													
E1b-1-1: Literature review													
E1b1-2: Select Materials & Develop Work Plan													
E1b1-3: Conduct Testing													
E1b1-4: Analysis & Interpretation			JP										
E1b1-5: Standard Testing Procedure and Recommendation for Specifications	P			D		JP				F			
E1b-2: Feasibility of determining rheological and fracture properties of asphalt binders and mastics using simple indentation tests (modified title)													UWM
E1b-2i. Literature Review													
E1b-2ii. Proposed SuperPave testing modifications													
E1b-2iii. Preliminary testing and correlation of results	JP												
E1b-2iv. Feasibility of using indentation tests for fracture and rheological properties							D			F			
E2a: Comparison of Modification Techniques													UWM
E2a-1: Identify modification targets and material suppliers													
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							D			F			
E2c: Critically Designed HMA Mixtures													UNR
E2c-1: Identify the Critical Conditions													
E2c-2: Conduct Mixtures Evaluations						D,F							
E2c-3: Develop a Simple Test					JP			D	F				
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													UNR/UWM
E2d-1: Identify Field Sections													
E2d-2: Identify the Causes of the Thermal Cracking									D	P		F	
E2d-3: Identify an Evaluation and Testing System	D			JP			F			P			
E2d-4: Modeling and Validation of the Developed System				JP			D			F, P			
E2d-5: Develop a Standard				JP			D			F, P			
E2e: Design Guidance for Fatigue and Rut Resistance Mixtures													AAT
E2e-1: Identify Model Improvements													
E2e-2: Design and Execute Laboratory Testing Program						JP							
E2e-3: Perform Engineering and Statistical Analysis to Refine Models													
E2e-4: Validate Refined Models													
E2e-5: Prepare Design Guidance									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			D, P			F			
E2b-2: Compatibility of RAP and Virgin Binders		P											WRI
E2b-3: Develop a Mix Design Procedure							JP, P				D	F	
E2b-4: Impact of RAP Materials on Performance of Mixtures											D	F	
E2b-5: Field Trials											D	F	
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				D							F		
E1c-1iii. Mixture Performance Testing													
E1c-1iv. Develop Revised Mix Design Procedures													
E1c-1v. Field Evaluation of Mix Design Procedures and Performance Recommendations							D			F			
E1c-2: Improvement of Emulsions' Characterization and Mixture Design for Cold Bitumen Applications													UWM/UNR
E1c-2i: Review of Literature and Standards													
E1c-2ii: Creation of Advisory Group													
E1c-2iii: Identify Tests and Develop Experimental Plan													
E1c-2iv. Develop Material Library and Collect Materials.													
E1c-2-v. Conduct Testing Plan													
E1c-2-vi. Develop Performance Selection Guidelines			D							F			
E1c-2-vii. Validate Performance Guidelines													
E1c-2-viii. Develop CMA Mix Design Guidelines													
E1c-2ix. Develop CMA Performance Guidelines					JP		D			F			

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

Work planned
Work completed
Parallel topic

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

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

Work planned
Work completed
Parallel topic
Delayed

PROGRAM AREA: VEHICLE-PAVEMENT INTERACTION

CATEGORY VP1: WORKSHOP

Work element VP1a: Workshop on Super-Single Tires (UNR)

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

This quarter, researchers focused on conducting field evaluations and developing laboratory methods to evaluate and predict frictional properties of asphalt mixes. Five test methods to investigate 18 field sites in the Madison and Milwaukee areas in the State of Wisconsin were utilized. Field sites varied in terms of aggregate characteristics, binder characteristics, design level, and age. Field test methods used in the investigation included the stationary laser profilometer (SLP), dynamic friction tester (DFT), circular track meter (CTM), British pendulum tester (BPT), and the sand patch (SP) test. For most of the field sites, researchers obtained mix design information from contractors. This information will be incorporated into statistical models that allow for the prediction of texture properties based on materials and mix design information. While results from the field and laboratory evaluations are still preliminary, the research team is optimistic that these results will lead to the achievement of the work element objectives.

Significant Results

The focus of analysis was comparison of response variables from the different field evaluations. The first comparison considered the micro-texture as measured by the BPT and DFT. Previous research indicated that the BPT results correspond to friction properties at the speed of approximately 10 km/hr, which can be compared to the DFT friction coefficient at the same speed (NCHRP, 2000). The data displayed a positive, linear relationship between the British pendulum number (BPN) and the friction coefficient, suggesting that the BPT may adequately capture micro-texture compared to the more complicated and expensive DFT. Researchers also considered SLP data for texture wavelengths corresponding to the micro-texture range. A good correlation was observed between the LTX 2-4 texture parameter and BPN. With further evaluation and verification, the SLP may adequately capture micro-texture. Such a finding would justify the use of the SLP as a single device that is capable of capturing both micro-texture and macro-texture within a laboratory setting.

Research this quarter also investigated relationships between devices in terms of macro-texture. Using texture spectral analysis techniques, researchers found good relationships between texture levels as measured by the SLP and other macro-texture evaluation techniques. The LTX A-B texture parameter, which refers to the texture distribution between center wavelengths of "A" and "B", was investigated for correlation with mean texture depth as measured by the SP method and with the speed constant S_p as determined by the CTM. The research team will investigate several relevant texture parameters arising from the texture spectral analysis including LTX 4-32, LTX 4-64, LTX 4-128, LTX 8-32, LTX 8-64, and LTX 8-128 parameters. Subsequent research will identify one of these parameters as the most correlated macro-texture indicator. When combined with the micro-texture indicator, the combination of these two indicators shall provide a means to estimate the International Friction Index (IFI) parameter in a laboratory environment and serve as the basis for developing friction guidelines for HMA mix designs.

Significant Problems, Issues and Potential Impact on Progress

Researchers realized that the integrity of lab samples and field cores collected from a past Wisconsin Highway Research Program (WHRP) project had been compromised due to inadequate storage methods. The distortion of the lab samples and field cores became evident when field sections and freshly-prepared laboratory samples exhibited significantly higher texture levels compared to the lab samples and field cores. This issue will be overcome in the next quarter as the team acquires loose mix samples from area contractors, compacts these samples in the laboratory, and analyzes these samples using the proposed test methods.

Work Planned Next Quarter

The team plans the following activities for the next quarter:

- Obtaining loose mix samples from area contractors that will be compacted using a Superpave gyratory compactor (SGC) under controlled conditions. Corresponding field measurements will be taken on the constructed pavements.
- Drafting a paper for publication in the Transportation Research Record and presentation at the Transportation Research Board annual meeting that highlights significant research findings to date for the VP2a work element.
- Drafting a final report for the VP2a work element.

Cited References

National Cooperative Highway Research Program, 2000, "Evaluation of Pavement Friction Characteristics: A Synthesis of Highway Practice." *Report 291*, Transportation Research Board, Washington, D.C.

CATEGORY VP3: MODELING

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

Work Done This Quarter

Continued the work on the *3D-Move Analysis* software to add new features. A subroutine for performance analysis was integrated into the 3D-Move version 2.0 software and is currently being evaluated internally for bugs and errors. The locations (or response points) where the pavement responses are to be evaluated for performance analysis have been implemented into the 3D-Move program.

Assisted user's with issues ranging from usage questions, concepts clarifications, and bugs. The 3D-Move Analysis software developing team worked on fixing the reported bugs.

Significant Results

One of the important inputs to the 3D-Move program is the location (or response points) where the pavement responses are to be evaluated. In the 3D-Move Analysis, response points can be defined in two ways for both static and dynamic case. They are:

- Individual Response Points
- Response Data Array(Grid Format)

Figure VP3a.1 shows the input window for Individual Response Points for static case. As shown in the figure VP3a.1, "graphical display" is introduced to show the pavement structure with all response points defined using Individual Response Points and Response Data Array. Major changes to the existing 3D-Move (Version 1.2) relative to the specification of Individual Response Points and Response Data Array and importance of graphical display are discussed below.

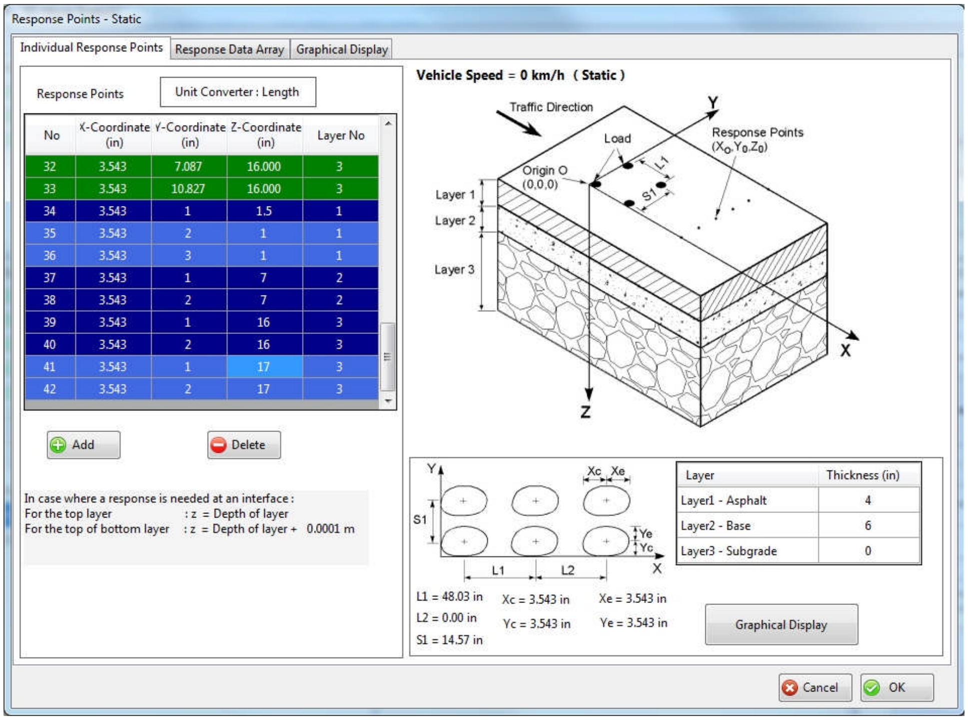


Figure VP3a.1. Input window for Individual Response Points if static and performance analysis is selected.

Individual Response Points

In this case, user needs to specify the coordinates (x, y and z) of the responses points. Figure VP3a.1 shows the input window for Individual Response points for static case. Once user enters a z-value for a response point, program will display the layer number that corresponds to the specified response point. Response points can be added by clicking Add button and removed by clicking Delete button. In the right bottom of window, axle configuration is displayed for the previously selected Axle Configuration and Contact Stress Distribution option. The figure shows the input window for the Individual Response Points and they are color coded. Some response points are automatically generated for performance analysis by the program and they are displayed in green and those points cannot be deleted by the user. If z-values of response points which are added by user are matched with z-value of performance points automatically generated by program, those added response points will be considered for performance analysis and filled by dark blue color. Other points filled by light blue color will not be considered for performance analysis. This colored display scheme will help user to differentiate the automatically generated points and the added response points. Though some points will not be considered for performance analysis, output will be generated for all the points.

Response Data Array (Grid Format)

This is another way to define points at which the responses are to be computed. In this case, a rectangular grid points which are formed by a set of lines horizontal and vertical lines are the response points. User can define any number of arrays (rectangular grid). Additional arrays can be added by clicking the Add button shown in the left side of the window and corresponding spacings for each array have to be provided in the right side of the window. There is no limitation on the number of array.

Graphical display

Pavement structure plot is included in this revised version to make the display the response points graphically. This is a 2D plot and is drawn to scale. Figure VP3a.2 shows a pavement structure plot with some response points. The pavement structure plot is composed of pavement layer, load diagram and response points. Either X-Z or Y-Z plane can be selected for display. The layers are labeled on the right side of plot to identify the layer number and layer type. In addition, layer depth is also shown for each of the pavement layer.

To enhance the features of the graphical display, three selection options are included in the plot. They are:

1. Selection of Points;
2. Selection of Plane (X-Z or Y-Z plane);
3. Selection of Depth or Layers.

On top of the pavement, loads are shown and are drawn to scale. To draw the load diagram, loaded area length or width is considered and selection of length or width of the loaded area depends on the plane selected for the graphical display (middle right of window). This load diagram will assist user to identify the location of the points by comparing with the location of the loading.

Figure VP3a.2 shows the pavement structure plot for X-Z plane at x=3.543”. The Individual Response Points automatically generated by program and added by the user are shown in the figure. These points are displayed in different color so that user can easily distinguish between the points that were automatically generated and those added by the user. Figure VP3a.3 shows the array points (light green) if the “Response Data Array” option is selected. If “Response Points – Both” is selected, program will show all the points on that plane with different color scheme. Furthermore the size of the plot can be enlarged or reduced by selecting the options provided at the bottom right corner.

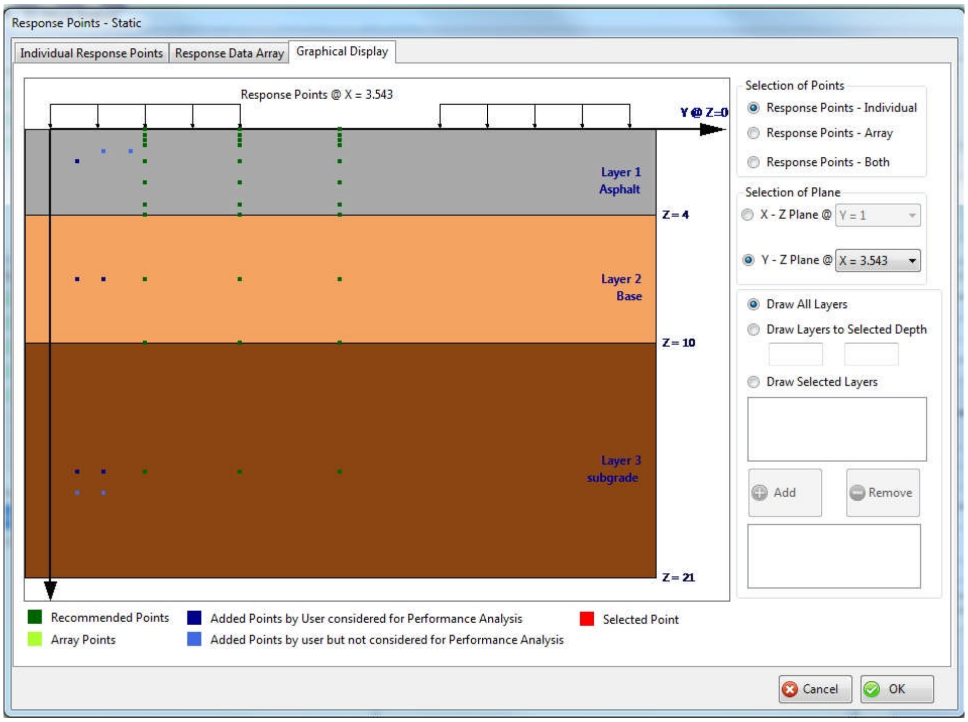


Figure VP3a.2. Graphical display for Individual Response Points on Y-Z plane.

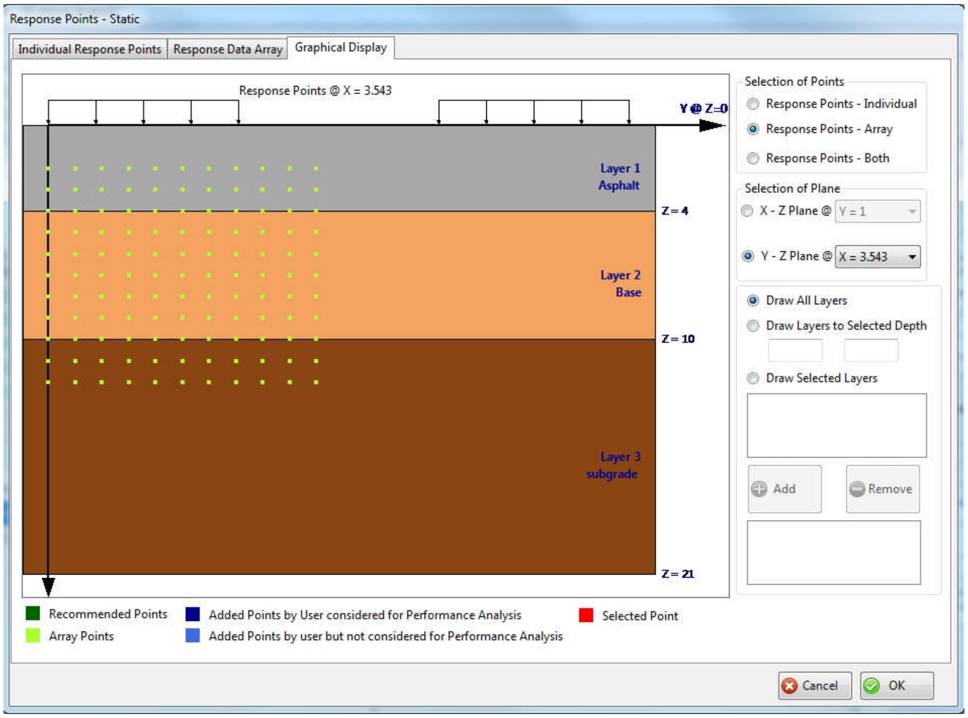


Figure VP3a.3. Graphical display for Array Points on Y-Z plane.

Performance Models

Traffic window has been modified as shown in figure VP3a.4 to include seasonal variation of loading repetitions. This traffic window allows for evaluation of the design number of load repetitions for each season, and then it is added to get total counts of load repetitions over the design period.

The pavement distresses output summary window was reformatted (figure VP3a.5) to include a top window that displays the distress summary of individual layers and a bottom window that displays the distress summary of the pavement structure.

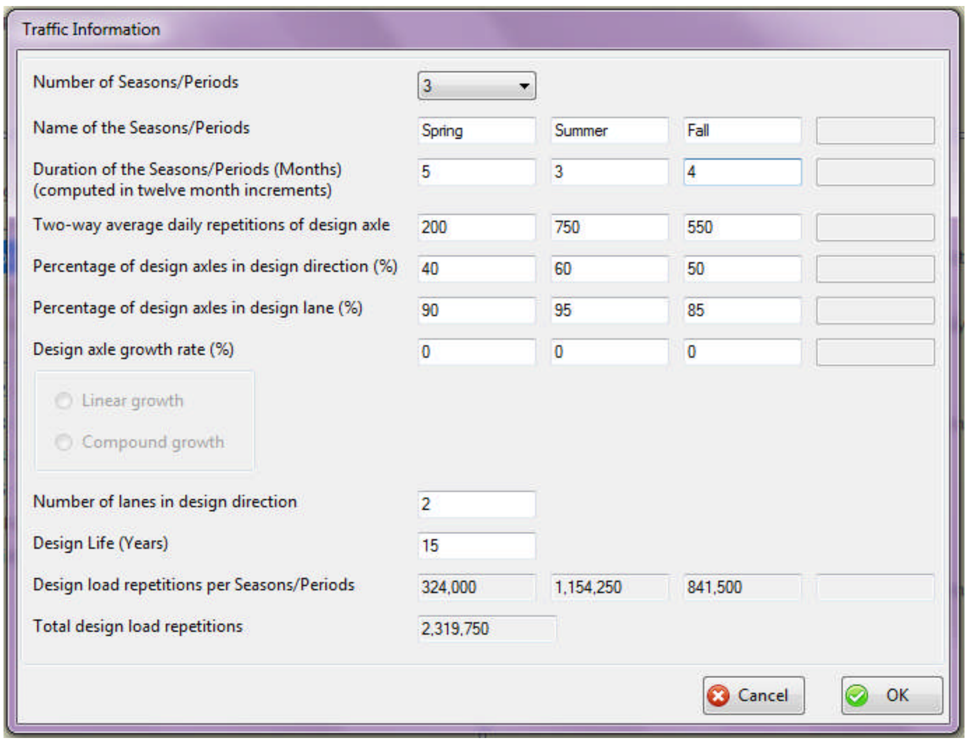
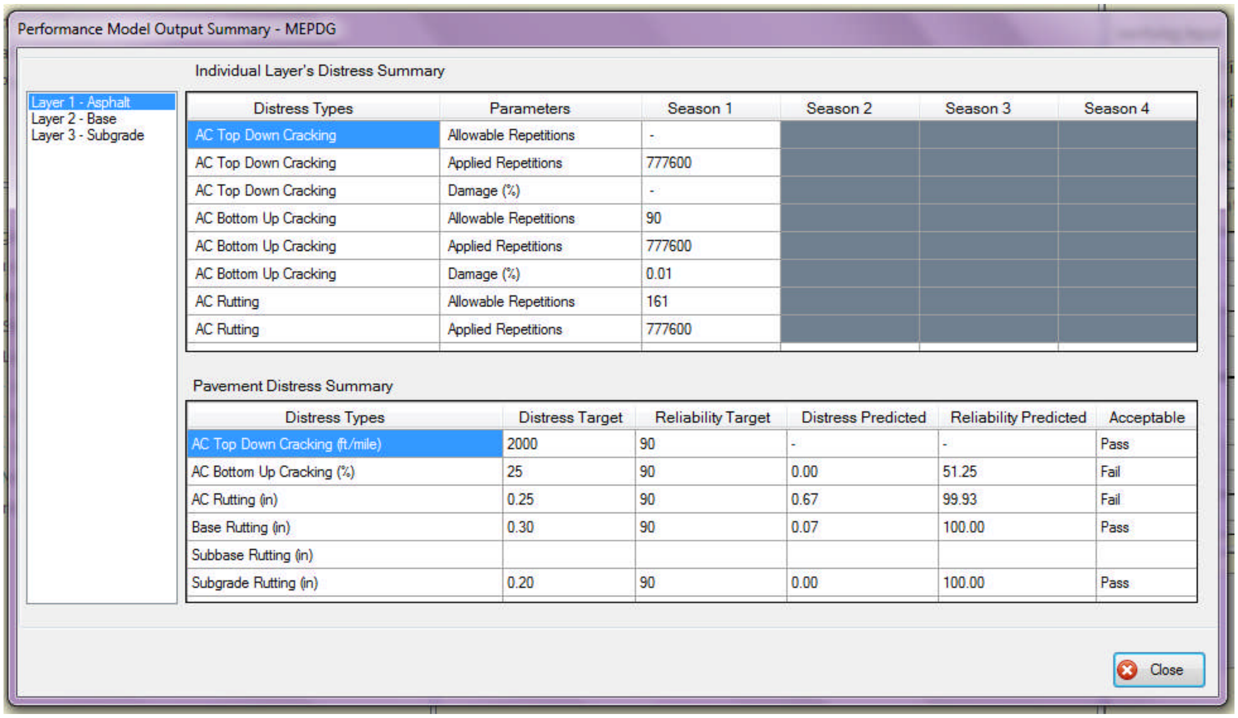


Figure VP3a.4. Traffic input window.



Performance Model Output Summary - MEPDG

Layer 1 - Asphalt
Layer 2 - Base
Layer 3 - Subgrade

Individual Layer's Distress Summary

Distress Types	Parameters	Season 1	Season 2	Season 3	Season 4
AC Top Down Cracking	Allowable Repetitions	-			
AC Top Down Cracking	Applied Repetitions	777600			
AC Top Down Cracking	Damage (%)	-			
AC Bottom Up Cracking	Allowable Repetitions	90			
AC Bottom Up Cracking	Applied Repetitions	777600			
AC Bottom Up Cracking	Damage (%)	0.01			
AC Rutting	Allowable Repetitions	161			
AC Rutting	Applied Repetitions	777600			

Pavement Distress Summary

Distress Types	Distress Target	Reliability Target	Distress Predicted	Reliability Predicted	Acceptable
AC Top Down Cracking (ft/mile)	2000	90	-	-	Pass
AC Bottom Up Cracking (%)	25	90	0.00	51.25	Fail
AC Rutting (in)	0.25	90	0.67	99.93	Fail
Base Rutting (in)	0.30	90	0.07	100.00	Pass
Subbase Rutting (in)					
Subgrade Rutting (in)	0.20	90	0.00	100.00	Pass

Close

Figure VP3a.5. Pavement distresses summary output.

Significant Problems, Issues and Potential Impact on Progress

The release of version 2.0 of the software was delayed because of extensive verification of the performance model subroutine.

The 3D-Move Analysis verification plan was postponed until the release of the version 2.0 of the software that will have the various new features and address the various bugs.

Work Planned Next Quarter

Continue working on the 3D-Move model to make it a menu-driven software. Finalize the beta evaluation of the performance evaluation subroutine. Continue to solve any issues and bugs that users may encounter. Continue to maintain the 3D-Move Forum.

TABLE OF DECISION POINTS AND DELIVERABLES FOR VEHICLE-PAVEMENT INTERACTION

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for Changes in Delivery Date
VP2a-4: Run parametric studies on tire-pavement noise and skid response (UWM)	Draft Report	Draft report on proposed design guideline for noise reduction, durability, safety and costs	1/10	10/11	Software issues with the KUNDT tube for noise measurements. In addition, the laser spot size and variability necessitated a system re-design.
VP2a-7: Proposed optimal guideline for design to include noise reduction, durability, safety and costs (UWM)	Final Report	Final report on proposed design guideline for noise reduction, durability, safety and costs	1/12	4/12	Final report submission date moved back to allow at least 6 months between draft and final report submission.
VP3a-4: Overall Model (UNR)	Software	Release of version 2.0 of the 3D-Move pavement response model	06/11	9/11	The extensive evaluation of the performance model subroutine delayed the release of the new version of the software
	Draft report	Summarizing *3D-Move Analysis* software	12/11	N/A	N/A
	Final report		06/12	N/A	N/A
	Software	Release of final version of the 3D-Move pavement response model	03/12	N/A	N/A

Vehicle-Pavement Interaction Year 5	Year 5 (4/2011-3/2012)												Team
	4	5	6	7	8	9	10	11	12	1	2	3	
(1) Workshop													
VP1a: Workshop on Super-Single Tires													UNR
(2) Design Guidance													
VP2a: Mixture Design to Enhance Safety and Reduce Noise of HMA													UWM
VP2a-1: Evaluate common physical and mechanical properties of asphalt mixtures with enhanced frictional skid characteristics													
VP2a-2: Evaluate pavement macro- and micro-textures and their relation to tire and pavement noise-generation mechanisms													
VP2a-3: Develop a laboratory testing protocol for the rapid evaluation of the macroand micro-texture of pavements				P									
VP2a-4: Run parametric studies on tire-pavement noise and skid response													
VP2a-5: Establish collaboration with established national laboratories specialized in transportation noise measurements. Gather expertise on measurements and analysis													
VP2a-6: Model and correlate acoustic response of tested tire-pavement systems					JP	P							
VP2a-7: Proposed optimal guideline for design to include noise reduction, durability, safety and costs						P	D			F			
(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			SW						D			F, SW	

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

Work planned
Work completed
Parallel topic

Vehicle-Pavement Interaction Years 2 - 5	Year 2 (4/08-3/09)				Year 3 (4/09-3/10)				Year 4 (04/10-03/11)				Year 5 (04/11-03/12)				Team
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	
(1) Workshop																	
VP1a: Workshop on Super-Single Tires																	UNR
(2) Design Guidance																	
VP2a: Mixture Design to Enhance Safety and Reduce Noise of HMA																	UWM
VP2a-1: Evaluate common physical and mechanical properties of asphalt mixtures with enhanced frictional skid characteristics				DP													
VP2a-2: Evaluate pavement macro- and micro-textures and their relation to tire and pavement noise-generation mechanisms				DP													
VP2a-3: Develop a laboratory testing protocol for the rapid evaluation of the macroand micro-texture of pavements		M&A												P			
VP2a-4: Run parametric studies on tire-pavement noise and skid response						JP		D	JP								
VP2a-5: Establish collaboration with established national laboratories specialized in transportation noise measurements. Gather expertise on measurements and analysis																	
VP2a-6: Model and correlate acoustic response of tested tire-pavement systems										JP, P				JP, P			
VP2a-7: Proposed optimal guideline for design to include noise reduction, durability, safety and costs												P		P	D	F	
(3) Pavement Response Model Based on Dynamic Analyses																	
VP3a: Pavement Response Model to Dynamic Loads																	UNR
VP3a-1: Dynamic Loads			JP														
VP3a- 2: Stress Distribution at the Tire-Pavement Interface																	
VP3a-3: Pavement Response Model						SW, v. β					JP						
VP3a-4: Overall Model											SW		SW		D	F, SW	

Deliverable codes	Deliverable Description
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Work planned
Work completed
Parallel topic

PROGRAM AREA: VALIDATION

CATEGORY V1: FIELD VALIDATION

Work element V1a: Use and Monitoring of Warm Mix Asphalt Sections (WRI)

Work Done This Quarter

No monitoring activity during the last quarter.

Significant Results

None.

Significant Problems, Issues and Potential Impact on Progress

None.

Work Planned Next Quarter

It is planned to monitor the Manitoba WMA sections in August 2011. It is planned to monitor the Yellowstone WMA project in September 2011. It appears that core samples will be allowed for the first time since the sections have been in service.

Work element V1b: Construction and Monitoring of Additional Comparative Pavement Validation Sites (WRI)

Work Done This Quarter

The Kansas comparative pavement performance site was monitored in May 2011. There is noticeable difference in performance of the sections. With the different asphalt sources being in the bottom lift of a three-lift pavement structure, diagnosing the real cause of the different performance is challenging.

During the monitoring, Kansas DOT personnel were present for observation and discussion. Kansas DOT has interest in constructing high-RAP comparative performance sections using two different asphalt sources (same grade) with comparable no-RAP sections. There is also a possibility of including lower RAP-content sections. Discussions are underway with KDOT to finalize construction for the 2012 construction season.

Significant Results

None.

Significant Problems, Issues and Potential Impact on Progress

None.

Work Planned Next Quarter

It is planned to monitor the Manitoba RAP sections in August 2011.

CATEGORY V2: ACCELERATED PAVEMENT TESTING

Work element V2a: Accelerated Pavement Testing including Scale Model Load Simulation on Small Test Track

Work Done This Quarter

No activity this quarter. This work element was included in order to accommodate any accelerated testing that may occur during the project.

Significant Results

None.

Significant Problems, Issues and Potential Impact on Progress

None.

Work Planned Next Quarter

No accelerated (field) testing is planned.

Work element V2b: Construction of Validation Sections at the Pecos Research & Testing Center

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

Efforts this quarter focused on conducting mixture performance testing and round robin binder testing in collaboration with the Western Cooperative Test Group (WCTG). Binder data to date were summarized and compared to mixture data, which were presentated at the Rocky Mountain Asphalt User Producer Group (RMAUPG) annual meeting. As June marks the final month of the 2010-2011 Western Cooperative Test Group (WCTG) round robin binder testing program, researchers anticipate having a data summary available during the next quarter, which will be incorporated into the final ARC report. Mixture testing involved flow number testing of loose mix samples contributed by WCTG members for comparison to multiple stress creep and recovery (MSCR) binder results. Researchers also focused on expanding collaborative efforts with WCTG and RMAUPG in order to enhance data collection protocols and expand the current investigation to include the effects of altitude and pressure on rolling thin-film oven (RTFO) results.

Significant Results

Results compiled from binder and mixture tests suggest several interesting trends. First, standard PG tests demonstrate low average and median coefficient of variation (COV) values, suggesting that current PG test protocols are well understood and well integrated into laboratories across the country. COV values appear to be reasonable and consistent among labs. For PG+ tests, higher average and median COV values are observed for ductility, toughness and tenacity, and MSCR tests. Figure V3a.1 is an example of data collected for the MSCR test. These results suggest that issues remain with many of the PG+ tests, and that these issues must be resolved if any of these proposed tests are to be integrated into existing test protocols and performance specifications.

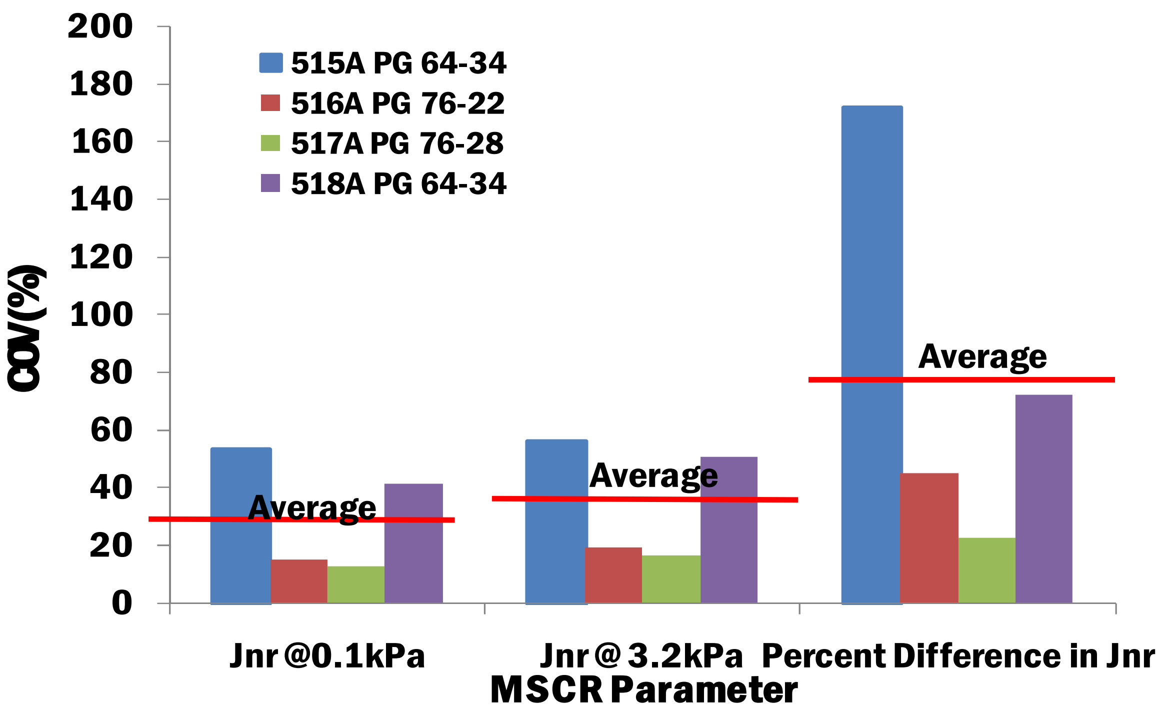

Figure V3a.1. Coefficient of variation of the MSCR results for data collected from more than 25 labs.

Binder MSCR results were also compared to mixture rutting results to understand the relationship between binder and mixture properties. As shown in Table V3a.1, when compared to MSCR binder test results, mixture test results in terms of flow number (FN) indicate a similar relative ranking.

Table V3a.1. Comparison of binder and mixture ranking of WCTG binders and mixtures.

ID	Binder Ranking		Mixture Ranking
	Jnr @ 0.1 kPa	Jnr @ 3.2 kPa	FN @ 150 psi
515A	6	6	2
516A	1	1	1
517A	2	2	4
518A	4	4	5
519A	5	5	6
520A	3	3	3

Problems and Implications for Work

No significant problems were encountered this quarter.

Work Planned Next Quarter

Work in the next quarter will focus on the following tasks:

- Finalizing data analysis and results for the 2010-2011 WCTG round robin binder testing program.
- Drafting a final report for the V3a work element.
- Coordinating mixture testing and binder testing for the 2011-2012 WCTG testing program.
- Coordinating post-ARC activities with the RMAUPG steering committee.

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)

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

Work Done This Quarter

None

Significant Results

None

Significant Problems, Issues and Potential Impact on Progress

Only two agencies have committed to the construction of MEPDG sites: the Washoe RTC in northern Nevada in 2008, The South Dakota DOT in 2009/2010. 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 has been reduced.

Work Planned Next Quarter

None

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

<u>Work Done This Quarter</u>

In this quarter, the research team continued validation efforts of newly develop binder testing procedures such as the Single Edge Notch Beam (SENB). Fracture properties of Long Term Pavement Performance (LTPP) binders obtained with the SENB were compared to field thermal cracking performance.

Tables V3b-3.1 and V3b-3.2 show the fracture energy (G_f) and fracture toughness (K_{IC}) of the LTPP binders measured at -12 and -24°C, respectively. Due to the different climatic conditions in the LTPP sections, it was decided to normalize the amount of cracking in each section to its corresponding Freeze Index reported for each section in the database. Freeze index is an indicator of the severity of frost in a given region in terms of degree days (Huang 2004).

Table V3b-3.1 shows the ranking of the binders based on normalized field performance and each binder fracture criterion at -12°C. Based on the rankings shown, there is a recognizable relationship between the low temperature pavement performance and the binder fracture properties. The binders generally ranked similarly to the field performance when ranked by G_f. K_{IC} rankings were similar at -24°C, but deviated when tested at -12°C.

It is recognized that the ranking and correlation between the field and the experimental data at the two testing temperatures is significantly affected by the proximity of the corresponding field temperature history of each particular binder to the testing temperature. A better correlation may be achieved if SENB tests are conducted at a temperature related to the minimum observed field temperature.

Table V3b-3.1. SENB results at -12°C for LTPP binders.

SHRP ID	**No. of Transverse cracks per section/ Freeze Index (×10^{-3})**	**RANK**	**K_{IC} (kPa.m$^{0.5}$)**	**RANK**	**G_f (J/m^2) (total)**	**RANK**
370901	702.58	7	26.83	6	5.45	7
370903	343.25	6	55.03	1	6.24	6
90961	9.26	4	31.98	5	44.20	2
90962	6.18	2	37.57	4	11.87	4
90903	24.71	5	38.54	3	10.98	5
89a902	7.01	3	23.12	7	103.82	1
350903	1	1	40.93	2	21.31	3

Table V3b-3.2. SENB results at -24°C for LTPP binders

SHRP ID	No. of Transverse cracks per section/ Freeze Index ($\times 10^{-3}$)	RANK	K_{IC} (kPa.m$^{0.5}$)	RANK	G_f (J/m^2) (total)	RANK
370901	702.58	7	36.70	7	1.97	6
370903	343.25	6	36.87	6	1.96	7
90961	9.26	4	58.43	1	11.91	2
90962	6.18	2	42.61	5	2.48	5
90903	24.71	5	47.59	3	2.83	4
89a902	7.01	3	48.12	2	15.20	1
350903	1	1	45.64	4	3.50	3

Significant Results

Figures V3b-3.1 and V3b-3.2 show the relationship between fracture properties of the LTPP binders and normalized number of transverse cracks per section. Figures V3b-3.1 shows a significant relationship between K_{IC} at -24°C and field performance. It is observed that binders that had the lowest number of thermal cracks had higher K_{IC} values, while binders for which the SENB indicated low K_{IC} values exhibited the highest amount of thermal cracking in the field. The shape and trend of this curve is very similar to the curves previously reported in Phase I of the Pooled Fund Project on Low Temperature Cracking in which fracture properties of asphalt mixtures obtained with the Semi-Circular Bending Test (SCB) were compared to field performance measured in MnROAD sections.

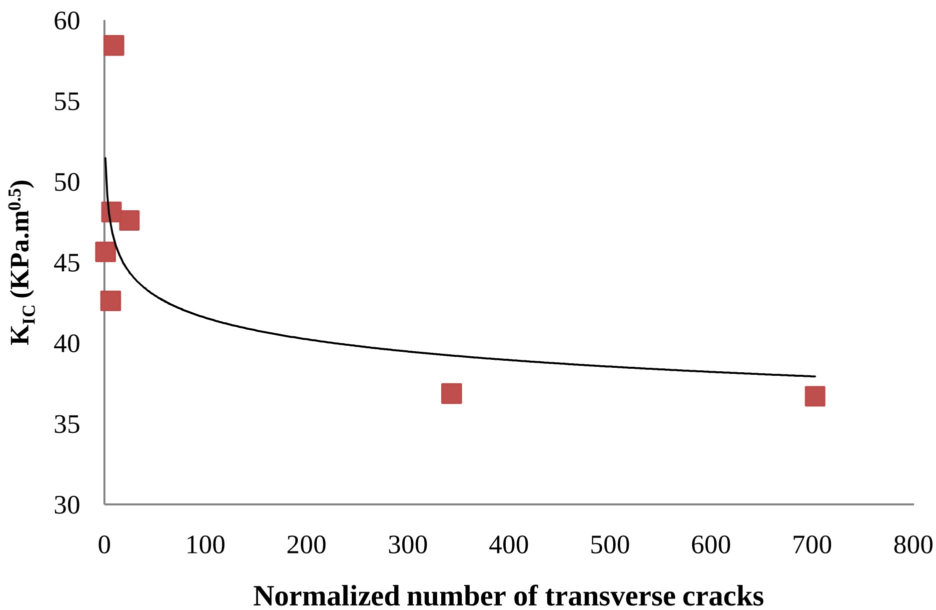

Figure V3b-3.1. Graph. Fracture toughness at -24°C vs. normalized number of transverse cracks on LTPP sections.

Similar trends are also observed for fracture energy, both at -12 and -24°C (figure V3b-3.2). The LTPP pavement sections with the highest normalized number of transverse cracks had relatively low binder fracture energy. These results indicate the potential of using measurements of binder low temperature fracture properties as thermal cracking performance indices.

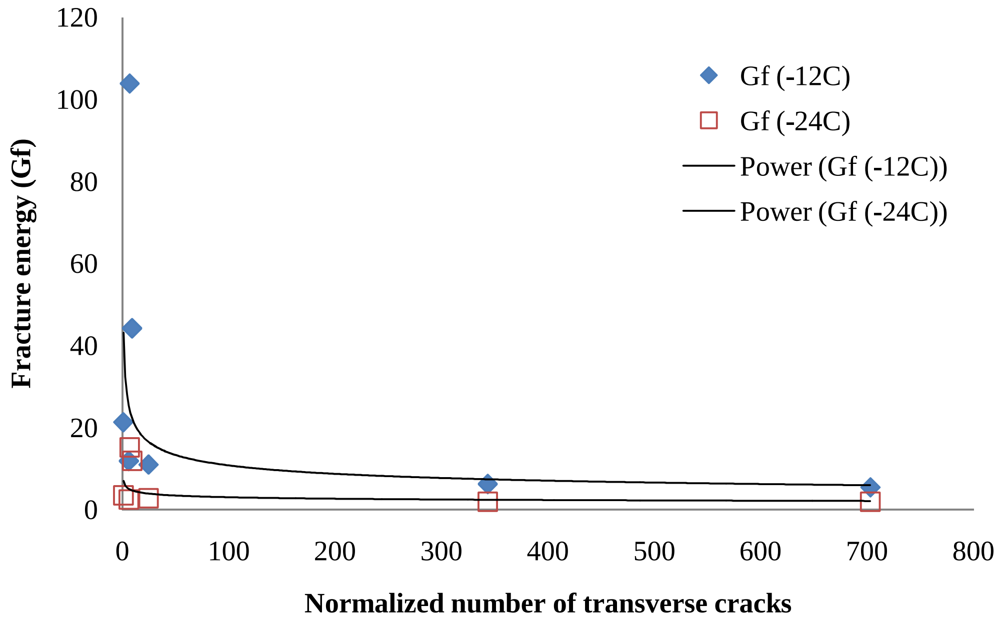

Figure V3b-3.2. Graph. G_f vs. normalized number of transverse cracks at -12°C and -24°C.

Work Planned Next Quarter

The research team will continue performing SENB tests on the LTPP binders in order to further investigate correlations between field performance and laboratory results. Efforts will be made to define a field performance criterion that takes the minimum pavement temperature experienced in each section into account.

Alternative test temperatures that may better represent field conditions will be considered and tested, if necessary. Furthermore, experimental protocols developed for rutting of asphalt binders will be compared to LTPP field performance collected in the previous quarter.

The research team will work on an outline for the final report corresponding to validation efforts of the Linear Amplitude Sweep (LAS), SENB, and other test procedures developed in the Consortium.

Cited References

Huang, Y.H., 2004, *Pavement Analysis and Design*, ed. 2, Pearson-Prentice Hall, NJ, 31-32.

Work Element V3c: Validation of PANDA (TAMU)

Work Done this Quarter

Please refer to the details presented in work elements M4c, F1d-8, and F3c. These work elements outline what has already been accomplished in validating the constitutive models that are implemented in PANDA as well as the validation work that will be carried out in the coming quarter.

We have started to carry out the ARC 2x2 matrix validation plan.

Significant Results

See the significant results sections in work elements M4c, F1d-8, and F3c.

Significant Problems, Issues and Potential Impact on Progress

See the significant results sections in work elements M4c, F1d-8, and F3c.

Work Planned Next Quarter

Focus will be placed on validation of PANDA using the ARC 2x2 matrix validation plan and on the structural simulations of the ALF sections.

PANDA Software

Work Done This Quarter

In this quarter, work has been started on creating a stand-alone finite element software that can be used for predicting the performance of asphalt pavements. A four-node two-dimensional element has been created and programmed. This element can be used to solve plane stress, plane strain, and axisymmetric problems. Moreover, the finite element global solver based on the Newton-Raphson technique has been created. It can descritize the problem into global time increments and local iterations within each time increment for increased solution accuracy. The program in written in Fortran 90.

Significant Results

None

Significant Problems, Issues and Potential Impact on Progress

None

Work Planned Next Quarter

Work will be completed on creating 8-node and 9-node two-dimensional elements. This will give the user the flexibility to use different types of two-dimensional elements in conducting the finite element analysis for desired accuracy and geometry description. Moreover, a tensor library is going to be built that can be used to conduct various mathematical operations necessary for implementing the PANDA continuum damage model.

Work Element V3d: Engineered Properties Testing Plan (TAMU)

Work Done this Quarter

The work completed this quarter relates to work described in Work Elements F2c and E1a.

Work Planned Next Quarter

Please refer to Work Elements F2c and E1a.

TABLE OF DECISION POINTS AND DELIVERABLES FOR VALIDATION

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
V3a-1: Evaluation of the PG-Plus practices and the motivations for selecting the "plus" tests. (UWM)	Draft Report	Detailed analysis of PG and PG+ tests	10/08	9/11	Extended time was needed to start the joint effort between Western Cooperative Test Group (WCTG), the Rocky Mountain Asphalt User-Produce Group (RMAUPG), and UW-Madison which is generating data from PG and PG+ tests run in more than 40 different laboratories.
	Final Report	Report on 508 format on benefits of PG+ and new ARC tests in comparison to PG tests. Repeatability of PG+ and newly developed ARC procedures	12/08	3/12	
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 (UWM)	Draft Report	Refer to Draft Report for V3a-1	4/09	9/11	
V3a-4: Development of specification criteria for new tests based on field evaluation of construction and performance (UWM)	Draft Report	Refer to Draft Report for V3a-1	7/09	9/11	Refer to Draft Report for V3a-1
V3a-5: Interviews and surveys for soliciting feedback on binder tests and specifications (UWM)	Draft Report	Report summarizing collaboration between Western Cooperative Test Group (WCTG), the Rocky Mountain Asphalt User-Produce Group (RMAUPG) and UW-Madison	12/11	N/A	N/A
	Final Report	Report in 508 format on Development and maintenance of database for evaluation of PG, PG+, and new ARC tests.	1/12	6/12	Final report submission date moved back to allow at least 6 months between draft and final report submission.

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
V3b-3: Select LTPP Sites to Validate New Binder Testing Procedures (UWM)	Draft Report	Report summarizing characterization of LTPP binders by means of the Linear Amplitude Sweep (LAS), Single Edge-Notch Beam (SENB) and Bitumen Bond Strength (BBS) tests.	12/11	N/A	N/A
	Final Report	Final report in 508 format on validation/verification of fatigue, thermal cracking, and moisture damage procedures using LTPP binders.	1/12	6/12	Final report submission date moved back to allow at least 6 months between draft and final report submission.
V3c: Validation of PANDA (TAMU)	PANDA Workshop	Workshop on PANDA Models and Validation Results	8/11	N/A	N/A
	Draft Report	Documentation of PANDA Models and Validation	11/11	N/A	N/A
	Final Report (M5, M4c, F1b-1, F1c, F1d-8, F3c, and V3c)	Documentation of PANDA Models and Validation	3/12	6/30/12	N/A
	UMAT Material	PANDA Implemented in Abaqus	3/12	N/A	N/A
	Software	Standalone Software to support the use of and future utility and flexibility of PANDA	3/12	N/A	N/A

Validation Year 5	Year 5 (4/2011-3/2012)												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.						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													
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			P						JP				
V3a-5: Interviews and surveys for soliciting feedback on binder tests and specifications		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/ WRI
V3b-1: Design and Build Sections										D		F	UNR
V3b-2: Additional Testing (if needed)													
V3b-3: Select LTPP Sites to Validate New Binder Testing Procedures					JP				D	F			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													
V3c: Validation of PANDA													TAMU
V3d: Engineered Properties Testing Plan	JP		JP										

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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											D	F		
V3a-2: Detailed analysis of all PG-Plus tests being proposed or in use today, documentation of benefits and costs of these tests, and comparison with new tests				P	D												
V3a-3: Development of protocols for new binder tests and database for properties measured						JP				P							
V3a-4: Development of specification criteria for new tests based on field evaluation of construction and performance						D		P	P			JP	P		JP		
V3a-5: Interviews and surveys for soliciting feedback on binder tests and specifications									P		JP		P		D	F	
V3b: Validation of the MEPDG Asphalt Materials Models and Early Verification of Technologies Developed by ARC using new MEPDG Sites and Selected LTPP sites																	UNR/UWM
V3b-1: Design and Build Sections																D, F	
V3b-2: Additional Testing (if needed)																	
V3b-3: Select LTPP Sites to Validate New Binder Testing Procedures					DP			P		JP, DP		P		JP	D	F	
V3b-4: Testing of Extracted Binders from LTPP Sections																	
V3b-5: Review and Revisions of Materials Models																	
V3b-6: Evaluate the Impact of Moisture and Aging																	
V3c: Validation of PANDA																	**TAMU**
V3d: Engineered Properties Testing Plan										P(2)	JP	P(3), JP					

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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) (AAT, WRI)

This work element has been completed. Six early development products were identified.

Work element TD2: Develop Early Products (Year 3) (AAT, WRI)

Work Done This Quarter

Table TD2.1 summarizes the progress on the Products for Early Development. The test method for Automated Flocculation Titrimetric Analysis has been published as an ASTM standard method of test, ASTM D6703 - 07 Draft AASHTO Standards have been completed for other 5 products; however, the Draft AASHTO Standard for simplified continuum damage fatigue analysis for the Asphalt Mixture Performance Tester, is being revised significantly based on the findings of the analyses being conducted in the continuum damage fatigue model refinement in Work Element E2e. The Draft AASHTO Standard for Determination of Polymer in Modified Asphalt is available on the outreach portion of the ARC website at: http://www.arc.unr.edu/Outreach.html#TechDevelopmentProducts.

Table TD2.1. Summary of progress on early development products.

No.	Product	ARC Research Program	Format	Estimated Completion Data	ARC Partner	Draft AASHTO Standard?
1	Simplified Continuum Damage Fatigue Analysis for the Asphalt Mixture Performance Tester	Prior	Test Method	9/30/2011	AAT	Yes
2	Wilhelmy Plate Test	Prior	Test Method	Completed	TTI	Yes
3	Universal Sorption Device	Prior	Test Method	Completed	TTI	Yes
4	Dynamic Mechanical Analysis	Prior	Test Method	Completed	TTI	Yes
5	Automated Flocculation Titrimetric Analysis	Prior	Test Method	Completed	WRI	No (ASTM)
6	Determination of Polymer in Asphalt	Prior	Test Method	Completed	WRI	Yes

Significant Problems, Issues and Potential Impact on Progress

None.

Work Planned Next Quarter

AAT will continue revising the Draft AASHTO Standard for simplified continuum damage fatigue analysis for the Asphalt Mixture Performance Tester. Based on the ratings from the ETGs, support will be provided for advancing the selected products through AASHTO for publication as Provisional AASHTO Standards.

Work element TD3: Identify Products for Mid-Term and Long-Term Development (Years 2, 3, and 4) (AAT, TTI, UNR, UW-M, WRI)

This work element has been completed. A total of 38 mid- and long-term products were identified. Table TD3.1 summarizes these products.

Table TD3.1. Summary of mid- and long-term technology development products.

No.	Product	ARC Work Element	Format	Estimated Completion Date	ARC Partner
7	A Method for the Preparation of Specimens of Fine Aggregate Matrix of Asphalt Mixtures	M1c	Test Method	12/31/2010	TTI
8	Measuring intrinsic healing characteristics of asphalt binders	F1d	Test Method	12/31/2012	TTI / UT Austin
9	Lattice Micromechanical Model for Virtual Testing of Asphalt Concrete in Tension	F3b	Analysis Program	2/28/2012	NCSU
10	Cohesive Zone Modeling as an Efficient and Powerful Tool to Predict and Characterize Fracture Damage of Asphalt Mixtures Considering Mixture Microstructure, Material Inelasticity, and Moisture Damage	F3b	Performance Predicting Model	12/31/2010	University of Nebraska
11	Pavement Analysis Using Nonlinear Damage Approach (PANDA)	F3c	Test Method	12/31/2012	TTI
12	Test Methods for Determining the Parameters of Material Models in PANDA (Pavement Analysis Using Nonlinear Damage Approach)	F3c E1a	Test Method	12/31/2011	TTI
13	Continuum Damage Permanent Deformation Analysis for Asphalt Mixtures	E1a	Test Method	9/30/2011	TTI
14	Characterization of Fatigue and Healing Properties of Asphalt Mixtures Using Repeated Direct Tension Test	E1a	Test Method & Data Analysis Program	9/30/2011	TTI
15	Nondestructive Characterization of Tensile Viscoelastic Properties of Undamaged Asphalt Mixtures	E1a	Test Method & Data Analysis Program	Completed	TTI
16	Nondestructive Characterization of Field Cores of Asphalt Pavements	E1a	Test Method & Data Analysis Program	9/30/2011	TTI

Table TD3.1 continued. Summary of mid- and long-term technology development products.

17	Self-Consistent Micromechanics Models of Asphalt Mixtures	E1a	Analytical Model & Data Analysis Program	6/30/2011	TTI
18	Nondestructive Characterization of Anisotropic Viscoelastic Properties of Undamaged Asphalt Mixtures under Compressive Loading	E1a	Test Method	Completed	TTI
19	Mix Design for Cold-In-Place Recycling (CIR)	E1c	Practice	12/31/2011	UNR
20	Mix Design for Cold Mix Asphalt	E1c	Practice	3/31/2012	UNR
21	Evaluation of RAP Aggregates	E2b	Practice	4/30/2011	UNR
22	Identification of Critical Conditions for HMA mixtures	E2c	Practice	12/31/2011	UNR
23	Thermal Stress Restrained Specimen Test (TSRST)	E2d	Test Method	9/30/2011	UNR
24	HMA Thermal Stresses in the Intermountain Region	E2d	Model	3/31/2012	UNR
25	Dynamic Model for Flexible Pavements 3D-Move	VP3a	Software	3/31/2011	UNR
26	Bitumen Bond Strength Test (BBS)	M1a	Test Method	Completed	UWM
27	Elastic Recovery – DSR	F2a	Test Method	12/31/2010	UWM
28	Linear Amplitude Sweep (DSR)	F2e	Test Method	Completed	UWM
29	Binder Yield Energy Test (BYET)	F2e	Test Method	Completed	UWM
30	Rigden Voids for fillers	F2e	Test Method	9/30/2011	UWM
31	Binder Lubricity Test – DSR	E1c	Test Method	12/31/2010	UWM
32	RAP Binder PG True Grade Determination	E2b	Test Method / Software	3/31/2011	UWM
33	Single Edge Notch Bending	E2d	Test Method	5/31/2011	UWM
34	Binder Glass Transition Test	E2d	Test Method	5/31/2011	UWM
35	Asphalt Mixture Glass Transition Test	E2d	Test Method	5/31/2011	UWM
36	Planar imaging/ Aggregate Structure	E1b	Test Method/ Software	3/31/2011	UWM

Table TD3.1 continued. Summary of mid- and long-term technology development products.

37	Gyratory Pressure Distribution Analyzer (GPDA)	E1c	Test Method	Completed	UWM
38	Improved Oxygen and Thermal Transport Model of Binder Oxidation in Pavements	F1c	Methodology, Publication	3/31/2011	TAMU
39	Field Validation of an Improved Oxygen and Thermal Transport Model of Binder Oxidation in Pavements	F1c	Methodology, Publication	3/31/2011	TAMU
40	Validation of an improved Pavement Temperature Transport Model for use in an Oxygen and Thermal Transport Model of Binder Oxidation in Pavements	F1c	Methodology, Publication	3/31/2011	TAMU
41	Pavement Air Voids Size Distribution Model for use in an Oxygen and Thermal Transport Model of Binder Oxidation in Pavements	F1c	Methodology, Publication	3/31/2011	TAMU
42	Improved Understanding of Fast-Rate, Constant-Rate Binder Oxidation Kinetics Mechanism through the Effects of Inhibitors	F1c	Publication	3/31/2011	TAMU
43	Improved Understanding of Fatigue Resistance Decline with Binder Oxidation	F1c	Publication	3/31/2011	TAMU
44	Micromechanical Properties of Various Structural Components in Asphalt using Atomic Force Microscopy (AFM)	F2d	Test and Analysis Method	3/31/2011	TAMU

Work Element TD4: Develop Mid-Term and Long-Term Products (Years 3, 4, and 5) (AAT, TTI, UNR, UW-M, WRI)

Responses to the product rating request issued to the ETGs by the FHWA were compiled by the research team. Only 12 individuals responded to the rating request. Each respondent did not rate all of the products, so the number of responses for each product varied from 5 to 10. Table TD 4.1 summarizes the responses. Average ratings and comments for each of the mid and long-term technology development products are given in table TD4.2. Thirteen products received average ratings above 3.0. The remaining products received average ratings between 2.25and 3.0. The ratings and the comments will be considered in selecting the effort that will be expended on each of the mid- and long-term products.

Table TD4.1. Summary of mid- and long-term technology development product ratings.

Product #	Product Title	Value			Urgency		# of Respondents			
		Research	Agency	Industry			Research	Agency	Industry	Urgency
7	A Method for the Preparation of Specimens of Fine Aggregate Matrix of Asphalt Mixtures	3.63	3.29	2.89	3.13		8	7	9	8
8	Measuring intrinsic healing characteristics of asphalt binders	3.43	2.67	2.63	2.71		7	6	8	7
9	Lattice Micromechanical Model for Virtual Testing of Asphalt Concrete in Tension	3.29	1.67	2.25	2.71		7	6	8	7
10	Cohesive Zone Modeling as an Efficient and Powerful Tool to Predict and Characterize Fracture Damage of Asphalt Mixtures Considering Mixture Microstructure, Material Inelasticity, and Moisture Damage	3.43	2.00	2.00	2.43		7	6	8	7
11	Pavement Analysis Using Nonlinear Damage Approach (PANDA)	3.29	2.17	2.38	2.57		7	6	8	7
12	Test Methods for Determining the Parameters of Material Models in PANDA (Pavement Analysis Using Nonlinear Damage Approach)	3.00	2.00	2.00	2.50		8	7	9	8
13	Continuum Damage Permanent Deformation Analysis for Asphalt Mixtures	4.00	2.86	2.44	3.00		8	7	9	8
14	Characterization of Fatigue and Healing Properties of Asphalt Mixtures Using Repeated Direct Tension Test	3.50	2.86	2.33	2.63		8	7	9	8
15	Nondestructive Characterization of Tensile Viscoelastic Properties of Undamaged Asphalt Mixtures	3.13	2.43	2.11	2.00		8	7	9	8
16	Nondestructive Characterization of Field Cores of Asphalt Pavements	4.00	3.29	2.89	3.00		8	7	9	8
17	Self-Consistent Micromechanics Models of Asphalt Mixtures	3.14	2.00	1.88	2.00		7	6	8	7
18	Nondestructive Characterization of Anisotropic Viscoelastic Properties of Undamaged Asphalt Mixtures under Compressive Loading	3.63	2.29	2.11	2.13		8	7	9	8
19	Mix Design for Cold-In-Place Recycling (CIR)	3.38	4.14	3.78	3.88		8	7	9	8
20	Mix Design for Cold Mix Asphalt	3.13	3.71	3.33	3.38		8	7	9	8
21	Evaluation of RAP Aggregates	3.78	4.38	3.90	4.11		9	8	10	9

Product #	Product Title	Value			Urgency		# of Respondents			
		Research	Agency	Industry			Research	Agency	Industry	Urgency
22	Identification of Critical Conditions for HMA mixtures	3.50	3.43	3.11	2.75		8	7	9	8
23	Thermal Stress Restrained Specimen Test (TSRST)	3.13	2.57	2.67	2.38		8	7	9	8
24	HMA Thermal Stresses in the Intermountain Region	3.00	2.67	2.75	2.86		7	6	8	7
25	Dynamic Model for Flexible Pavements 3D-Move	3.00	2.33	2.13	2.29		7	6	8	7
26	Bitumen Bond Strength Test (BBS)	2.43	2.33	2.63	2.57		7	6	8	7
27	Elastic Recovery – DSR	3.00	3.50	3.13	3.00		7	6	8	7
28	Linear Amplitude Sweep (DSR)	3.43	3.17	3.00	3.29		7	6	8	7
29	Binder Yield Energy Test (BYET)	2.86	2.50	2.25	2.43		7	6	8	7
30	Rigden Voids for fillers	2.29	2.33	2.25	2.14		7	6	8	7
31	Binder Lubricity Test – DSR	3.38	2.50	2.78	2.56		9	8	10	9
32	RAP Binder PG True Grade Determination	3.50	3.43	3.11	3.25		8	7	9	8
33	Single Edge Notch Bending	3.13	3.00	3.00	3.13		8	7	9	8
34	Binder Glass Transition Test	3.14	2.00	2.25	2.57		7	6	8	7
35	Asphalt Mixture Glass Transition Test	3.43	2.50	2.38	2.86		7	6	8	7
36	Planar imaging/ Aggregate Structure	3.00	2.14	2.33	2.00		8	7	9	8
37	Gyratory Pressure Distribution Analyzer (GPDA)	3.00	2.71	3.00	2.88		8	7	9	8
38	Improved Oxygen and Thermal Transport Model of Binder Oxidation in Pavements	4.00	2.57	2.78	3.00		8	7	9	8
39	Field Validation of an Improved Oxygen and Thermal Transport Model of Binder Oxidation in Pavements	3.71	2.33	2.63	2.86		7	6	8	7
40	Validation of an improved Pavement Temperature Transport Model for use in an Oxygen and Thermal Transport Model of Binder Oxidation in Pavements	3.67	2.20	2.57	2.83		6	5	7	6
41	Pavement Air Voids Size Distribution Model for use in an Oxygen and Thermal Transport Model of Binder Oxidation in Pavements	3.67	2.20	2.43	2.50		6	5	7	6
42	Improved Understanding of Fast-Rate, Constant-Rate Binder Oxidation Kinetics Mechanism through the Effects of Inhibitors	3.71	2.50	2.75	2.43		7	6	8	7
43	Improved Understanding of Fatigue Resistance Decline with Binder Oxidation	3.71	2.50	2.50	2.71		7	6	8	7
44	Micromechanical Properties of Various Structural Components in Asphalt using Atomic Force Microscopy (AFM)	3.71	1.67	2.00	1.71		7	6	7	7

Table TD4.2. Average rating and comments for mid-and long-term technology development product.

#	Product Title	Sum	Comments
21	Evaluation of RAP Aggregates	4.04	R3: Low RAP aggregate is already being done in that contactors are meeting volumetric. Maybe this is only for high use of RAP R4: We're operating blindly now R11: needed R12: Description and equipment not detailed enough in current version
19	Mix Design for Cold-In-Place Recycling (CIR)	3.79	R3: We seem to be trying to make everything fit Superpave, which is wrong. There are mix designs out there for cold-in-place, why not start with what works with them and improve the system. R4: This saves $; is sustainable; efficient; we needed this yesterday! R7: Very useful study especially for municipalities R11: Very needed R12: Description and equipment to be detailed for completion (end 2011)
20	Mix Design for Cold Mix Asphalt	3.39	R3: Similar to 19, we have cold mix asphalt mixes which work so why not improve the existing system instead of creating a new one. R4: This saves $; is sustainable; efficient; we needed this yesterday! R11: Not critical only for patching R12: Description and equipment to be detailed for completion (end 2012)
32	RAP Binder PG True Grade Determination	3.32	R3: The true grade would only be a concern with high RAP mixes. R4: $ better spent on determining how RAP's binder acts in mix R11: Come up with better mix test
16	Nondestructive Characterization of Field Cores of Asphalt Pavements	3.29	R3: What about lift thickness. Should there be a minimum thickness for this test. R11: What type of characterization
7	A Method for the Preparation of Specimens of Fine Aggregate Matrix of Asphalt Mixtures	3.23	R3: It is only one part of mix and how do you validate that is the total mix, the fines are the one effecting the mix R:11 For agencies an industry just use mix tests
28	Linear Amplitude Sweep (DSR)	3.22	R11: Needs validation
22	Identification of Critical Conditions for HMA mixtures	3.20	R3: Is this just another plus specification or another binder classification R11: What distresses and what can you do about it R12: Description and equipment to be detailed for completion (end 2011)
27	Elastic Recovery – DSR	3.16	R3: There is no data suggesting that this will be any better than current elastic recovery method. Temperature plays a key part in elastic recovery and this method does not look at that. R7: Elastic recovery is used to determine if polymers are added to binders. This can be achieved by the BYET – study #29 R11: One bad test for another

#	Product Title	Sum	Comments
38	Improved Oxygen and Thermal Transport Model of Binder Oxidation in Pavements	3.09	R2: We need a better mixture aging model, and this one has potential. R3: There are many variables which are not addressed. Did weather, low bid of the job, whose aggregate and binder do you use in the model. Do you have to rerun this to make any sense after the job has been awarded and then what? R4: Need to better understand aging R11: Needed R12: Coordination with WRI FPIII work on oxidation needed
13	Continuum Damage Permanent Deformation Analysis for Asphalt Mixtures	3.08	R11: Continuum damage for rutting is still to be proven R12: Replace worship by workshop in recommended next steps
33	Single Edge Notch Bending	3.06	R2: We've demonstrated the need for a binder fracture test. This one looks promising. R3: Why not use the ABCD R4: Proven technology, should work here R7: I believe in Canada they are using this test in their specs – I am not sure what will be added by this study. R11: Need validation
37	Gyratory Pressure Distribution Analyzer (GPDA)	2.90	R4: Why? R11: In 15 years it has shown little value
39	Field Validation of an Improved Oxygen and Thermal Transport Model of Binder Oxidation in Pavements	2.88	R4: Need to better understand aging #41, FDOT needs now, it's why OGFC's are giving ½ half the service life of conventional pavements Industry desperately needs a pavement weatherometer as a tool R11: needed R12: Coordination with WRI FPIII work on oxidation to be mentioned
8	Measuring intrinsic healing characteristics of asphalt binders	2.86	R3: Does not take into account the freeze thaw cycles or moisture R4: Research tool, redefine to address healing with pavement pres prods R11: No real application at this time
43	Improved Understanding of Fatigue Resistance Decline with Binder Oxidation	2.86	R4: Need to better understand aging #41, FDOT needs now, it's why OGFC's are giving ½ half the service life of conventional pavements Industry desperately needs a pavement weatherometer as a tool R7: This is a good, however, very challenging topic The environment which changes from location to location, binder properties,…etc are factors that should be included in the development of a model. R11: Give me rheological properties
42	Improved Understanding of Fast-Rate, Constant-Rate Binder Oxidation Kinetics Mechanism through the Effects of Inhibitors	2.85	R4: Need to better understand aging #41, FDOT needs now, it's why OGFC's are giving ½ half the service life of conventional pavements Industry desperately needs a pavement weatherometer as a tool R11: Just research R12: Coordination with WRI FPIII work on oxidation to be mentioned
14	Characterization of Fatigue and Healing Properties of Asphalt Mixtures Using Repeated Direct Tension Test	2.83	R7: If the AMPT can be used then this is a good study. R11: Next generation fatigue test for researchers.

#	Product Title	Sum	Comments
24	HMA Thermal Stresses in the Intermountain Region	2.82	R4: Only if researched on specimens subjected to accl'd aging, otherwise 1's R11: Limited use look for mix problems R12: Description and equipment to be detailed for completion (end 2012)
40	Validation of an improved Pavement Temperature Transport Model for use in an Oxygen and Thermal Transport Model of Binder Oxidation in Pavements	2.82	R4: Need to better understand aging #41, FDOT needs now, it's why OGFC's are giving ½ half the service life of conventional pavements Industry desperately needs a pavement weatherometer as a tool R11: Same as 39, what is the difference from field validation
31	Binder Lubricity Test – DSR	2.80	R2: Not very useful. Good idea, but need to test WMA mixtures instead, not just the binder. R3: Problem is that if you look at the viscosity of the 64-22 and 76-22 it show much higher numbers that what is actually out in the field. 90C and higher test temperatures are too high. They might work for these two grades but would not work for the 58 or lower grades. I do not see this as a test used to determine the amount of WMA additive or with the foamed material. Did the WMA binder in the lab get correlated to the field? Our experience would say no. R4: ? why, needs aggregates for any meaning R7: A correlation to a workability test for mixtures such as the ones listed in NCHRP 9-43 is recommended R9: Compaction is a method leading to performance as measured by density (or permeability). Agencies are moving toward performance and away from method, leaving the method choices up to the contractors. R11: Not the best approach
35	Asphalt Mixture Glass Transition Test	2.79	R4: Could be 0's R11: Research tool R12: Compare with TSRST outcome
41	Pavement Air Voids Size Distribution Model for use in an Oxygen and Thermal Transport Model of Binder Oxidation in Pavements	2.70	R4: Need to better understand aging #41, FDOT needs now, it's why OGFC's are giving ½ half the service life of conventional pavements Industry desperately needs a pavement weatherometer as a tool R11: Has to be part of 38 or 38 will not work
23	Thermal Stress Restrained Specimen Test (TSRST)	2.68	R7: The use of a cylindrical specimen in the TSRST has already been available. Correlation with field performance would be better objective. UMass Dartmouth would like to be included in the round robin study (if the study is conducted) R11: Already done R12: Description and equipment to be detailed for completion (09/2011)
11	Pavement Analysis Using Nonlinear Damage Approach (PANDA)	2.60	R4: Modeling is important but we have more immediate needs to allocate funds. Models need to take into consideration the proper aging of pavements. Current aging techniques pavements are limited and have little correlation to actual aging R11: Next generation design guide 2020 +
18	Nondestructive Characterization of Anisotropic Viscoelastic Properties of Undamaged Asphalt Mixtures under	2.54	R11: You need nonlinear response and that only comes with damage R12: Replace worship by workshop in recommended next

#	Product Title	Sum	Comments
	Compressive Loading		steps
29	Binder Yield Energy Test (BYET)	2.51	R3: Why determine modification type? What are performance grade binders? To what purpose does this need to be know? R11: Ductility test drop
34	Binder Glass Transition Test	2.49	R3: What performance of the mix can be tested to say that this test is meaningful? R4: Fraass Breaking Pt works for now R7: Study #35 for mixtures should be explored before the binder study #34 R11: Research tool R12: Compare proposed method outcome to DSR and DSC traditionally used
26	Bitumen Bond Strength Test (BBS)	2.49	R3: Is this an anti-strip test if so than temperature needs to be addressed? R4: Test in current condition is poor R11: Just test mix
9	Lattice Micromechanical Model for Virtual Testing of Asphalt Concrete in Tension	2.48	R4: Modeling is important but we have more immediate needs to allocate funds. Models need to take into consideration the proper aging of pavements. Current aging techniques pavements are limited and have little correlation to actual aging R11: Long term research for 2030 design
10	Cohesive Zone Modeling as an Efficient and Powerful Tool to Predict and Characterize Fracture Damage of Asphalt Mixtures Considering Mixture Microstructure, Material Inelasticity, and Moisture Damage	2.46	R4: Modeling is important but we have more immediate needs to allocate funds. Models need to take into consideration the proper aging of pavements. Current aging techniques pavements are limited and have little correlation to actual aging R7: It is not clear what equipment will be used. Furthermore, the analysis of fracture characteristics using the push-pull test should be finalized first (that is just the opinion of this reviewer) R11: Long term research 2030 +
25	Dynamic Model for Flexible Pavements 3D-Move	2.44	R7: The work sounds similar to the work related the PANDA R11: Need to demonstrate possible applications and time line R12: Description and equipment not detailed enough in current version
15	Nondestructive Characterization of Tensile Viscoelastic Properties of Undamaged Asphalt Mixtures	2.42	R3: There has many studies showing that phase angle is not a good property to set a specification on. R11: To do what
12	Test Methods for Determining the Parameters of Material Models in PANDA (Pavement Analysis Using Nonlinear Damage Approach)	2.38	R4: Modeling is important but we have more immediate needs to allocate funds. Models need to take into consideration the proper aging of pavements. Current aging techniques pavements are limited and have little correlation to actual aging R11: Next generation design guide 2020 +
36	Planar imaging/ Aggregate Structure	2.37	R11: Research tool R12: Validation needed

#	Product Title	Sum	Comments
44	Micromechanical Properties of Various Structural Components in Asphalt using Atomic Force Microscopy (AFM)	2.27	R7: The description needs to state how nano indentation can be done at intermediate and high temperatures. I doubt this can be done easily. Also, I am not sure if the AFM is as accurate as a nano indenter device. R11: Nice toy R12: Coordination with WRI ARC work on AFM to be mentioned
17	Self-Consistent Micromechanics Models of Asphalt Mixtures	2.25	R4: I know there is not 0! R11: Change the name
30	Rigden Voids for fillers	2.25	R4: British have a procedure, why? R11: Done 20 year ago

Significant Problems, Issues and Potential Impact on Progress

None.

Work Planned Next Quarter

The research team will continue with the development of the mid- and long-term technology development products.

PROGRAM AREA: TECHNOLOGY TRANSFER

CATEGORY TT1: OUTREACH AND DATABASES

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

Work Done This Quarter

The ARC website was maintained and updated. The ARC quarterly technical progress report, January 1- March 31, 2011, was uploaded to the ARC website. The ARC newsletter (Vol. 6, Issue 1) was uploaded to the website. The following references and files were updated:

- List of Publications and Conference Proceedings under the "Publications" webpage.
- List of Presentations and Posters under the "Outreach" webpage.

The 3D-Move Discussion Group Forum was also maintained.

Significant Results

None

Significant Problems, Issues and Potential Impact on Progress

None

Work Planned Next Quarter

Continue maintaining and updating the ARC website. Update the list of Publications and Conference Proceedings. Update the list of Presentations and Posters and the list of Theses and White Papers. Post information and new releases for 3D-Move. Maintain the 3D-Move Discussion Group Forum.

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

Work Done This Quarter

Published the ARC Newsletter Vol. 6, Issue 1.

Significant Results

None

Significant Problems, Issues and Potential Impact on Progress

None

Work Planned Next Quarter

Prepare and publish the ninth ARC Newsletter.

Work element TT1c: Prepare Presentations and Publications (All)

Presentations

Bahia, H, Velasquez, R., Moraes, R., *Improving Moisture Resistance of Asphalt Mixes by Direct Measurement of Bond Strength between Aggregates and Asphalts*. Presentation at 1st Congreso de Infraestructura del Transporte CITRANS, San Jose, Costa Rica, June 15th to16th, 2011.

Miller, Timothy, Hussain Bahia, and Raul Velasquez. "WCTG Data Analysis Update." *Rocky Mountain User/Producer Group Annual Meeting*, Tucson, AZ, 20 April 2011.

Moraes, R., Velasquez, R., Bahia, H., *Understanding Adhesion and Cohesion of Asphalt-Aggregate Systems Using the Bitumen Bond Test and the Sessile Drop Method*. Abstract accepted for 5th Eurasphalt and Eurobitume Congress, Istanbul, Turkey, 13th to 15th June, 2012.

Moraes, R., Velasquez, R., Bahia, H., *Selección de Materiales para Mezclas Asfálticas Resistentes al Daño por Humedad Utilizando el Método de La Gota Sésil*, XVI CILA – Congresso Ibero-Latino Americano do Asfalto, Rio de Janeiro, Brazil, 20th to 25th November, 2011.

Moraes, R., Velasquez, R., Bahia, H., *Selection of Moisture Damage Resistant Materials for Asphalt Mixtures Using the Bitumen Bond Strength Test and Sessile Drop Method*. Presentation for the 2011 Petersen Asphalt Research Conference, Laramie, Wyoming, 11th to 13th July, 2011.

University of Wisconsin-Madison, A paper entitled "Evaluation of Using the MSCR Test for Modified Binders' Specification" was submitted to the 56th Annual Conference of Canadian Technical Asphalt Association, November 2011.

Velasquez, Raul, Timothy Miller, and Hussain Bahia. "Asphalt Research Consortium (ARC) Update." *Rocky Mountain User/Producer Group Annual Meeting*, Tucson, AZ, 20 April 2011.

Publications

Bahia, H, Velasquez, R., Moraes, R., *Improving Moisture Resistance of Asphalt Mixes by Direct Measurement of Bond Strength between Aggregates and Asphalts*. Presentation at 1st Congreso de Infraestructura del Transporte CITRANS, San Jose, Costa Rica, June 15th to16th, 2011.

Li, Derek D., and M. L. Greenfield, 2011, High Internal Energies of Proposed Asphaltene Structures. *Energy Fuels*, in press.

Moraes, R., Velasquez, R., Bahia, H., *Understanding Adhesion and Cohesion of Asphalt-Aggregate Systems Using the Bitumen Bond Test and the Sessile Drop Method*. Abstract accepted for 5th Eurasphalt and Eurobitume Congress, Istanbul, Turkey, 13th to 15th June, 2012.

Tabatabaee, H.A., Velasquez, R., Bahia, H.U., Li, Z., "On the Importance of Fracture Properties of Asphalt Binders for Low Temperature Cracking of Asphalt Pavements" Abstract submitted to ISAP 2012.

Texas A&M University, "Microstructure-Based Inherent Anisotropy of Asphalt Mixtures," ASCE *Journal of Materials in Civil Engineering*, accepted for publication.

Texas A&M University, "Anisotropic Viscoelastic Properties of Undamaged Asphalt Mixtures," ASCE *Journal of Transportation Engineering*, accepted for publication.

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

<u>Work Done This Quarter</u>

The following list describes the work items completed or in progress this quarter:

- Continued training and usability feedback
- Bug fixes and performance enhancements
- User interface improvements
- File management system
- Deployment plan status
- Help System
- Public user interface
- Uploading data – status

<u>Significant Results</u>

<u>*Continued training and usability feedback*</u>

As planned, a workshop and round table session was held at the University of Nevada, Reno, as a follow-up to the Web-based training session held in February. This workshop was held on May 12, 2011. During this session, suggestions and feedback were gathered from each ARC organization to assess user-interface and feature improvements that would ease the use of the database. The following list summarizes the items discussed at the workshop:

- Performance issues were reported when entering measures (Fixed – See performance enhancements)

- As the number of materials increased, the Material Tree selector should display the material description. (Fixed – see user interface improvements)
- The File upload system should support standard keywords. The user interface should allow multiple files to be uploaded and default data associated with those uploaded files. (Fixed – see file management system)
- A facility needed to be created for replicate measures and the standard deviation between those measures (Fixed – see user interface improvements)
- In the measure viewer, it should be possible to select measures for different materials using the material selection tree. (Fixed – see user interface improvements)
- Try to develop a facility to import existing Excel data using UWM data as a prototype. (Working – see file management system)

Note that selected team members will participate in Web meetings roughly every five weeks

Bug Fixes and Performance Enhancements

The task of fixing bugs and making minor adjustments to the user interface continues. These fixes include such items as storing default values in fields to improve the user interface and data entry process.

As the database has entered full-scale use, it has become populated with a significant number of materials, properties, measures, and data files. Coinciding with this data population, users began to experience slowing response times in entering measures.

Testing began to identify the source of the problem and possible resolutions. Through testing, performance of the database (SQL Server) proved acceptable. The performance of the IIS server was also acceptable but could be improved. The lag was determined to be caused primarily by the transfer of large Web pages over the Internet from server to client and back, and preservation of some view state information that also increased page size.

Therefore, the code was reworked to minimize unneeded information being transferred across the Internet at the expense of additional calls to the database. Previously, the old values of each measure field were transmitted back from the user so the application could check for updates. Now, the application makes additional calls to the database to make the check. While minimizing database calls is generally desirable, this technique is appropriate for an application such as the ARC database, which has a relatively low number of users working with complex and extensive data entry forms. At this time, the database is able to handle the additional requests without overloading the database server.

The reconfigured process has resulted in a substantial performance improvement, and users now report satisfactory speed. Performance optimization, such as this, is common in late-stage development. While we follow best practices at every stage, it is often difficult to know which specific routines will create bottlenecks until they are encountered through full-scale testing.

Finally, the Web server currently hosting the ARC database will be upgraded to IIS version 7.5 during the next quarter. While not visible to the ARC user community, the application itself will be reconfigured to work with the latest Microsoft Framework version, and take advantage of the performance improvements possible with this version of IIS. Thus, after the upgrade, users should see additional performance improvements.

User Interface Improvements

The Material Tree previously displayed the material label for each material. However, as the number of materials grows, the material label does supply adequate descriptive information to identify the material. The material tree now shows the material description as shown in figure TT1d.1.

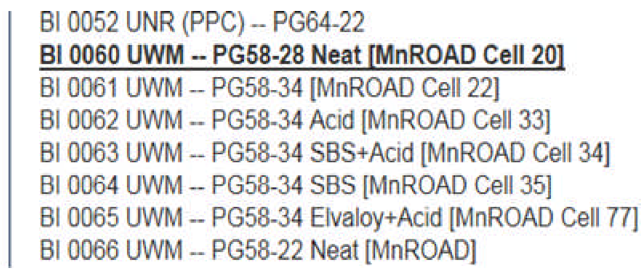


Figure TT1d.1. Material tree with description.

The material tree on the Measure Viewer page now contains a multi-select feature to allow for retrieval of measures by multiple materials. While users could always import all materials into a spreadsheet and refine their search there, having this filtering ability within the ARC database was important because the connections between the data are most readily perceived using the application tools. Figure TT1d.2 shows new the multi-select feature. As shown, the material selector has been modified such that the material descriptions appear. In addition, multiple materials can be selected simultaneously. Selected materials appear in the list box below the selection tree.

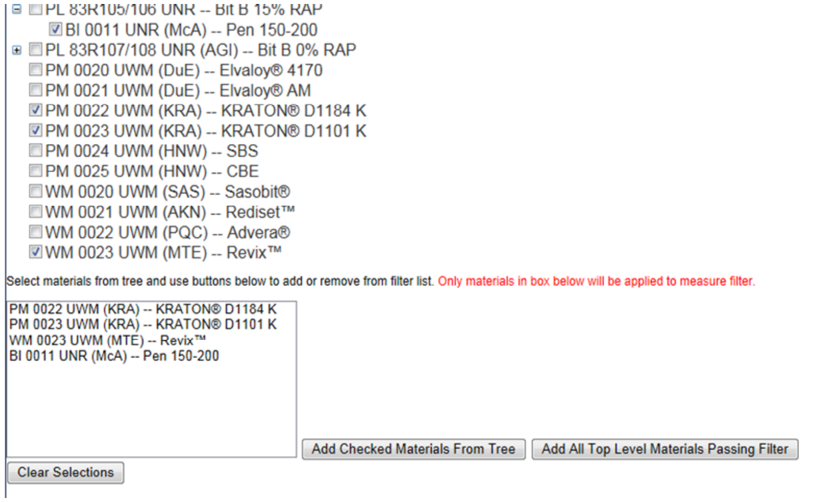


Figure TT1d.2. Multi-select feature.

File Management System

Development of the File Management system continues after significant feedback from the May 12 workshop and subsequent on-line conferences, in addition to the planned work for this quarter.

- The user interface should allow users to select multiple files at once. (Completed)
- The user interface should allow keywords to be associated with files and file groups. (Completed)
- The user interface should allow files to be associated with a material type for searching purposes. (Completed)
- Instead of arbitrary keywords being used, a hierarchical keyword list should be used so as to better structure data. (Working)

A multi-file select feature was added to the form that allows users to assign default values to the uploaded files. Figure TT1d.3 shows part of the form application to multi-file selection. As shown in the figure, files to be added appear in the list box. When the Upload List button is clicked all of the selected files will be uploaded and the default values applied. These values can be updated at any time.

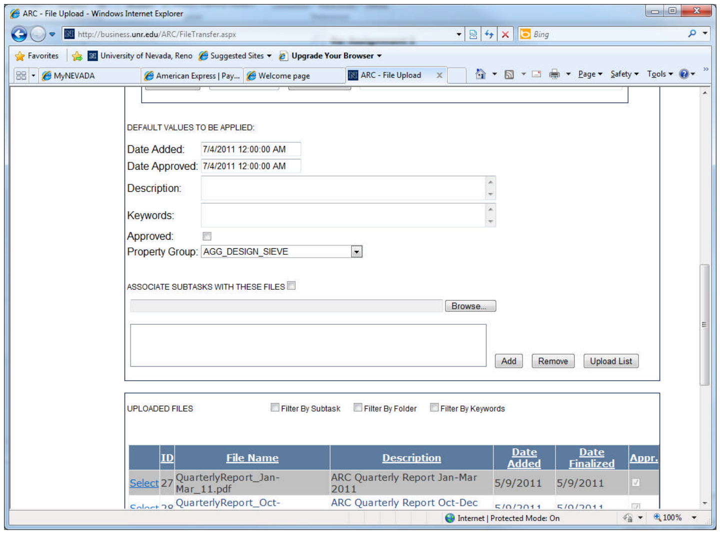


Figure TT1d.3. Form application for multi-file selection.

Finally, it should be noted that even the multi-file upload feature requires that client files be selected one at a time. Should the FHWA and consortium agree that client software, such as Silverlight, be installed on client computers, multi-file selection becomes possible. During the roundtable conference, the topic of report (file) keywords was discussed. It was decided that a feature was needed that would allow users to define report keywords based on a hierarchical list of pre-defined keywords. The list of hierarchical keywords has been proposed and is under review. The hierarchical keyword selection feature is made up of groups of drop-down boxes containing the suggested keyword. Users may also add keywords beyond those suggested. Originally, the keyword list was made up of a two-level hierarchy. This hierarchy will likely be expanded to three or four levels depending on the review. Figure TT1d.4 shows the keyword selection feature.

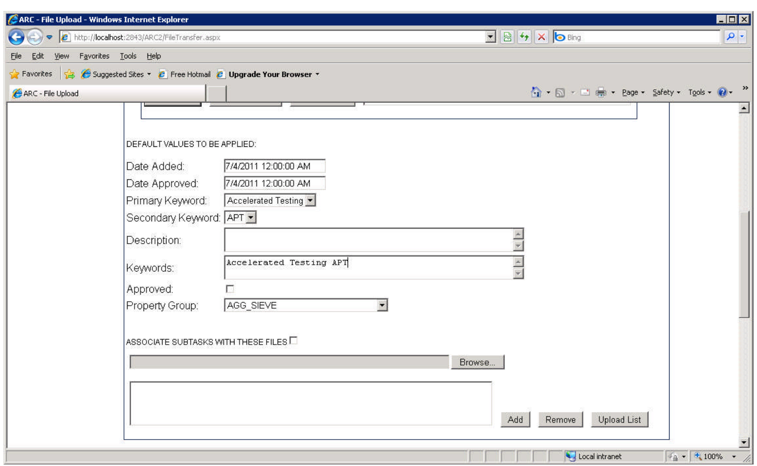


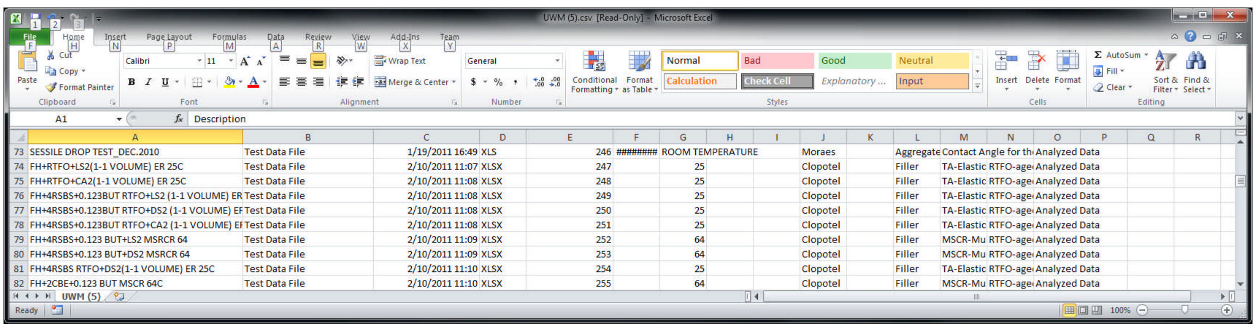
Figure TT1d.4. Keyword selection feature.

The data structure for the keyword selection feature might be implemented in a couple of ways.

- Create a static XML structure that can store the hierarchical keywords.
- Expand the database to store the keyword list.

As we expect the number of keywords to be relatively static, we have chosen a simple XML implementation to store the keywords, rather than creating additional tables, stored procedures, and links. Once the list of keywords has been finalized, they will be added to the database. We expect this task to be completed next quarter. In addition, consortium members recommend that some additional search fields be added. At this time the content of these fields is under review.

UWM has created significant test data for several properties and generated the associated test data files. Members of the roundtable workshop suggested that it would be beneficial to be able to upload this data and generate the necessary database a records that would associate the data with specific materials, properties, tests, and so on instead of uploading these files one at a time. Figure TT1d.5 shows a segment of this file.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
73	SESSILE DROP TEST_DEC.2010	Test Data File	1/19/2011 16:49	XLS	246	########	ROOM TEMPERATURE			Moraes		Aggregate	Contact Angle for th	Analyzed Data				
74	FH+RTFO+LS2(1-1 VOLUME) ER 25C	Test Data File	2/10/2011 11:07	XLSX	247		25			Clopotel		Filler	TA-Elastic	RTFO-age	Analyzed Data			
75	FH+RTFO+CA2(1-1 VOLUME) ER 25C	Test Data File	2/10/2011 11:08	XLSX	248		25			Clopotel		Filler	TA-Elastic	RTFO-age	Analyzed Data			
76	FH+4RSBS+0.123BUT RTFO+LS2 (1-1 VOLUME) ER	Test Data File	2/10/2011 11:08	XLSX	249		25			Clopotel		Filler	TA-Elastic	RTFO-age	Analyzed Data			
77	FH+4RSBS+0.123BUT RTFO+DS2 (1-1 VOLUME) EF	Test Data File	2/10/2011 11:08	XLSX	250		25			Clopotel		Filler	TA-Elastic	RTFO-age	Analyzed Data			
78	FH+4RSBS+0.123BUT RTFO+CA2 (1-1 VOLUME) EF	Test Data File	2/10/2011 11:08	XLSX	251		25			Clopotel		Filler	TA-Elastic	RTFO-age	Analyzed Data			
79	FH+4RSBS+0.123 BUT+LS2 MSRCR 64	Test Data File	2/10/2011 11:09	XLSX	252		64			Clopotel		Filler	MSCR-Mu	RTFO-age	Analyzed Data			
80	FH+4RSBS+0.123 BUT+DS2 MSRCR 64	Test Data File	2/10/2011 11:09	XLSX	253		64			Clopotel		Filler	MSCR-Mu	RTFO-age	Analyzed Data			
81	FH+4RSBS RTFO+DS2(1-1 VOLUME) ER 25C	Test Data File	2/10/2011 11:10	XLSX	254		25			Clopotel		Filler	TA-Elastic	RTFO-age	Analyzed Data			
82	FH+2CBE+0.123 BUT MSCR 64C	Test Data File	2/10/2011 11:10	XLSX	255		64			Clopotel		Filler	MSCR-Mu	RTFO-age	Analyzed Data			

Figure TT1d.5. UWM excel data.

At this time, the database development team has received sample data files. Following an online meeting, the following actions are planned:

- Presently, some records have missing or ambiguous data points. The development team will work iteratively with UWM and their consultants to modify the structure of the Excel file to account for the database's storage of core and composite materials.

- An organizational scheme needs to be developed to store the associated uploaded data files. This task will be a work item for next quarter.

Deployment Plan Status

The Deployment Plan was submitted to the ARC consortium and the FHWA last quarter. At this time, no decision has been made about hosting the ARC database in the long-term. However, the FHWA has been presented with the current hosting requirements. Should those hosting requirements change, the FHWA and consortium will be notified.

Help System

Work continues on the Help system as modifications are made to existing forms and new forms are created. At this point, nearly all Help pages correspond to the existing application pages. Due to pressing changes, the time spent on the Help system was less than expected.

Public User Interface

Some changes were made to the public user interface such as the ability to select measures for multiple materials. At the May workshop, it was decided that external (non-Arc consortium) users would need to request an account to gain access to the database. Presently, the account request form has been created. In addition, code development is underway that will supply the infrastructure to restrict external users to specific Web forms or parts of those Web forms. Figure TT1d.6 shows the prototype application form.

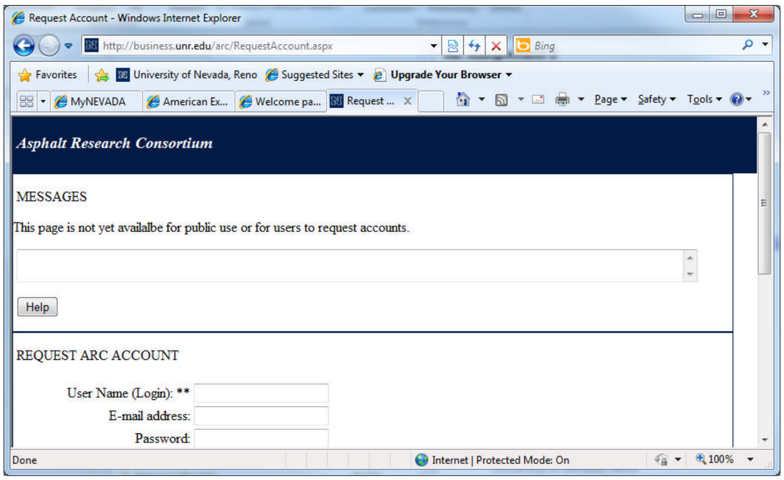


Figure TT1d.6. External user application form.

Uploading Data – Status

Users have started to upload significant data into the database along with starting to upload the accompanying support files and reports. The following table summarizes the volume of data entered so far in selected database entities.

Table TT1d.1 Summary of records.

Item Description	**Number of records**
Materials	83
Quantitative properties	112
Qualitative properties	30
Quantitative measures	1078
Qualitative measures	19
Multi-dimensional measures	1635

Significant Problems, Issues and Potential Impact on Progress

None

Work Planned for Next Quarter

- Continue with bug fixes and user-interface enhancement, and database documentation.
- Complete development of the keyword hierarchy.
- Finalize the design of the public interface and continue development based on implementation decisions made by ARC consortium members.
- Design and develop a data import subsystem to import UWM data and possibly use this subsystem as a prototype to import other data.

In addition, selected ARC members will continue to hold Web meetings roughly every five weeks to monitor status.

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

Work Done This Quarter

Uploaded the quarterly technical progress report and the ARC newsletter to the ARC website. Updated the “Publications” and “Outreach” web pages.

Significant Results

None.

Significant Problems, Issues and Potential Impact on Progress

None.

Work Planned Next Quarter

Upload the ARC quarterly technical progress report to the ARC website. Publish the ARC newsletter on the ARC website.

Work Element TT1f: Workshops and Training (UNR lead)

Work Done This Quarter

A workshop and round table session was held at the University of Nevada, Reno, as a follow-up to the Web-based training session held in February. This workshop was held on May 12, 2011. During this session, suggestions and feedback were gathered from each ARC organization to assess user-interface and feature improvements that would ease the use of the database.

Significant Results

None

Significant Problems, Issues and Potential Impact on Progress

None

Work Planned Next Quarter

None

TABLE OF DECISION POINTS AND DELIVERABLES FOR TECHNOLOGY TRANSFER

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for Changes in Delivery Date
TT1a: Development and Maintenance of Consortium Website (UNR)	Progress report	Upload quarterly progress report and newsletter	07/11	N/A	N/A
	Newsletter	Upload newsletter	07/11	N/A	N/A
	Progress report	Upload quarterly progress report and newsletter	10/11	N/A	N/A
	Newsletter	Upload newsletter	11/11	N/A	N/A
	Progress report	Upload quarterly progress report and newsletter	01/12	N/A	N/A
	Newsletter	Upload newsletter	03/12	N/A	N/A
	Progress report	Upload quarterly progress report and newsletter	04/12	N/A	N/A
TT1b: Communications (UNR)	Newsletter	Publish newsletter	07/11	N/A	N/A
	Newsletter	Publish newsletter	11/11	N/A	N/A
	Newsletter	Publish newsletter	03/12	N/A	N/A
TT1d: Development of Materials Database (UNR and All)	Workshop	Training for "super users" and "sub users" on how to use the materials database and validation section and to evaluate the potential errors, bugs and the ease of use of the database system.	04/11	Complete	N/A
	Database	Materials database software	03/12	N/A	N/A
TT1f: Workshops and Training (UNR and All) (TAMU)	Workshop	Training for "super users" and "sub users" on how to use the materials database and validation section and to evaluate the potential errors, bugs and the ease of use of the database system.	04/11	Complete	N/A
	Workshop	PANDA software training	8/11	N/A	N/A

Technology Transfer Year 5	Year 5 (4/2011-3/2012)												Team
	4	5	6	7	8	9	10	11	12	1	2	3	
(1) Outreach and Databases													
TT1a: Development and Maintenance of Consortium Website													UNR
TT1b: Communications													UNR
TT1c: Prepare presentations and publications													UNR
TT1d: Development of Materials Database													UNR
TT1d-1: Identify the overall Features of the Web Application													
TT1d-2: Identify Materials Properties to Include in the Materials													
TT1d-3: Define the Structure of the Database													
TT1d-4: Create and Populate the Database													
TT1e: Development of Research Database													UNR
TT1e-1: Identify the Information to Include in the Research Database													
TT1e-2: Define the Structure of the Database													
TT1e-3: Create and Populate the Database													
TT1f: Workshops and Training													UNR

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

Work planned
Work completed
Parallel topic

Technology Transfer	Year 2 (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