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INTRODUCTION

This document is the Quarterly Report for the period of October 1 to December 31, 2012 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, Advanced Asphalt Technologies, and the National Center for Asphalt Technology.

This Quarterly Report continues the new format presented in the previous quarterly report. The format is based on reporting on the anticipated project deliverables and was developed in consultation with FHWA AOTR, Mr. Eric Weaver. At this point in the project, much of the planned work is completed or nearing completion, therefore, many of the Subtasks and some Work Elements have coalesced into a larger product(s), as planned. The Table of Deliverables is presented following this introduction. The research progress is being presented as a Status Report based upon the identified project deliverables. The project deliverables are grouped into three areas, Reports, Test Methods and Practices, and Models and Software. In addition, this Quarterly Report reports on Other Research Activities which may develop deliverables as the work progresses. The project deliverables result from research that was grouped into seven areas, Moisture Damage, Fatigue, Engineered Paving Materials, Vehicle-Pavement Interaction, Validation, Technology Development, and Technology Transfer. The report begins with a Table of Deliverables that identifies the title of the deliverable, expected draft delivery date, and expected final delivery date. The table is updated each quarter.

The Quarter of October 1 to December 31, 2012 is third quarter of the Year 6 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.

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.

TABLE OF ASPHALT RESEARCH CONSORTIUM DELIVERABLES
(Note: Highlighted areas show changes)

Deliverable	Description	Draft Delivery Date	Final Delivery Date	ARC Partner	Staff Assignment	Notes
Summary Report	Comprehensive Summary Report (Level 1) (Report summarizing all work elements in significant detail to provide a single source documentation of ARC accomplishments)	4/30/2013	12/15/2013	TAMU	All	Reference level 2 and 3 deliverables for details
Report A	Summary report on Moisture Damage (Level 2)	1/31/2013	9/30/2013	TAMU	Masad	Reference level 3 deliverables for details
Report B	Characterization of Fatigue Damage and Relevant Properties (Level 2)	2/28/2013	10/31/2013	TAMU	Bhasin	Reference level 2 and 3 deliverables
Report C	PANDA: Pavement Analysis using a Nonlinear Damage Approach (Level 2)	3/31/2013	11/30/2013	TAMU	Darabi	Summary of PANDA methodology including descriptions of methods for indentifying model parameters

Deliverable	Description	Draft Delivery Date	Final Delivery Date	ARC Partner	Staff Assignment	Notes
Report D	Characterization of Asphalt Binders using Atomic Force Microscopy (Level 2)	3/31/2013	10/31/2013	TAMU	Little	Summary report on methodology for characterizing the phases of asphalt binder with description of composite implications
Report E	Lattice Model and Continuum Damage to Fracture (Level 2)	1/31/2013	9/30/2013	NCSU	R. Kim	Comprehensive report on lattice model
Report F	Microstructure Cohesive Zone Modeling for Moisture Damage and Fatigue Cracking (Level 2)	1/31/2013	8/31/2013	UNL	Y.R. Kim	Comprehensive report of cohesive zone model
Report G	Design System for HMA Containing a High Percentage of RAP Material	12/31/2013	3/31/2014	UNR	Sebaaly Hajj	
Report H	Critically Designed HMA Mixtures	5/31/2013	11/30/2013	UNR	Hajj Sebaaly	
Report I	Thermal Cracking Resistant Mixes	8/31/2013	12/31/2013	UNR	Hajj Sebaaly	
Report J	Pavement Response Model to Dynamic Loads 3D Move	3/31/2013	9/30/2013	UNR	Hajj Sebaaly	
Report K	Development of Materials Database	6/30/2013	12/31/2013	UNR	Hajj Ekedahl	
Report L	Development and Validation of the Bitumen Bond Strength Test (BBS)	Completed 10/31/11	3/31/2013	UWM	Hanz	
Report M	Development of Test Procedures for Characterization of Asphalt Binder Fatigue and Healing	Completed 10/31/11	6/30/2013	UWM	Tabatabaee	Final pending receipt of peer review comments

Deliverable	Description	Draft Delivery Date	Final Delivery Date	ARC Partner	Staff Assignment	Notes
Report N	Guideline for Selection of Modification Techniques	9/30/2013	3/31/2014	UWM	Tabatabaee	6 months scheduled for peer review
Report O	Characterization of Binder Damage Resistance to Rutting	6/30/2013	12/31/2013	UWM	Tabatabaee	Draft extended 6 months
Report P	Quantifying the Impacts of Warm Mix Asphalt on Constructability and Performance	3/31/2013	10/31/2013	UWM	Hanz	
Report Q	Improvement of Emulsion Characterization and Mixture Design for Cold Bitumen Applications	9/30/2013	3/31/2014	UWM	Hanz	Final moved up 3 months
Report R	Studies on Tire-Pavement Noise and Skid Response	Completed 12/31/11	6/30/2013	UWM	Roohi	Extended 3 months for NTIS formatting
Report S	Molecular dynamics results for multiple asphalt chemistries	5/31/2013	12/31/2013	URI	Greenfield	
Report T	Progress Toward a Multi-scale Model of Asphalt Pavement- Including Test Methods for Model Input Parameters	5/31/2013	12/31/2013	WRI	Pauli	
Report U	Design Guidance for Fatigue and Rut Resistance Mixtures	9/30/2013	3/31/2014	AAT	Bonaquist Christensen	NTIS format report with Technical Brief
Report V	Continuum Damage Permanent Deformation Analysis for Asphalt Mixtures (Level 2)	2/28/2013	10/31/2013	TAMU	Lytton/Luo	Reference appropriate level 3 deliverables
Report W	Characterization of Fatigue and Healing Properties of Asphalt Mixtures (Level 2)	2/28/2013	10/31/2013	TAMU	Lytton/Luo	Reference appropriate level 3 deliverables

Deliverable	Description	Draft Delivery Date	Final Delivery Date	ARC Partner	Staff Assignment	Notes
Report X	Characterization of Field Cores of Asphalt Pavements (Level 2)	2/28/2013	10/31/2013	TAMU	Lytton/Luo	Reference appropriate level 3 deliverables
Report Y	Water Vapor Diffusion in Pavement and Its Effects on the Performance of Asphalt Mixtures (Level 2)	3/31/2013	11/30/2013	TAMU	Lytton/Luo	Reference appropriate level 3 deliverables
Report Z	Effect of Extraction Methods on the Properties of Aggregates in Reclaimed Asphalt Pavement (NTIS format)	3/1/2013		UNR	Hajj Sebaaly	
AASHTO Method	Simplified Continuum Damage Fatigue Analysis for the Asphalt Mixture Performance Tester	3/31/2013	9/30/2013	AAT	Bonaquist Christensen	Development documented in Report U
AASHTO Method	Wilhelmy Plate Test (Level 3)	1/31/2013	6/30/2013	TAMU	Bhasin	Referenced in Reports A & B
AASHTO Method	Universal Sorption Device (Level 3)	1/31/2013	6/30/2013	TAMU	Bhasin	Referenced in Reports A & B
AASHTO Method	Dynamic Mechanical Analysis (Level 3)	1/31/2013	6/30/2013	TAMU	Kassem	Referenced in Reports A & B
ASTM Method	Automated Flocculation Titrimetric Analysis	Completed		WRI	Harnsberger Pauli	ASTM D-6703
AASHTO Method	Determination of Polymer in Asphalt	Completed		WRI	Harnsberger	
AASHTO Method	A Method for the Preparation of Specimens of Fine Aggregate Matrix of Asphalt Mixtures (Level 3)	1/31/2013	6/30/2013	TAMU	Kassem	Referenced in Reports A & B
AASHTO Method	Measuring intrinsic healing characteristics of asphalt binders	1/31/2013	6/30/2013	TAMU/ UT	Bhasin	Referenced in Report B
AASHTO Method	Test Methods for Determining the Parameters of Material Models in PANDA (Pavement Analysis Using Nonlinear Damage Approach) (Level 3)	2/28/2013	7/31/2013	TAMU	Kassem Darabi	Referenced in Report C

Deliverable	Description	Draft Delivery Date	Final Delivery Date	ARC Partner	Staff Assignment	Notes
Test Method & Model	Continuum Damage Permanent Deformation Analysis for Asphalt Mixtures (Level 3)	2/28/2013	10/31/2013	TAMU	Lytton/Luo	Referenced in Report V
Test Method & Model	Characterization of Fatigue and Healing Properties of Asphalt Mixtures (Level 3)	3/31/2013	9/30/2013	TAMU	Lytton/Luo	Referenced in Report W
Test Method Analysis Program	Nondestructive Characterization of Tensile Viscoelastic Properties of Undamaged Asphalt Mixtures (Level 3)	2/28/2013	10/31/2013	TAMU	Lytton/Luo	Referenced in Reports W & Y
Test Method & Model	Characterization of Field Cores of Asphalt Pavements (Level 3)	3/31/2013	10/31/2013	TAMU	Lytton/Luo	Referenced in Reports W & X
Test Method Analysis Program	Nondestructive Characterization of Anisotropic Viscoelastic Properties of Undamaged Asphalt Mixtures under Compressive Loading (Level 3)	2/28/2013	10/31/2013	TAMU	Lytton/Luo	Referenced in Report V
AASHTO Practice	Mix Design for Cold-In-Place Recycling (CIR)	12/31/2013		UNR	Sebaaly Hajj	Detailed in Report Z
AASHTO Practice	Mix Design for Cold Mix Asphalt	9/30/2013	3/31/2014	UWM	Hanz	6 months for ETG review
AASHTO Practice	Evaluation of RAP Aggregates	12/31/2012		UNR	Sebaaly	Detailed in Report G
AASHTO Practice	Identification of Critical Conditions for HMA mixtures	12/31/2012		UNR	Hajj Sebaaly	Detailed in Report H
AASHTO Method	Determining Thermal Crack Properties of Asphalt Mixtures Through Measurement of Thermally Induced Stress and Strain	Completed 5/31/2012		UNR	Hajj Velasquez	Detailed in Report I
AASHTO Method	Determining Asphalt Binder Bond Strength by Means of the Bitumen Bond Strength Test (BBS)	Completed	3/31/13	UWM	Hanz	Approved as AASHTO TP-91

Deliverable	Description	Draft Delivery Date	Final Delivery Date	ARC Partner	Staff Assignment	Notes
AASHTO Method	Measurement of Asphalt Binder Elastic Recovery in the Dynamic Shear Rheometer (DSR)	Completed 1/31/2013	6/30/2013	UWM	Tabatabaee	Combine ER, DSR, and BYET
AASHTO Method	Estimating Fatigue Resistance of Asphalt Binders Using the Linear Amplitude Sweep (LAS)	Completed	6/30/2013	UWM	Tabatabaee	Approved as AASHTO TP-101
AASHTO Method	Binder Yield Energy Test (BYET)	1/31/2013	6/30/2013	UWM	Tabatabaee	Combine with ER, DSR, BYET
AASHTO Method	Measurement of Rigden Voids for fillers	Completed 1/31/2013	6/30/2013	UWM	Roohi	6 months for review
AASHTO Method	Measurement of Asphalt Binder Lubricity Using the Dynamic Shear Rheometer (DSR)	3/31/2013	9/30/2013	UWM	Hanz	6 months for review
AASHTO Method	Procedure for Evaluation of Coating for Cold Mix Asphalt	3/31/2013	9/30/2013	UWM	Hanz	Draft extended 3 months
AASHTO Method	Cold Mix Laboratory Specimen Preparation Using Modified SGC Molds	6/30/2013	12/31/2013	UWM	Hanz	Draft extended 6 months
AASHTO Method Software	RAP Binder PG True Grade Determination	Completed 9/30/2012	6/30/2013	UWM	Hanz	Action pending ETG comments
AASHTO Method	Measurement of Asphalt Binder Fracture Properties Using the Single Edge Notch Bending Test	Completed 9/30/2012	6/30/2013	UWM	Tabatabaee	Action pending ETG comments
AASHTO Method	Test Method for Measurement of the Glass Transition Temperature of Asphalt Binders	Completed 1/31/2013	6/30/2013	UWM	Tabatabaee	Action pending FHWA/ETG comments
AASHTO Method	Test Method for Measurement of the Glass Transition Temperature of Asphalt Mixtures	3/31/2013	6/30/2013	UWM	Tabatabaee	Combined with UNR TSRST procedure

Deliverable	Description	Draft Delivery Date	Final Delivery Date	ARC Partner	Staff Assignment	Notes
AASHTO Method Software	Analysis of Asphalt Mixture Aggregate Structure through Use of Planar Imaging and Image Processing & Analysis System (IPAS)	3/31/2013	9/30/2013	UWM	Roohi	Action pending ETB comments
AASHTO Method	Determining the Resistive Effort of Asphalt Mixtures during Compaction in a Gyrator Compactor using an Internal Device	Completed ASTM	3/31/2013	UWM	Hanz	ASTM Standard approved
AASHTO Method	Micromechanical Properties of Various Structural Components in Asphalt using Atomic Force Microscopy (AFM) (Level 3)	3/31/2013	8/31/2013	TAMU	Little	Appendix in Report D
AASHTO Method	Test Method for Fatigue of Binder and Mastics: A cyclic direct tension test that can provide direct evaluation of fatigue for binder and mastic. It can also provide model validation and model parameter inputs.	4/30/2013	10/31/2013	VT	Wang	
AASHTO Method	Evaluate Healing using Continuum Damage Approach (Level 3)	3/31/2013	8/31/2013	TAMU/ UT	Bhasin	Appendix in Report B
Test Method & Analysis Program	Self-Consistent Micromechanics Models of Asphalt Mixtures (Level 3)	2/28/2013	10/31/2013	TAMU	Lytton/Luo	Referenced in Report W
AASHTO Method & Analysis Program	Rutting Prediction of Asphalt Binder Considering Stress-Dependence of Creep Behavior (Level 3)	3/31/2013	9/30/2013	TAMU	Little	References to Dissertation & journal papers
AASHTO Method	Method to determine surface roughness of aggregate and fines based on AFM	9/30/2013	4/30/2014	WRI	Grimes	Will be subject of Tech. Pub.
AASHTO Method	A method to determine ductile-brittle properties via AFM measurements	4/30/2013	11/30/2013	WRI	Grimes	Will be subject of Tech. Pub.
AASHTO Method	AFM-based micro/nano-scale cyclic direct tension test	3/31/2013	10/31/2013	WRI	Grimes	Will be subject of Tech. Pub.

Deliverable	Description	Draft Delivery Date	Final Delivery Date	ARC Partner	Staff Assignment	Notes
AASHTO Method	Measurement and Texture Spectral Analysis of Pavement Surface Profiles Using a Linear Stationary Laser Profiler (SLP)	Completed 9/30/2012	3/31/2013	UWM	Roohi	Pending FHWA review
Model	HMA Thermal Stresses in Pavement	3/31/2014		UNR	Hajj	Detailed in Report I
Software	Dynamic Model for Flexible Pavements 3D-Move	9/30/2013		UNR	Hajj Siddharthan	Detailed in Report J
Model & Test Method	Improved Oxygen and Thermal Transport Model of Binder Oxidation in Pavements (Level 3)	2/28/2013	10/31/2013	TAMU	Glover	Part of Report B & Summary Report References to Dissertations and Journal Papers
Model & Test Method	Pavement Air Voids Size Distribution Model for use in an Oxygen and Thermal Transport Model of Binder Oxidation in Pavements (Level 3)	2/28/2013	10/31/2013	TAMU	Glover	Part of Report B & Summary Report References to Dissertations and Journal Papers
Model	Approaches to interpret MD simulation results and experimental data to quantify the composition and temperature dependence of free energy.	3/31/2013		URI	Greenfield	Detailed in Report S
Model and Software	Phase-Field Model of Asphalt Binder Fracture and COMSOL Code for Model	1/31/2013	10/31/2013	VT	Wang	Detailed in Report T
Software	PANDA Software (Pavement Analysis using a Nonlinear Damage Approach)	12/31/2013	6/20/2014	TAMU	Sun-Myung Kim	

REPORTS

REPORT A: SUMMARY REPORT ON MOISTURE DAMAGE

Included Work Elements/Subtasks

Subtask M2b-1: Measurement of diffusion of water through thin films of asphalt binders and through mortars

Status and Work Planned: The work under this work element is completed. The findings are documented in a dissertation that is being reformatted as a chapter in the level 2 report A on moisture damage. Procedures to measure diffusivity of water through asphalt binders and mortars will be in the Appendices to the level 2 report A on moisture damage.

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

Status and Work Planned: The work in this quarter is on schedule. In this quarter, more specimens were tested following the experimental testing plan. All the data are summarized in the following table:

Table 1. Summary of the fracture parameters for specimens fabricated with Nustar and Valero binder.

Aggregate	Binder Type	Specimens ID	Air Void (%)	Conditioning RH (%)	Fracture Parameters	
					n'	A'
Hanson Limestone	Nustar PG76-22	4_A0	8.05	0	3.23	4.38E-17
		5_A0	6.79	100	9.02	2.54E-42
		8_A0	7.82	100	10.99	7.25E-51
		9_A6	7.49	0	5.97	4.86E-29
		10_A6	7.64	0	5.15	1.74E-25
	Valero PG64-16	7_A0	7.54	0	2.96	6.83E-16
		8_A0	6.91	100	11.44	1.09E-52
		9_A0	7.35	100	10.52	1.06E-48
		11_A6	6.58	0	7.94	1.59E-37
		12_A6	7.37	0	8.12	2.56E-38

Table 1 shows that as the relative humidity conditioning increases to 100%, the fracture parameter n' tends to increase for both Nustar and Valero specimens, which indicates that the saturated vapor pressure in the specimens significantly decreases the fatigue resistance of the asphalt mix material. The modified Paris Law parameter A' tends to decrease as the relative humidity condition increases. This decrease is not adequate to offset the increase of $n^{'}$. The testing results also indicate that the presence of moisture induces more fatigue damage than aging at 60°C for a period of six weeks. These results indicate that the presence of moisture in the asphalt due to vapor diffusion increases the fatigue cracking of asphalt mixes significantly.

In this quarter, the wind speed effect was considered in modeling the vapor diffusion process in pavement by using the Crank-Nicolson numerical method. The flux boundary condition, including wind speed at the pavement surface, was formulated as follows:

$$\frac{\partial u}{\partial x} = f(u) * (u_a - u_s) \tag{1}$$

Where $\frac{\partial u}{\partial x}$ = the rate of potential evaporation (PE); u_a = the suction in the air; u_s = the suction at the pavement surface; and $f(u)$ is a function which depends on the wind above the surface of the pavement and can be expressed as follows:

$$f(u) = h * (1 + \alpha_m) \tag{2}$$

Where h = coefficient of vapor transfer at the boundary surface; and α_m = the mass exchange coefficient of water vapor due to the wind at surface. Specifically, Equation 3 indicates that the wind speed increases the water vapor mass exchange at the surface α_m:

$$\alpha_m = K\sqrt{\frac{V}{L}} \tag{3}$$

where V = the wind speed, m/sec; and L = the length over which the wind blows; the largest α_m occurs if the wind blows across the width of the highway, m. Based on the work done by Afanas'ev, the K can be expressed as:

$$K = 0.662\lambda_m (P_{rm})^{1/3} (\frac{1}{\upsilon})^{1/2} \tag{4}$$

where P_{rm} = Prandtl number for air; v = the kinematic viscosity of air, m^2/sec; and λ_m is considered as a constant at the air temperature of 20 °C and was taken as $2.54 \times 10^{-3} kg / (s^{-1} \cdot m^2)$.

Figure 1 shows that as the time after placement increases, the asphalt surface layer gradually wets up due to the moisture movement from the subgrade soil into the base course and then into the surface layer. The closer to the pavement surface, the lower is the relative humidity in the asphalt layer. The moisture builds up in the asphalt mixture at such a fast rate that the RH in the surface asphalt layer reaches 90% in approximately 90 days, and the RH level increases with time within the asphalt layer. These modeling results illustrate that the wind speed on the pavement surface will significantly increase the water vapor diffusion in pavement.

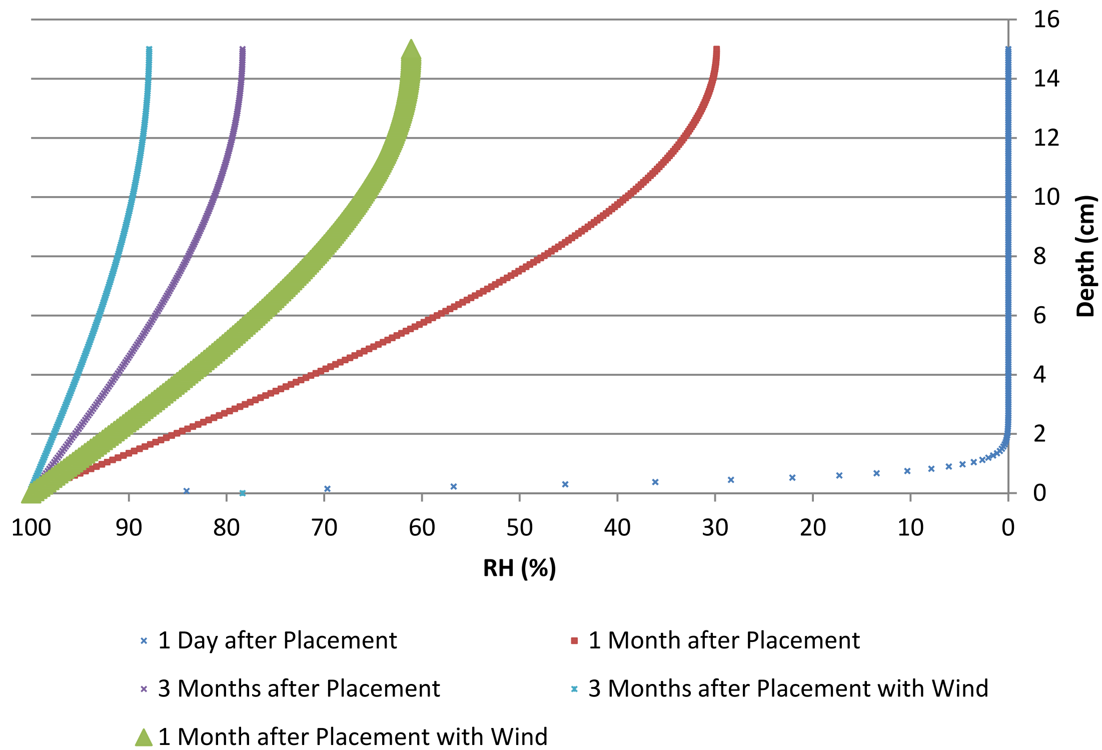


Figure 1. Wind speed effect on water vapor diffusion in pavement.

REPORT B: CHARACTERIZATION OF FATIGUE DAMAGE AND RELEVANT PROPERTIES

Included Work Elements/Subtasks

Subtask F1b-1: Nonlinear viscoelastic response of asphalt binders and mortars under cyclic loading.

Status and Work Planned: On schedule. We have completed the work associated with the constitutive modeling that accounts for nonlinearity and the three dimensional stress state of asphalt binder. This work has been documented in two detailed journal articles. The findings will be formatted as a Chapter for Report B, which is the level 2 report B addressing fatigue damage. Following the feedback from the models ETG, it has been recognized that characterization of the nonlinear response and the effect of the three dimensional stress state is very important at the mortar and mixture length scales. To this end, this model is being applied to asphalt mortar specimens, the findings of which are elaborated under on-going technical research.

Work Element F1d: Healing.

Status and Work Planned: On schedule. We have completed the work associated with characterizing the intrinsic healing of asphalt binders as well as the overall healing in asphalt composites (mortars) using the viscoelastic continuum damage or work potential theory. The protocol is currently being revised and will be applied to different modes of loading and other core ARC materials as discussed in the on-going technical research. Findings from work element F1d are being summarized as a chapter in the level 2 report B on fatigue damage.

Work Element F1b: Viscoelastic Properties

Subtask F1b-1: Viscoelastic properties under cyclic loading

Status and Work Planned:

During previous quarter, specimen geometry appropriate for testing with the Arcan apparatus was selected based on finite element modeling. Recall that the Arcan apparatus is being used to evaluate the material response under a combination of stress-states, which is more realistic representation of the stress-state being experienced by the material in the field. Figures F1b1. and F1b.2 illustrate a FAM test specimen in the Arcan fixture and typical results from a load controlled test. The pattern on the sample surface is for Visual Image Correlation (VIC) for strain measurement. Trial tests were done to test calibration and accuracy of VIC apparatus.

This quarter, work was focused on performance evaluation of required components and procedures for conducting the test. These include use of appropriate adhesive, shaping the specimen with least possible damage with appropriate tools, and providing sufficient texture to specimen so that VIC can measure strain more accurately. Some tests were conducted to identify extent of damage caused by specific load and loading rate. The results from these tests were used to establish the range of loads and loading rates for subsequent testing and analysis.

Figure F1b.1. Illustration of a failed FAM test specimen in the Arcan apparatus to identify limits of loading and loading rate; the Arcan apparatus is used to evaluate material response under multi-axial stress states.

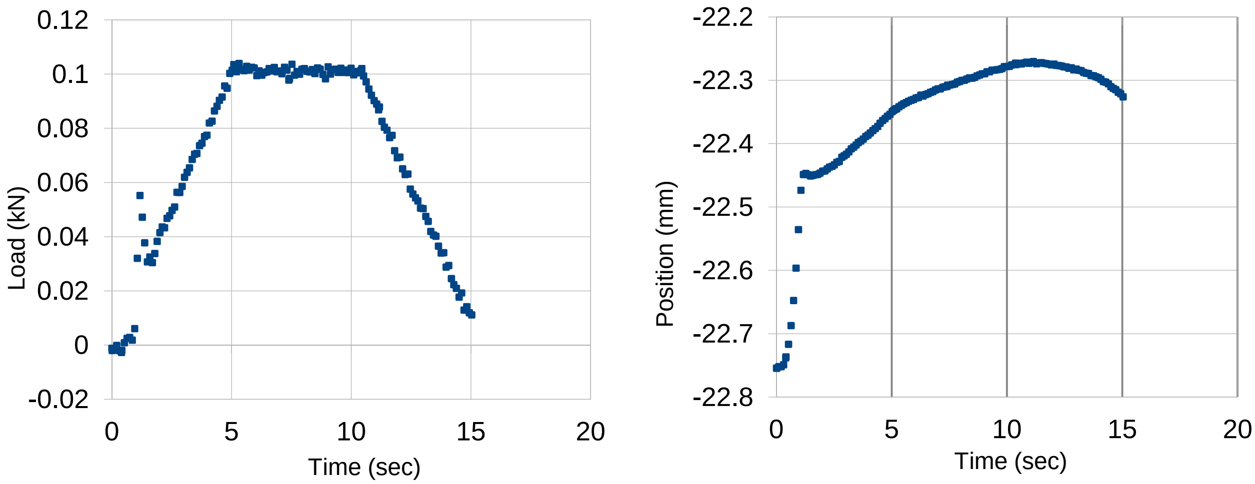


Figure F1b.2. Typical results from the Arcan apparatus in which the specimen can be subjected to multi-axial stress state

Significant Results

Testing is in progress and there are no significant conclusions at this time.

Significant Problems, Issues and Potential Impact on Progress

None.

Work Planned Next Quarter
In next quarter, we plan to test more samples to measure strains under multi-axial loading.

Work Element F1c: Material Properties: Aging

Subtask F1-c: Develop a Transport Model of Binder Oxidation in Pavements

Status and Work Planned: This project has produced a regular and comprehensive progression of developments in the modeling of asphalt binder oxidation in pavements. The work has included improvements to the transport model, a better understanding of binder oxidation kinetics, measurements of binder material properties and their changes due to binder oxidation, and work towards understanding and quantifying the effect of binder oxidation on mixture properties. The work on binder oxidation kinetics included measurements on five ARC and SHRP binders.

A key element of the development process is model validation using pavement cores. The civil engineering effort previously received cores from the Yellowstone National Park ("YNP") site and completed testing on the warm mix cores but this did not include x-ray CT measurements. The hot mix cores have been scheduled for x-ray CT imaging. Following this work, the civil engineering effort will complete their core testing and then pass the hot mix cores to or group for binder characterization.

POV testing was completed on the binder we received from the YNP test site. The longest aging times were completed and testing of the binder was performed (CA levels using FTIR, and tested for rheological properties using DSR). These aging data can now be used to determine the reaction kinetics parameters for the YNP binder.

The civil engineering effort HMA core testing has not yet been completed. X-ray CT testing is planned for the near future, and will be followed by completion of the core testing required to be completed prior to our receipt of the cores for binder testing.

Work Planned Next Quarter

Work in the final quarter of the project will continue with validation, to the extent appropriate pavement materials are available.

We plan to continue with our model validation using the YNP HMA cores. After x-ray CT and civil engineering's testing of the HMA cores is complete, we will perform volumetric testing (bulk specific gravity, accessible air voids, maximum theoretical specific gravity, and total air voids), as required, on the YNP cores. After this we will perform extraction, recovery, and binder property measurement. Depending on progress, we may be able to complete aging model calculations using the testing results. The aging model calculations can then be compared to the measured properties of the extracted and recovered binder.

The results of work element F1c is being incorporated in a level 2 report on fatigue damage. The chapter in which F1c is discussed addresses the impact of aging on fatigue damage.

Work Element F1d: Healing

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

Work Done This Quarter

In the previous quarter, we proposed to use an improved single-specimen protocol to measure the overall healing in asphalt composites in shear mode using a dynamic shear modulus. The characteristic overall healing curve for the material is based on the same viscoelastic continuum damage (VECD) theory that is currently being used for the analysis of fatigue cracking resistance of asphalt mixtures.

The protocol proposed in earlier quarter incorporated a fatigue test with different durations of rest period introduced at multiple levels of damage on the same test specimen. The specimens were subjected to oscillatory torsional shear tests at 250,000 Pa, 10 Hz and 25^{o}C in a DSR. The rest periods were varied from 40, 20, 10 to 5 minutes at each of the three damage levels - 80%, 70% and 60% of the initial linear viscoelastic stiffness for the earlier report. The results were analyzed to obtain the healing values based on a single curve without any rest period, as illustrated in figure F1.d.1.

In this quarter, attempts have been made to validate that the healing results obtained by following the above mentioned protocol of experiments and data analysis are similar to the results obtained by performing similar tests using separate specimens per each same damage level each comprising different rest periods. The specimens used for validation purposes were obtained by coring the Superpave gyratory compacted fine aggregate matrix (FAM) specimens with same mix design volumetric and geometric properties as before. The value of controlled stress of 25,000 Pa and the test temperature of 25^{o}C were also kept same as before.

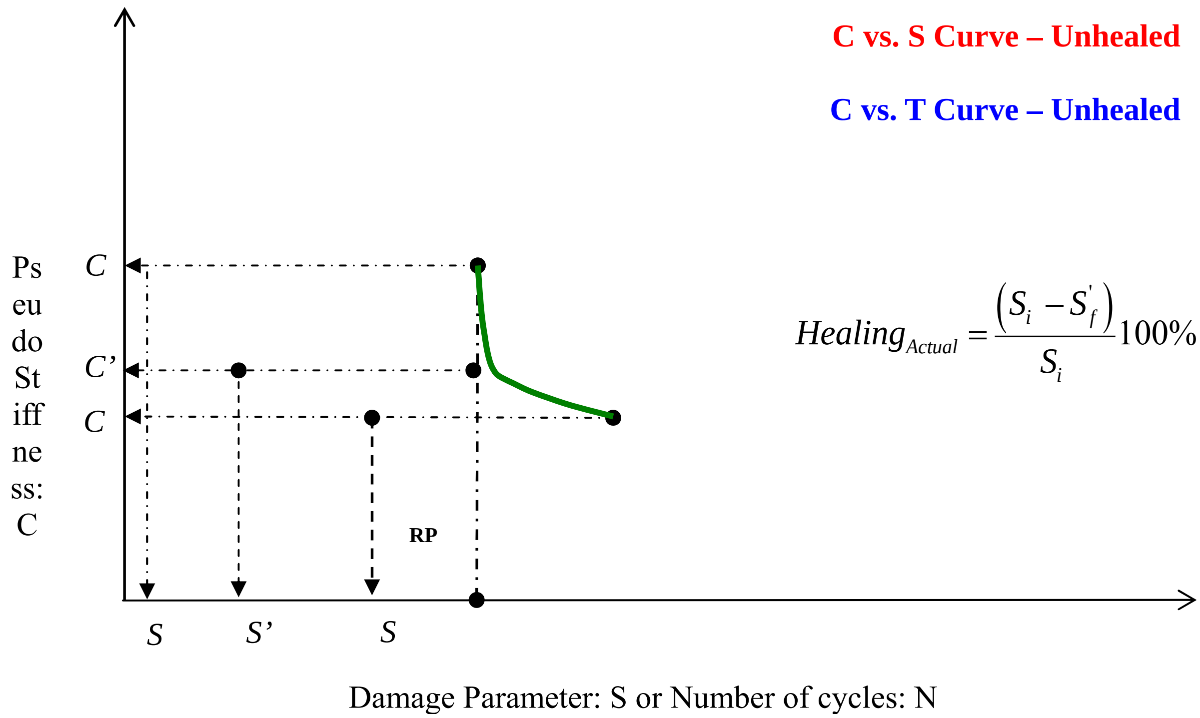


Figure F1d.1. Analytical method for determining the healing values from C vs. T and C vs. S curves.

Significant Results

The healing values obtained by performing the fatigue and healing tests using different specimens per each damage level are presented in figure F1.d.2 along with the values along with the results for obtained by performing the multi-step protocol for rest period and damage level at 10 Hz and 250,000 Pa. The figure clearly manifests that the test results obtained from different specimens for 0.60% target health level are almost the same as the ones obtained for same health level from the protocol proposed in last quarter. In both cases, the healing value increases with increase in rest period at certain damage level and vice versa. Similarly, the test specimens manifest more healing when the rest period is introduced at smaller level of damage when subjected to similar rest periods. All these observations tend to validate the significance of single specimen multi-step protocol proposed in last quarter.

More detailed and specific conclusions will be made based on the results from more ongoing tests for 70% and 80% target health levels. Since these analyses are based on the damage parameter from the continuum damage model, they are expected to be independent of the loading amplitudes and the frequencies. Next quarterly report will investigate and validate this fact in depth.

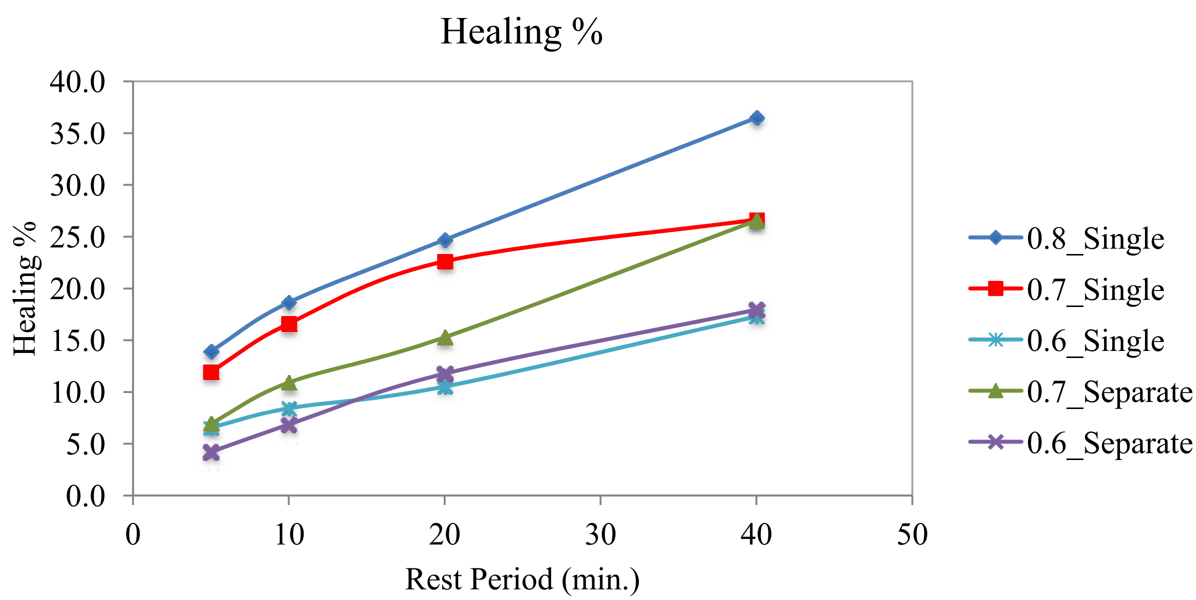


Figure F1d.2. Typical results from multiple combinations of rest period durations and damage levels using single and separate specimens (Materials: PG 67-22 binder and Limestone screenings < 1.19 mm; Geometry: 12.25mm diameter, 45 mm length; Loading: 250000 Pa, 10 Hz, 25^{o}C)

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

None.

<u>Work Planned Next Quarter</u>

The approach will be further validated by using one more mix design containing another different binder obtained from ARC, as well as tension-compression mode of loading, i.e., the second approach of characterizing healing mentioned in earlier report. Findings from work element F1d are being summarized in an appropriate chapter of the level 2 report B on fatigue damage.

<u>Work Element F1c</u>: Material Properties: Aging

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

<u>Status and Work Planned</u>: We are on Schedule in this Subtask.

This project has produced a regular and comprehensive progression of developments in the modeling of asphalt binder oxidation in pavements. The work has included improvements to the transport model, a better understanding of binder oxidation kinetics, measurements of binder material properties and their changes due to binder oxidation, and work towards understanding and quantifying the effect of binder oxidation on mixture properties. The work on binder oxidation kinetics included measurements on five ARC and SHRP binders.

A key element of the development process is model validation using pavement cores. Last quarter we received aged ARC cores for comparison to model calculations. Specimens that were received are from the Arizona test sites and were cored in December 2010. Fatigue testing was completed last quarter.

This quarter additional testing of the Arizona cores was performed. The following properties were determined: bulk specific gravity, accessible air voids, maximum theoretical specific gravity, and total air voids. The binder was extracted from the cores and recovered, and binder properties were measured. Binder properties that were determined include carbonyl area and DSR function. Binder kinetics could not be determined because the quantity of binder was insufficient for either POV or PAV testing.

Due to insufficient cored material, it is not possible to perform model validation using the Arizona cores, but it may be possible to perform equivalent validation procedures using the Yellowstone National Park cores and loose mix (see below).

Work in the final quarters of the project will continue with validation, to the extent appropriate pavement materials are available.

We plan to perform model validation using cores and loose mix from the Yellowstone National Park test sites. Cores have been received by the civil engineering department and should be available for our use within one month. We are planning to request loose mix, which was saved at the time of construction. If received, we intend to perform POV testing to determine binder kinetics parameters. Using the kinetics parameters, along with air void structure data and temperature data, we can use the developed model to predict carbonyl area as a function of aging time. The model prediction can be compared with measurements of carbonyl area in binder extracted from the cores.

Work also is proceeding on a chapter on aging modeling that will comprise a chapter in the level 2 fatigue damage report and will also be incorporated in the level 2 report on the PANDA and specifically to address the impact of aging.

<u>Included Work Elements/Subtasks</u>

<u>Work Element F2c</u>: Mixture Testing Protocol (TAMU)
<u>Work Element E1a</u>: Analytical and Micro-mechanics Models for Mechanical Behavior of Mixtures (TAMU)

<u>Status and Work Planned</u>:
The work on this report is on schedule. In this quarter, a technical paper entitled "Characterization of Viscoplastic Yielding of Asphalt Concrete" was prepared and submitted to Journal of Construction and Materials for review.

Furthermore, work was performed to summarize the constitutive models, testing protocols, data analysis methods and processing programs, testing results and material properties developed and determined in all previous quarterly reports for the characterization of the permanent deformation of asphalt mixtures. The investigated properties of the ARC mixtures include the anisotropy, viscoelasticity, viscoplasticity and viscofracture. The investigated variables of the mixtures include two types of ARC asphalt binder (Valero and NuStar), two air void contents (4% and 7%) and three aging periods (0, 3, 6-month continuous aging at 60°C). The effects of each variable on the material properties of the mixtures were analyzed and discussed.

In addition, the draft of a level 2 report on this subject has been initiated and several chapters of the final report were completed including: 1) Literature Review; and 2) Anisotropic Viscoelasticity of Undamaged Asphalt Mixtures. Work will be continued in finishing the writing of the level 2 report in next quarter.

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

Status and Work Planned:
The work under this element is on schedule. Detailed methods and models are documented in Test Method and Model "Characterization of Fatigue and Healing Properties of Asphalt Mixtures" (No. 32) in the table of deliverables.

In the last quarter, the relationships between the fatigue resistance of asphalt mixtures and the modified Paris' Law parameters (A' and n') were studied. The fatigue resistance of asphalt mixtures is found to be measured by the value of n'. A smaller value of n' corresponds to better resistance of an asphalt mixture to fatigue cracking. Such an index is simple to use in terms of material comparison and selection for fatigue cracking. In order to find a similar index to measure the healing ability of asphalt mixtures, the characteristics of the healing curve were studied this quarter. Twenty types of asphalt mixtures were tested to verify that the index obtained from the healing curve can correctly represent the healing ability of different asphalt mixtures.

Healing curve of an asphalt mixture shows the relationship between the extent of healing and the rest time. The extent of healing is defined as the difference between the damage density at any time and the initial damage density before healing starts. It is observed from the healing curve that there is a rapid increase of the extent of healing at the beginning of the rest time. Then the change of the extent of healing gradually decreases as the rest time increases. Such characteristics of the healing curve can be described by three indexes: 1) short-term healing rate, which represents the healing speed of an asphalt mixture at the beginning of the rest time; 2) long-term healing rate, indicating the healing speed of the asphalt mixture after a long rest time; and 3) healing rate scale, which reflects the overall ability of the asphalt mixture to heal. Based on these three indexes, the extent of healing measured from the test can be predicted using a mathematical model with R-squared nearly 1.

To verify the accuracy of using the indexes from the healing curve as indicators of healing ability, these indexes are compared to evaluate the effect of asphalt binder, effect of air void content, and the effect of aging on twenty types of asphalt mixtures. The testing and analysis of the results include:

- Comparing AAD and AAM mixtures, which have the same aggregate, both the short-term healing rate and the healing rate scale of AAM mixtures are larger than those of AAD mixtures. This leads to the conclusion that the AAM mixtures have better healing ability than the AAD mixtures. Comparing NuStar and Valero mixtures, which have the same aggregate, the NuStar mixtures have better healing ability than Valero mixtures.

- Comparisons are performed on asphalt mixtures with 4% air void content and 7% air void content. It is found that the asphalt mixtures with 4% air void content always have better healing ability than those with 7% air void content, regardless the type of asphalt binder, aging, and temperature.

- The change of the healing ability due to the change of temperature is investigated by comparing the indexes at 10, 20, and 30°C, respectively. The results indicate that the temperature has significant influence on the healing ability of the asphalt mixtures: the healing ability is the highest at 30°C and it decreases rapidly when the temperature decreases; the healing of asphalt mixtures at 10°C is much slower and the extent is smaller.

- Comparisons are conducted on unaged and aged specimens for all AAD, AAM, NuStar, and Valero mixtures. There is a considerable reduction of the indexes from unaged asphalt mixtures to those aged. This fact suggests that the healing speed becomes smaller and smaller as the aging time increases.

The test results prove that the indexes obtained from the healing curve can be used as indicators of healing ability of different asphalt mixtures. In the next quarter, a further step will be taken to relate these healing indexes to fundamental material properties. It is expected that the healing behaviors can be predicted from rapid nondestructive tests on undamaged asphalt mixtures rather than through destructive tests.

Findings from work element E1a are being prepared as a chapter in the level 2 report on fatigue damage.

REPORT C: PAVEMENT ANALYSIS USING A NONLINEAR DAMAGE APPROACH (PANDA)

Included Work Elements/Subtasks

Work Element M4c: Unified Continuum Model
Subtask F1d-8: Coordinate Form of Healing Parameter with Micromechanics and Continuum Damage Models (TAMU)
Work Element F3c: Development of Unified Continuum Model (TAMU)
Work Element V3c: Validation of PANDA

Status and Work Planned: All the constitutive equations that are necessary for simulating the thermo-hygro-chemo-mechanical behavior of asphalt mixtures and the performance of asphalt pavements have already been incorporated into PANDA. These constitutive equations account for rutting, fatigue damage, micro-damage healing, moisture-induced damage, and oxidative aging. The developed models were calibrated and validated against several experimental data including Nottingham data, Accelerated Loading Facility (ALF) data, and most of the ARC Mix No. 1 data.

The focus of the current and future work is on further calibration and validation of PANDA against ARC test results as well as the other available and collected experimental data (Waterways Experiment Station data and Ohio test sections). In addition, most of the current and future efforts are on finalizing the reports. As documented in the list of deliverables, we are preparing a report that includes the theory of models included in PANDA, test methods and procedures to determine the models' parameters.

Work Element M4c: Unified Continuum Model

Status and Work Planned: The moisture-induced damage model as part of PANDA has been developed and numerically implemented (Shakiba et al. 2013). A continuum-based model for the effect of the pore water pressure on crack evolution and propagation has been developed and is being implemented in PANDA. The pore water pressure accelerates crack evolution and propagation due to presence and flow of moisture through the asphalt cracks and voids as a result of fast traffic loading. The focus will be placed on evaluating the model for different cases that involve different boundary conditions. Emphasis is also placed on the consideration of the scouring effect and washing away of the mastic due to flow of moisture through the asphalt cracks and void as a result of fast traffic loading.

Three-dimensional (3D) micromechanical moisture-damage simulations have been completed. Several simulations on the 3D micromechanical model have been done in order to investigate the effect of moisture conditioning time, moisture content, material properties parameters, strain rate, and temperature at both tension and compression. The results show the crack propagation and damage concentration after moisture conditioning the specimens. These simulations can be used to conduct virtual moisture-damage simulation experiments.

The ARC experimental data on moisture-conditioned specimens has been received from North Carolina State University. The results were processed and examined for the quality control purposes. The shortcomings have been reported and replicates have conducted when the results of moisture-conditioned specimens were not consistent. The model calibration has been started based on the available data. The moisture-induced damage model parameters have been obtained using the repeated creep recovery test results. The model will be validated against the cyclic strain controlled tests on moisture conditioned specimens. The focus of the next quarter is on further validation of moisture-induced damage model in PANDA against the ARC experimental data in both tension and compression.

Cited References

Shakiba, M., Abu Al-Rub, R.K., Darabi, M.K., You, T., Masad, E.A., Little, D., "A continuum coupled moisture-mechanical damage model for asphalt concrete," Transportation Research Board, 2013, accepted for presentation and publication.

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

Status and Work Planned: The micro-damage healing model has been developed, implemented, and validated against experimental data including the ALF data in tension [see e.g., Abu Al-Rub et al. (2010), Abu Al-Rub and Darabi (2012), Darabi et al. (2012a, 2012b, 2012c, 2013)].

It is shown that the PANDA model is capable of predicting the fatigue damage response of asphalt concrete subjected to different loading conditions. The data and analysis demonstrate that micro-damage healing occurs not only during the rest period, but also during the cyclic strain controlled tests in the absence of the resting time. The ALF database includes the experimental data on four mixtures that differ in the binder type. The model will be further validated against the ALF data on the mixtures with modified binder.

During this quarter, a simple and straightforward method has been developed to systematically identify damage and healing models implemented in PANDA. This method uses uniaxial constant strain rate tests at three different strain rates to calibrate damage and micro-damage healing models. The focus during the coming quarter will be on developing a program that can read the experimental data and automatically identify these parameters.

Furthermore, the effect of the time-dependent stress recovery during the healing mechanism on the micro-damage healing evolution rate has been investigated at micro-scale. Contributions of both instantaneous wetting and time-dependent intrinsic healing on evolution of micro-damage healing has been incorporated to enhance the micro-damage healing evolution function at micro-scale. It has been shown that micro-damage healing has significant effects on the stress field near the crack tip. Relationships for the stress intensity factor in the presence of the micro-damage healing have been developed. The focus is placed on relating the micro-damage healing model parameters at continuum scale to the material properties measured at micro-scale.

The main focus of the coming quarter is on further validation of the micro-damage healing model against available experimental data. The ARC data under tensile loading conditions are available and has been provided by North Carolina State University. Therefore, the focus of the coming quarter is to continue analyzing this data to further validate the micro-damage healing model as part of PANDA.

Cited References

Abu Al-Rub, R.K., Darabi, M.K., Little, D., Masad, E.A., "A micro-damage healing model that improves prediction of fatigue life of asphalt mixes," International Journal of Engineering Science, Vol. 48, No. 11, pp. 966-990, 2010. http://dx.doi.org/10.1016/j.ijengsci.2010.09.016

Darabi, M.K., Abu Al-Rub, R.K., Little, D.N. "A continuum damage mechanics framework for modeling micro-damage healing," International Journal of Solids and Structures, Volume 49, No. 3-4, pp. 492-513, 2012a. http://dx.doi.org/10.1016/j.ijsolstr.2011.10.017

Abu Al-Rub, R.K., Darabi, M.K., "A thermodynamic framework for constitutive modeling of time- and rate-dependent materials, Part I: Theory," *International Journal of Plasticity*, Vol. 34, pp. 61-92, 2012. http://dx.doi.org/10.1016/j.ijplas.2012.01.002

Darabi, M.K., Abu Al-Rub, R.K., Masad, E.A., Little, D.N., "A thermodynamic framework for constitutive modeling of time- and rate-dependent materials, Part II: Numerical aspects and application to asphalt concrete," International Journal of Plasticity, Vol. 35, pp. 100-134, 2012b. http://dx.doi.org/10.1016/j.ijplas.2012.02.003

Darabi, M.K., Abu Al-Rub, R.K., Masad, E.A., Little, D.N., "Constitutive modeling of fatigue damage response of asphalt concrete materials," Transportation Research Board, 2013, accepted.

Darabi, M.K., Abu Al-Rub, R.K., Masad, E.A., Little, D.N., "Constitutive modeling of fatigue damage response of asphalt concrete materials with consideration of micro-damage healing," International Journal of Solids and Structures (under review).

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

Status and Work Planned: 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 based on compression and tension data at different temperatures. The laboratory tests needed to calibrate and validate PANDA for the first ARC Mixture are completed, and the data have been analyzed. The viscoelastic and viscoplastic models have been calibrated against the ARC test data. The nonlinear viscoelasticity model parameters are identified at different stress and confinement levels. It is shown that the confinement level has significant effects on the nonlinear viscoelastic response of asphalt concrete. A model has been formulated and proposed to relate the nonlinear viscoelastic model parameters to the stress and confinement levels (Rahmani et al., 2013). A code has been developed to automatically identify the linear and nonlinear viscoelastic model parameters. Moreover, a key-element in the constitutive modeling of the viscoplastic deformation of asphalt concrete has been developed and validated. This key-element is a newly proposed viscoplastic deformation mechanism called "*viscoplastic hardening-relaxation*". The viscoplastic hardening-relaxation refers to the partial recovery in the hardening ability of the asphalt concrete during the rest period (or unloading time). Therefore, the asphalt concrete can accumulate more permanent deformation during the next loading cycle. In fact, it is shown in Darabi et al. (2012a, 2012b, 2013) that none of the available viscoplasticity theories are capable of predicting the accumulation of permanent deformation in asphalt mixtures under cyclic loading conditions, specifically at high temperatures. Therefore, the physically-based viscoplastic hardening-relaxation mechanism should be incorporated for effective modeling of the permanent deformation of asphalt concrete and in turn modeling the rutting performance of asphalt pavements.

Repeated creep-recovery test data on ARC mix No. 1 has been analyzed and a systematic procedure has been developed to calibrate the viscoplastic component of the PANDA model. This procedure will be implemented in the PANDA-Abaqus interface that will be used to simulate the performance of pavement sections. The focus of the next quarter is on developing and enhancing programs that automatically identify the model parameters associated with nonlinear viscoelastic, viscoplastic, hardening-relaxation, and damage components of PANDA. These programs will be implemented into the PANDA-Abaqus interface. These programs will give the user the capability to calibrate PANDA directly from the raw data without the need to manually analyze the experimental data.

The PANDA model with the incorporated viscoplastic hardening-relaxation constitutive model has been used in conducting a parametric study of the effect of pavement's boundary conditions and imposed different tire loading conditions. It has been shown that the incorporation of the hardening-relaxation mechanism significantly improves the prediction of rutting in asphalt pavements. Dr. Imad Al-Qadi from University of Illinois-Urban is helping in this task through predicting the contact pressures from different types of tires at different temperatures. Those predictions will be used as inputs into the realistic rutting and fatigue damage simulations using PANDA. This work is still undergoing and will be the focus of the next quarter.

We have developed and further validated a model which accounts for the viscoplastic hardening-relaxation behavior of asphalt mixtures under repeated loading conditions. This model was proven to be essential for predicting accumulation of permanent deformation and rutting in asphalt pavements. The results from this work has been presented in Darabi et al. (2012a, 2012b) and Huang et al. (2012).

We will continue the work on the effect of realistic loading and boundary conditions on the rutting and fatigue damage performance of asphalt pavements through using PANDA.

Cited References

Rahmani, E., Darabi, M.K., Abu Al-Rub, R.K., Kassem, E., Masad, E.A., Huang, C.-W., Little, D.N. "Effect of confinement pressure on the nonlinear-viscoelastic response of asphalt concrete at high temperatures," Construction and Building Materials, Under review.

Darabi, M.K., Abu Al-Rub, R.K., Masad, E.A., Huang, C.-W., Little, D.N. "A modified viscoplastic model to predict the permanent deformation of asphaltic materials under cyclic-compression loading at high temperatures," International Journal of Plasticity, Vol. 35, pp. 67-99, 2012. http://dx.doi.org/10.1016/j.ijplas.2012.03.001

Darabi, M.K., Abu Al-Rub, R.K., Masad, E.A., Little, D.N., "A cyclic hardening-relaxation viscoplasticity model for asphalt concrete materials," ASCE Journal of Engineering Mechanics, 2012. http://dx.doi.org/10.1061/(ASCE)EM.1943-7889.0000541

Huang, C.W., Darabi, M.K., Masad, E.A., Abu Al-Rub, R.K., Little, D.N., "Development, Characterization and Validation of the Nonlinear Viscoelastic-Viscoplastic and Softening Model of Asphalt Mixtures," International Journal of Plasticity, 2012, (In preparation).

Darabi, M.K., Abu Al-Rub, R.K., Masad, E.A., Little, D.N., "Constitutive modeling of cyclic viscoplastic response of asphalt concrete," Transportation Research Board, 2013, accepted.

Continuum-based Model for Aging

Status and Work Planned: In this quarter, the mechanistic-based phenomenological oxidative aging (or oxidative aging hardening) model has been developed and implemented into PANDA, Abu Al-Rub et al. (2012). An evolution function is proposed for the introduced oxidative aging internal state variable. The proposed aging model is formulated as a function of the diffused oxygen content and temperature evolution which ties the mechanical response of aged material to the underlying physics happening during the oxidative aging of asphalt concrete. Phenomenologically, the evolution of the aging internal state variable in asphalt concrete is related to the rate of carbonyl formation during the aging process of the asphalt binder. It is argued that oxidative aging mostly affects the viscous behavior of the aged material, such that the viscosity model parameters in the coupled nonlinear-viscoelastic, viscoplastic, and viscodamage constitutive models are defined as a function of the aging state variable. The qualitative capabilities of the model in capturing the effect of aging on mechanical response of asphalt concrete are verified against a wide range of simulations, Abu Al-Rub et al. (2012). The development of the aging model is coordinated with another project that is recently funded by the Qatar National Research Fund (QNRF). This project focuses on micromechanical modeling and introducing the effect of variation in material properties on the mixture response and performance.

During this quarter, the dynamic modulus test (DMT) data in both tension and compression as part of the ARC mix No. 1 testing plan have been analyzed. The compression and tension tests were conducted by TAMU and North Carolina State University, respectively. The aging model has been calibrated against these data. The compressive DMT test includes unaged, 3-months aged, and 6-months aged specimens at three different air voids being 4%, 7%, and 10%. The tensile DMT test also consists of unaged and 3 and 6-months aged samples but at only 7% air void for unaged and 4 and 7% air void for aged specimens. The analysis result for both compression and tension test showed that the aged specimens have higher modulus compared to the unaged samples. The effect of oxidative aging on nonlinear viscoelastic response of asphalt concrete has been investigated using dynamic modulus test data conducted on ARC mixture No. 1 for different air void percentages. It has been shown that the conventional shifting methods are not sufficient to capture nonlinear viscoelastic response of aged asphalt concrete materials. A mechanistic-based model has been proposed to couple the oxidative aging with the nonlinear viscoelastic model. Furthermore, a systematic and straightforward procedure has been developed to identify the model parameters associated with the oxidative aging model.

The more comprehensive data from TAMU and North Carolina State University such as repeated creep-recovery tests with various loading and resting times and cyclic fatigue tests are available and will be used for further calibration and validation of oxidative aging model. The focus in the coming quarter will be on investigating the effect of oxidative aging on fatigue response of asphalt mixtures. Therefore, the cyclic creep-recovery and cyclic stress/strain controlled tests will be used to further validate the oxidative aging model.

Cited References

Abu Al-Rub, R.K., Darabi, M.K., Kim, S.-M., Little, D.N., Glover, C.J., "Mechanistic-based constitutive modeling of oxidative aging in aging-susceptible materials and its effect on the damage potential of asphalt concrete," Construction & Building Materials, 2013, accepted.

Work Element V3c: Validation of PANDA

Status and Work Planned:

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. In this quarter, emphasis has been continued on the development of a systematic procedure for the identification of the nonlinear viscoelastic parameters of Schapery's nonlinear-viscoelastic model, Perzyna's viscoplastic model, and the damage model implemented in PANDA. Nonlinear viscoelastic and viscoplastic models are identified using a repeated creep-recovery test at various stress levels. It is concluded that the nonlinear viscoelastic material parameters are strongly dependent on the level of the confinement pressure such that these parameters should be made a function of the triaxial ratio (i.e. the ratio of the mean stress to the von Mises effective shear stress). The dynamic modulus tests as well as the repeated creep-recovery tests at various stress levels, conducted as part of the ARC testing plan, have already been used for calibrating the viscoelastic and viscoplastic models, respectively. The uniaxial constant strain rate tests in tension are also used to calibrate the damage component of PANDA model. The aging data based on the dynamic modulus test has also been used for calibration and validation of the oxidative aging model.

The laboratory tests needed to calibrate and validate PANDA for the first ARC Mixture are completed, and the data have been analyzed. The data in tension are now available as provided by North Carolina State University. The data received from NCSU have been analyzed and processed for quality control purposes. The shortcomings have been reported and replicates have been conducted when the test results were not consistent. The list of planned tests has been presented in the 6th year work plan. The planned testing on the first asphalt mixture is completed.

New experimental tests have been conducted by the Army Corps of Engineering at the Waterways Experiment Station, Vicksburg, Mississippi. Eight mixtures have been selected ranging from expected “poor” to “very good” rutting performance. The testing required for calibration of PANDA model have been conducted on these mixtures. Linear and nonlinear viscoelastic model parameters associated with these eight mixes are identified. Codes have been developed to automatically identify the model parameters using the experimental data. The focus will be placed on finalizing these codes for calibration of the viscoplastic and hardening-relaxation components of PANDA model. PANDA will be further calibrated and validated against the repeated creep-recovery tests at different stress levels and temperatures. Four of the eight mixtures will be used as part of the full-scale accelerated pavement testing. Once calibrated, PANDA will be used to rank the rutting performance of full-scale accelerated pavement testing.

PANDA will also be validated against the results of the Ohio perpetual pavement sections. This task is being jointly conducted by Texas A&M and University of Illinois at Urbana-Champaign Strain and stress data will be gathered at different locations of these sections in order to further validate PANDA.

REPORT D: CHARACTERIZATION OF ASPHALT BINDERS USING ATOMIC FORCE MICROSCOPY

Included Work Elements/Subtasks:
Work Element F2d: Asphalt Binder Microrheology and Microstructural Characterization

Status and Work Planned:

Task 1 - The study of the effect of chemical composition on asphalt-micro-rheology and their association to pavement performance characteristics has been **completed**. The study was performed using atomic force microscopy (AFM) and serves to validate and expand upon previous results presented for this work element as well as previous research performed by Pauli et al. (2003; 2009; 2011). A summary of this work follows under the heading *Major Findings*.

Task 2 - Additional testing of SHRP binder's AAB and AAD (aged and non-aged) as well as PG 64-22 binder with 2.5% SBS (elastomer) and PG 64-22 with 2.5% 7686 (plastomer) will be performed **as needed** to complete this work element and validate the results presented in quarterly previous reports. Furthermore, the next step required to test the "susceptible phase interface" hypothesis involves measuring the surface energy of asphalt using AFM, and combining those values with phase-specific modulus values to predict cracking susceptibility at the micro and ultimately the macro length scales. As highlighted previously, the asphalt microstructure undergoes significant changes due to natural and synthetic modification processes. Furthermore, a decrease in asphalt cohesive bond energy with aging typically results in a reduced amount of work required (due to load or temperature) to propagate a crack in asphalt. These microstructural changes and characteristics are the basis for exploring parameters related to bond energy and crack growth at the micro and nano scales. For instance, if a particular micro phase can be identified as having lower bond energy, then researchers can use this information (in conjunction with modulus values) to improve cracking prediction models and enhance the properties of asphalt via existing and new synthetic modification processes. It will essentially provide a major step towards linking micro and nano properties of asphalt to the in-field performance of asphalt concrete. The key difference in previous methods of measuring surface energy and the proposed protocol is that AFM will be used to measure surface energies of individual phases as opposed to random or grid-based surface energy measurements of the binder. The execution of this task is **currently underway** and the status is shown in Table F2d2 under the heading *Status and Work Planned*.

Task 3 - The TRB paper describing a method to numerically quantify viscoelastic properties of asphalt thin film using a corrected viscoelastic analytical solution has been accepted for presentation. Current work being completed includes the finalization and review of the ASCE Journal Paper Titled: "Finite Element Modeling of Atomic Force Microscope Indentation of Asphalt Thin Film" for submission. The next phase of this work has been revised. Previously the next targeted phase of this work involved obtaining viscoelastic properties of asphalt thin film using dynamic loading through AFM indentation and nano-indentation. The current focus of this work is to study the changes in microstructure of asphalt thin film due to specified types of loading. The "bee" structures that have been previously discovered have been shown to increase in concentration due to aging and due to increasing the *saturates* content. However, the effect of repetitive or constant loading on these “bee” structures has yet to be determined. The focus of this portion of work is to determine what structural changes the bee-like structures experience due to a controlled level of extension and repetitive tension causing fatigue. The list of upcoming deliverables associated with this task is shown in Table F2d2 under the heading *Status and Work Planned*.

Major Findings

Task 1 Completed. The primary objective of this task was to investigate the impact of asphalt chemical composition on the micro-rheology and performance characteristics of asphalt binder. The methods implemented in this study included adsorption-desorption chromatography analysis and a range of AFM and chemical force microscopy (CFM) techniques. It was revealed through the study that the *saturates* chemical fraction has a consistent and measureable effect on the asphalt microstructure that is observed with AFM, as shown in figure F2d1. Particular microstructures that emerged via chemical doping were then discovered to have unique chemical polarity, which explicitly impacts durability and performance of asphalt. The chemical polarity which was revealed in this study is shown graphically in figure F2d2 and presented in tabular form in table F2d1. The light and dark-colored phases shown in figure F2d1 (*Little to No* “Bee” Structuring) are referred to as the “continuous” and “dispersed” phases, respectively. Similarly, in figure F2d1 (*Dominant* “Bee” Structuring), the tubular phase and the surrounding matrix are referred to as the “bee” structure and “bee” casing phases, respectively.

It was revealed in this study that high *saturates* content causes a very similar “bee” structuring to occur as that which results from oxidative aging (reported in previous quarterly report). **The correlation between high *saturates* content and oxidative aging effects with respect to their cause of “bee” structuring remains unexplained.** It is especially unclear, because oxidative aging is largely understood to decrease the percentage of *saturate*s even further and subsequently increase the percentage of the more polar components of asphalt. In fact, many asphalt researchers cite the increase in the highly polar components as the reason for oxidative age-hardening. While aging and embrittlement remain one of the primary modes of failure for AC, it is indeed very interesting that a high *saturates* content in non-aged asphalt can cause a similar influence [as oxidative aging] on asphalt microstructure, chemical polarity, and pavement performance properties. The results presented herein clearly show that the asphalt which has more dominant “bee” structuring also contains a greater chemical polarity. This finding is in spite of the fact that a higher *saturates* content (least polar component of asphalt) is responsible for the highly polar “bee” structuring that occurs. A likely explanation for the apparent discrepancy in chemical model-performance behavior is that the high concentration of *saturates* allows the more highly polar components (such as asphaltenes and resins) to move about more freely and structure into rigid formations. These results are supported by Halstead (1985), who speculated decades ago that it is the inter-component relationship among the generic fractions, SARA, which governs the overall physical properties of asphalt rather than the quantity of any single component (Little et al. 1993). The findings from this research directly contribute to the improvement of modeling capability while also creating new prospects for enhancing the performance characteristics and durability of asphalt binder.

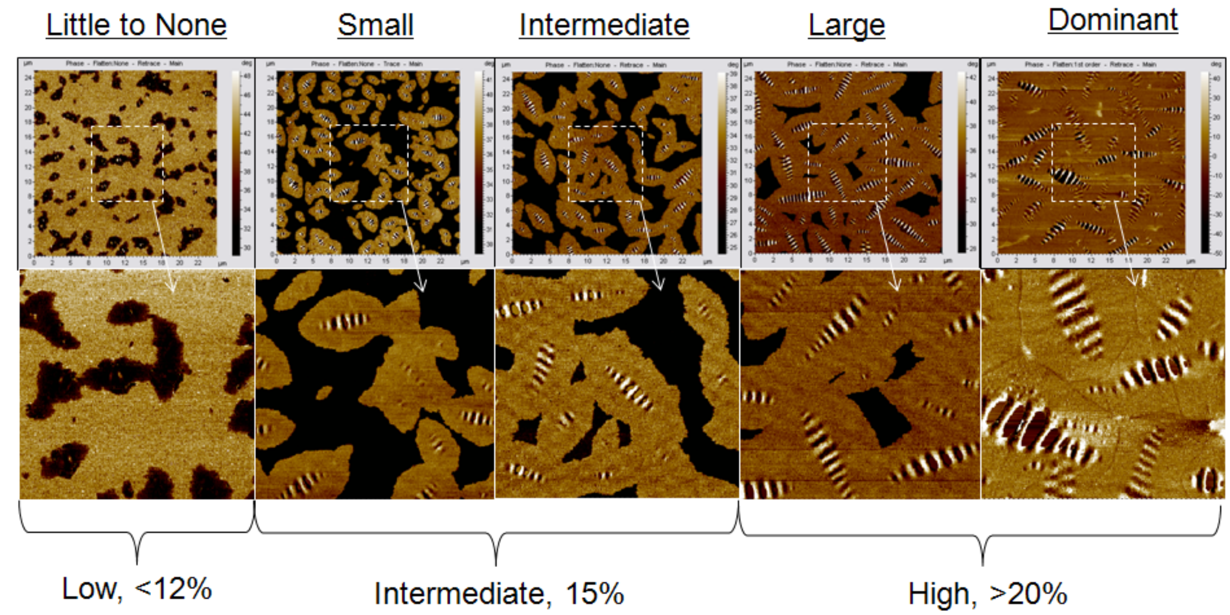


Figure F2d1. Different degrees of "bee" structuring. The "bee" structuring was found to be closely tied to the *saturates* content of the different asphalt binders. (Percentages shown represent the *saturates* content of the particular asphalt.)

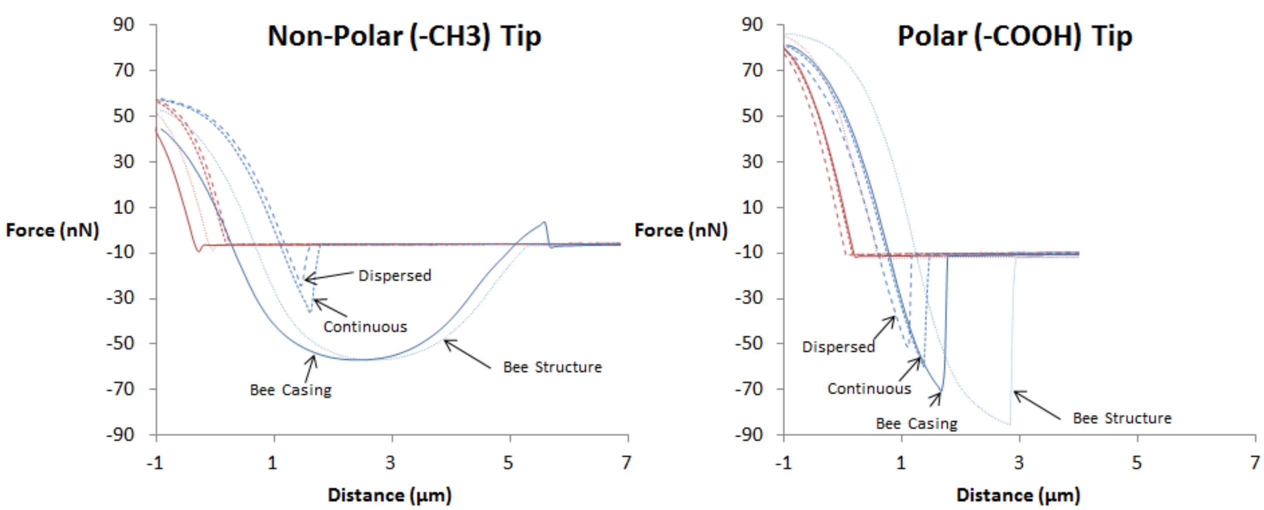


Figure F2d2. Average phase-specific pull-off (adhesion) forces measured with non-polar and polar chemically-treated tips.

Table F2d.1. Pull-off (adhesion) forces of discrete asphalt microstructural phases.

Asphalt "Bee" Structuring	Phase	Pull-off Force (nN)						Avg.	COV
Non Polar (CH_3 Tip)									
Minimal	Continuous	31.9	30.8	41.6	41.5	35.9	30.0	35.3	0.1361
	Dispersed	26.3	27.7	27.6	24.2	27.0	24.6	26.2	0.0532
Dominant	"Bee" Casing	56.9	56.9	56.9	56.9	56.9	56.8	56.9	0.0006
	"Bee" Structure	56.9	56.9	57.0	56.9	56.9	56.9	56.9	0.0004
Polar (COOH Tip)									
Minimal	Continuous	70.5	63.2	68.1	56.6	63.7	59.5	63.6	0.0741
	Dispersed	57.0	51.2	55.8	58.7	51.3	48.2	53.7	0.0690
Dominant	"Bee" Casing	70.5	70.2	65.2	69.8	71.8	73.8	70.2	0.0369
	"Bee" Structure	85.3	85.6	86.8	84.6	86.5	83.4	85.3	0.0136

<u>List of upcoming deliverables involving numerical analysis</u>

Date	Deliverable	Description of Deliverable	Status of Deliverable
1/1/2013	**Task 1 (Partial) – TRB Paper**	Structural Characterization of the Micromechanical Properties of Asphalt using Atomic Force Microscopy	Completed- Accepted for Presentation
1/1/2013	**Task 3 (Partial) – TRB Paper**	A Numerical Model for the Atomic Force Microscopy Indentation of Asphalt with Adhesion	Completed- Accepted for Presentation
1/30/2013	**Task 1 (Final)– Journal Paper**	The Effects of Chemical Composition on Asphalt Micro-rheology and Their Association to Pavement Performance Characteristics	Draft Completed – Scheduled for submission to *Int. J. Pavement Eng.*
1/30/2013	**Task 3 (Partial)– Journal Paper**	Finite Element Modeling of Atomic Force Microscope Indentation of Asphalt Thin Film	Draft Completed – Scheduled for submission to *J. Mat. Civil Eng.*
3/30/2013	**Task 2 (Final) – Journal Paper**	Evaluation of Asphalt Binder Crack Development Caused by Micro-delamination	On Schedule
3/30/2013	**Task 3 (Final) – Journal Paper**	Microstructural Changes in Asphalt Thin Film due to Constant and Repetitive Loading	On Schedule

REPORT E: MULTISCALE VIRTUAL FABRICATION AND LATTICE MODELING.

REPORT ON LATTICE MODEL AND CONTINUUM DAMAGE TO FRACTURE

Included Work Elements/Subtasks:
Work Element M4a: Lattice Micromechanics Model and Model to Bridge Continuum Damage and Fracture

Status and Work Planned: *Lattice Modeling*

This task is on schedule

Based on the findings presented in the previous quarter, the under-prediction of the dynamic modulus in the model is believed to originate from the lack of load path formations. This observation is consistent with experimental measurements taken by Underwood et al. [2]. The experimental investigations also reveal the existence of a coating of mastic on all the aggregate particles.

Based on the above observations, a new method is proposed to modify the microstructure generation algorithm. The proposed procedure adds a new phase to the material that considers the proximity of aggregate particles as the main factor for creating a load path between two aggregate particles. The new phase is referred to as *stiff mastic* and only exists between close enough aggregate particles. That is, close particles can potentially form a load path inside the specimen. The materials that form the path are the aggregate particles and stiff mastic that connects the particles to each other.

This proposed procedure shows substantial improvement in the prediction of the dynamic modulus for a single frequency. However, under-prediction can still be observed for other frequencies. This problem of changing time dependency can be handled by repeating the above procedure for multiple frequencies. The modulus of each phase must be adjusted accordingly for each frequency.

A combination of the above procedures has been implemented in a single program as part of the lattice modeling software. The results show promise in upscaling the G* from mastic scale to fine aggregate matrix (FAM) scale. It is important to note that most of the change in the behavior of the material usually happens in the transition from mastic to FAM. Figure 1 compares the simulation results with the experimental measurements presented in reference [2] for a S9.5B mix material. As can be observed in the figure, most frequencies indicate acceptable agreement between the experimental results and the predictions.

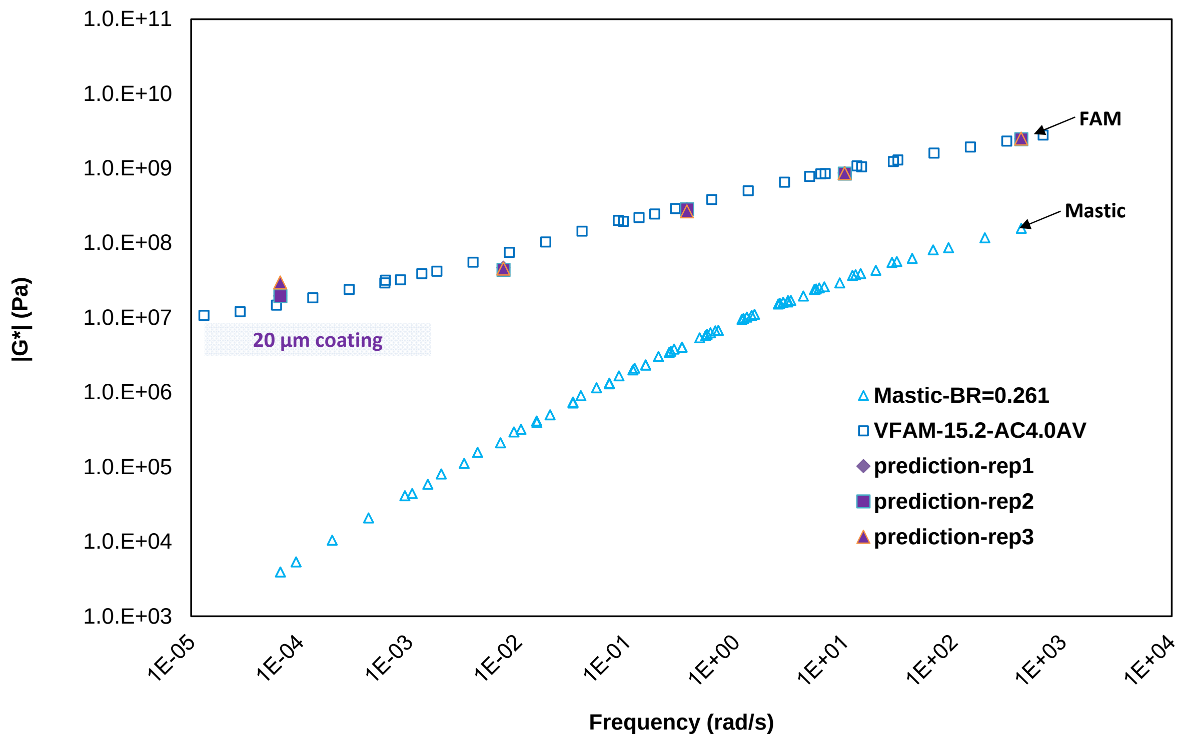


Figure 1. Dynamic modulus predictions for FAM from available mastic data.

The same procedure has been repeated for up-scaling from FAM to mix. Different thicknesses have been chosen for the coating layer; however, the results show no sensitivity to the thickness of the coating in the mix scale. In other words, the stiff mastic (new phase) does not form a load path in the mix scale, and therefore, no load paths contribute to the load-carrying capability of the specimen. This finding is in complete agreement with the experimental observations, as shown in figure 2. It is important to note that even when the new phase is excluded, promising predictions for the mix scale are still evident. The combination of the above simulations can provide a seamless prediction of the dynamic modulus from mastic to mix scale with acceptable accuracy, which is a key factor in predicting the long-term performance of asphalt concrete.

An important question is: Would the predictions be equally good for other mixtures with the presence of air voids? Investigations in this direction would be the focus for the next quarter.

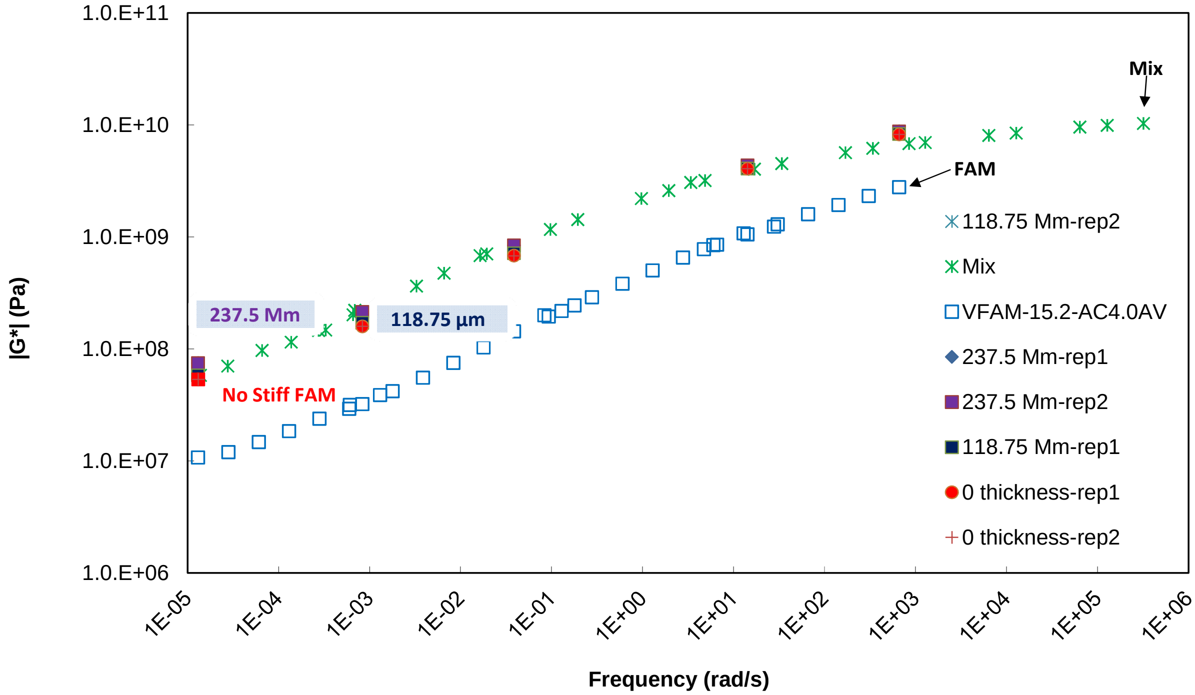


Figure 2. Dynamic modulus predictions for mix from available FAM data

<u>References</u>

[1]. Underwood B. S. *Multiscale Constitutive Modeling of Asphalt Concrete*. Thesis and Dissertation, 2011, North Carolina State University.

Continuum Damage to Fracture

This task is on schedule.

In the last quarter, it was found that after the drop in phase angle, the asphalt concrete outside the localization region experiences healing due to the relaxation of stress during controlled crosshead cyclic tests. During this quarter, it has been observed that the behavior of asphalt concrete inside the localization region is quite similar to that of the opening and closing of a macrocrack. Hence, it may be hypothesized that the modeling of the entire asphalt concrete specimen after localization can be done by linking two substructures in a series. The first substructure is governed by a healing model that is under stress relaxation, and the second substructure is governed by a fracture model that represents quasi-static macrocrack propagation.

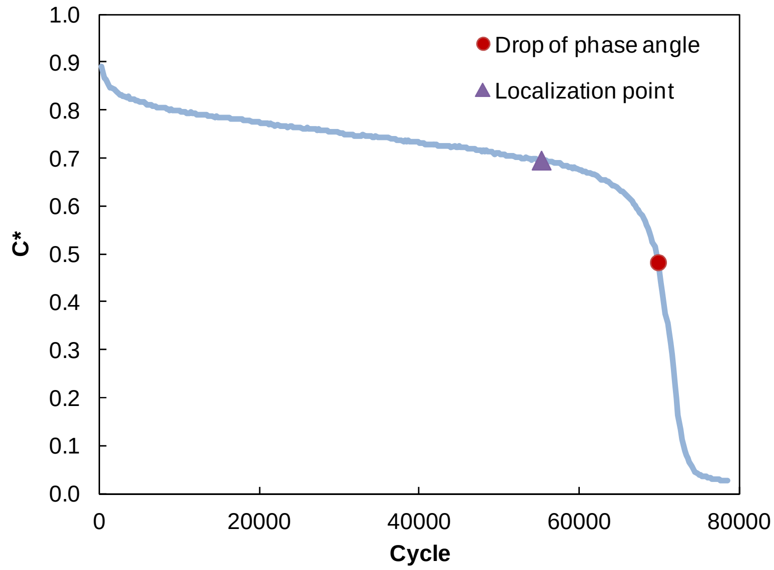


Figure 3. Schematic plot of failure point and localization point.

A research focus this quarter has been the development of the failure criteria associated with the viscoelastic continuum damage (VECD) model in predicting fatigue life. Approaches based on stiffness and dissipated energy were both explored and compared.

For the stiffness-based criterion, a much more consistent distribution of stiffness can be observed at the point of localization than at failure. The point of localization is defined as the end point of the stable damage accumulation in a stiffness diagram, and its relative location to the point of failure is shown in figure 3. Once the stiffness at localization is developed as a function of reduced frequency for a given mixture (see figure 2 for example), the fatigue life of this mixture under any load and temperature can be determined by running the VECD model to the corresponding localization stiffness first, and then extrapolating the predicted cycle at localization to the final failure. Even though this stiffness-based criterion provides an affordable prediction, it is still not considered to be an efficient approach, because the development of a localization envelope for each mixture would require material testing at multiple temperatures.

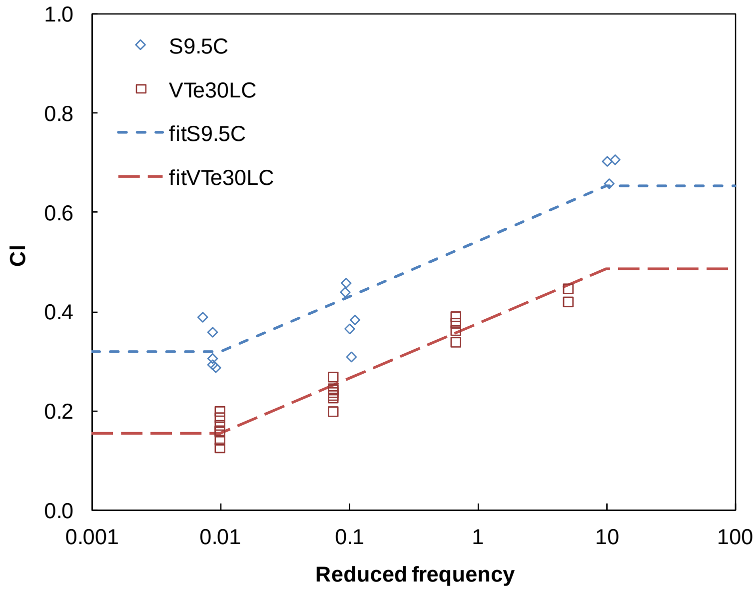


Figure 4. Development of localization envelope.

To avoid such a requirement, a new dissipated energy based-criterion is proposed. Currently, most of the established dissipated energy approaches for asphalt concrete mixtures are investigated through experiments only, in which the histories of stress, strain and phase angle are all available in advance. However, the VECD model mainly focuses on the quantification of damage and effective stiffness, while the change in time dependency in terms of phase angle is actually not captured. Therefore, traditional dissipated energy approaches cannot be implemented in the VECD model because the variation in phase angle cannot be evaluated. Instead, a new dissipated energy concept that is compatible with the VECD model has been developed as part of this research whereby the dissipated energy focuses only on the energy associated with stiffness reduction. Hence, dissipated energy can be predicted by the VECD model if the pseudo strain history is given. A characteristic relationship is found between the rate of proposed dissipated energy (also referred to as the *plateau rate*) and the fatigue life for a given mixture (figure 5) and this characteristic relationship seems to be unique among various temperatures when viscoelastic damage is the dominating mechanism for failure. Based on this observation, the proposed dissipated energy approach can be further utilized as a criterion to predict fatigue life for asphalt mixtures. Once the plateau rate is obtained from the VECD model, the corresponding fatigue life can be evaluated according to the developed characteristic relationship. In general, this criterion also provides a reasonable prediction of fatigue life and is believed to be more efficient than the previous approach shown in figure 2 because calibration tests are not required at multiple reduced frequencies.

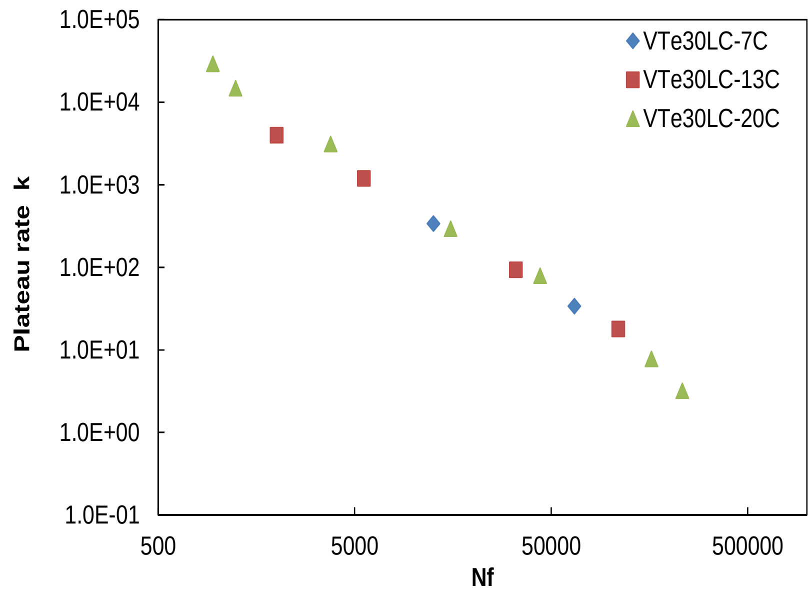


Figure 5. Relationship between plateau rate k and fatigue life N_f.

<u>Reference</u>

[2]. Underwood B. S. *Multiscale Constitutive Modeling of Asphalt Concrete*. Ph.D. dissertation, 2011, North Carolina State University.

REPORT F: MICROSTRUCTURE COHESIVE ZONE MODELING FOR MOISTURE DAMAGE AND FATIGUE CRACKING

Included Work Elements/Subtasks
Work Element/Subtask F3b-1: Model Development - Cohesive Zone Model

Status and Work Planned
This work element is complete. A draft report has been submitted, which is being put in 508 Format.

REPORT G: DESIGN SYSTEM FOR HMA CONTAINING A HIGH PERCENTAGE OF RAP MATERIAL

Included Work Elements/Subtasks
Work Element E2b: Design System for HMA Containing a High Percentage of RAP Materials

Status and Work Planned
On Schedule.

The following list describes the work items completed this quarter:

- A work plan was developed to evaluate the fundamental concepts behind the Dust Proportion (DP) specification. Mastic testing using the DSR bob and cup geometry at low shear has shown utility in predicting the compactability and subsequent performance of non-RAP mixes. This work was accepted for publication by the AAPT. It is expected that a similar characterization procedure can be applied to RAP mixtures.
- A literature review regarding fractionation procedures is underway. It is expected that the recently released draft NCHRP 09-46 final report will be the primary source of information on this topic.
- Completed the uniaxial thermal stress and strain test (UTSST) for the high RAP content mixtures from University of New Hampshire.

The following list the work planned for next quarter:

- Perform phase I of the DP work plan which include studying the rutting resistance of lab-produced RAP mixtures with several dust-to-binder proportions. Based on the anticipated results from phase I, potential factors will be included in phase II which will investigate the effect of dust-to-binder on fatigue life and endurance limit of RAP HMA mixtures.
- Continue the fractionation literature review.
- Develop a work plan to evaluate the effect of RAP on the blended binder viscosity of mixtures. This work is expected to overlap with the DP work significantly.
- Sample field mixtures from the Arizona RAP field sections. Construction date was delayed.

REPORT H: CRITICALLY DESIGNED HMA MIXTURES

Included Work Elements/Subtasks
Work Element E2c: Critically Designed HMA Mixtures

Status and Work Planned
Accelerated Schedule.

The following list describes the work items completed this quarter:

- Validated the findings of the FN study using three mixtures from the MnRoad interstate project and two mixtures from the MnRoad low volume traffic closed loop.
- A draft version of the AASHTO Standard Practice entitled "Determining the Asphalt Mixture Critical Conditions for Rutting Evaluation by Means of Dynamic Repeated Load Triaxial Test (RLT)" has been finalized.

The following list the work planned for next quarter:

- Finalize and submit a draft version of Report H to FHWA for review and input.
- Submit the AASHTO Draft practice to FHWA for review and input.

REPORT I: THERMAL CRACKING RESISTANT MIXTURES

Included Work Elements/Subtasks
Work Element E2d: Thermal Cracking Resistant Mixes for Intermountain States

Status and Work Planned
On Schedule.

The following list describes the work items completed this quarter:

- The thermal stress and thermal strain measurements are currently being conducted on laboratory aged and field validation samples following the development of the draft AASHTO standard using uniaxial thermal stress and strain test (UTSST). Thus far, approximately 20% of the UTSST to be conducted on the mixtures has been completed.
- The aging and testing for the field validation sections are underway with nearly all of the binder aging and testing being complete.
- Evaluation of the Core materials has also begun. Over 95% of the binder aging has been completed thus far, with almost 40% of the accompanying testing being complete.
- Subsequent to some recent findings related to the systematic shifting of the activation energy of binders aged in mixtures and in laboratory pans, additional mixtures have been prepared and aged at 85°C. All of the 0.5 and 1 month duration samples have been aged and half of the 3 month duration samples have completed aging. One third of these samples have been tested for dynamic modulus, and almost 30% have been extracted and recovered for the binder testing portion which has just begun.
- Preparation of the direct tension test specimens for polymer-modified asphalt mixtures.
- The UTSST test for the polymer-modified mixture has been completed to validate and evaluate the proposed procedure for determination of thermal visco-elastic properties of asphalt mixture in case of modified mixtures.
- Working on the approach to relate the mechanical properties of asphalt mixture to the chemical and rheological changes of asphalt binder due to aging.
- Finalizing the approaches to calculate temperature profile, amount of oxidation and calculation of thermal stress considering aging effect and nonlinear thermal coefficient of contraction.
- Assessing the relationship between the mixture and binder viscoelastic properties as a function of aging.

The following list the work planned for next quarter:

- All but complete the Core binder testing (one test cannot be completed until April).
- Conduct mix designs for selected core materials.
- Continue working on the subroutines for thermal cracking analysis tool.
- Perform the UTSST and direct tension tests on field validation mixtures and various aged mixtures.

REPORT J: PAVEMENT RESPONSE MODEL TO DYNAMIC LOADS 3D-MOVE

Included Work Elements/Subtasks
Work Element VP3a: Pavement Response Model to Dynamic Loads

Status and Work Planned
On Schedule.

Completed the writing for the User Guide, which is to accompany the 3D-Move Analysis when it is finally released as standalone software. The User Guide is an important document that can be used as a reference by the 3D-Move users as it gives 3D-Move formulation, its capabilities, relevant references, along with worked examples etc. The User Guide has been divided into the following chapters:

1. Introduction and Features of 3D-Move Analysis;
2. Formulation of 3D-Move Analysis;
3. Menus of 3D-Move Analysis;
4. Project Information;
5. Axle Configuration and Contact Pressure Distribution;
6. Vehicle Suspension and Road Roughness;
7. Traffic Information and Pavement Structure;
8. Material Characterization;
9. Performance Analysis;
10. Response Points;
11. Post Processing;
12. Appendices: Examples;
13. References.

REPORT K: DEVELOPMENT OF MATERIALS DATABASE

Included Work Elements/Subtasks
Work Element TT1d: Development of Materials Database

Status and Work Planned
On Schedule.

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

- Create a batch file renaming tool.
- Implement the system to approve test runs.
- Create a batch entry system for test run data (Unplanned).
- Enhance File Upload to send an e-mail to the administrator and updater confirming the success or failure of the upload (Unplanned). Create uploaded file consistency report.
- Enhancements to the role system.
- Status of the public user interface.
- Assess Ohio University with data upload.
- General bug fixes.

The following list the work planned for next quarter:

- Complete measure reports to be used by consortium members and possible public users.
- Complete role documentation system.
- Continue work on the public user interface.
- Revisit the FileLinker form as subsystem as necessary.
- It has been decided that a feedback system, similar to a blog, is needed for both public and internal users. This system was planned for inclusion this quarter but due to the unexpected development and bug fixes, the feedback system development has not started.
- Assist public and ARC users.

REPORT L: DEVELOPMENT AND VALIDATION OF THE BITUMEN BOND STRENGTH TEST (BBS)

Included Work Elements/Subtasks
Work Element M1a: Affinity of Asphalt to Aggregate

Status and Work Planned
Behind Schedule (Final Report Submission)

Work Completed: Final report comments were addressed. Revisions include: (a) section on the importance of controlling application and testing temperature and the effect of stiffness on the bond strength of asphalt-aggregate systems, (b) section reporting values of bond strength when using different substrates (i.e., glass, metal, and rock), (c) re-wording of failure modes as fully cohesive or fully adhesive failures are not observed in BBS testing, (d) section presenting direct contact angle measurements between binder and rock at different application temperatures, (e) section on mastic (i.e., mineral fillers + binder) bond measurements using the BBS. Internal review of report is in-progress.

Work Planned: Complete internal review of final report and submit to FHWA.

Reasons for Delay: Extensive revisions were made to the report that took longer than anticipated.

Revised Delivery Dates
Draft Report: 10/30/11 (Submitted)
Final Report: 3/31/2013 (Revised – Extended from 6/30/2012 and 9/30/2012)

REPORT M: DEVELOPMENT OF TEST PROCEDURES FOR CHARACTERIZATION OF ASPHALT BINDER FATIGUE AND HEALING

Included Work Elements/Subtasks
Work Element F1d: Healing
Subtask F1d-6: Evaluate Relationship Between Healing and Endurance Limit of Asphalt Binders
Work Element F2a: Binder Tests and Effect of Composition
Work Element F2e: Verification of the Relationship Between DSR Binder Fatigue Tests and Mixture Fatigue Performance

Status and Work Planned
Behind Schedule (Final Report Submission)

Work Completed: UW has submitted draft final report in full 508 format and is awaiting peer review feedback.

Work Planned: Address comments from peer review feedback and prepare final report.

Reasons for Delay: Delays have been realized in receiving peer review comments. Upon receipt of the comments, it is anticipated that approximately 2 to 3 months will be needed to revise and submit the final report.

Revised Delivery Dates
Draft Report: 10/30/11 (Submitted)
Final Report: Tentative: 6/31/2013, assumes review comments received by 3/31/13 (Originally Revised from 6/30/2012)

REPORT N: GUIDELINES FOR SELECTION OF MODIFICATION TECHNIQUES

Included Work Elements/Subtasks
Work Element E2a: Comparison of Modification Techniques
Work Element E3a: Effect of Extenders (such as Sulfur) and Alternative Binders (such as Bio-Binders) on Mixture Performance

Status and Work Planned
On Schedule

Work Completed: Microsoft Excel spreadsheet-based analysis tool has been developed for PG assessment based on modification type. Work on draft final guidelines for application of spreadsheet continued this quarter and is near completion. Extensive work on Work Element E3a: Effects of Extenders and Alternative Binders on Performance was also completed this quarter. The results of this work will be integrated into Report N.

Work Planned: Execute experimental plan for E3a, it is anticipated that all testing will be completed by 2013Q2. Begin work on combining results of Work Element E3a with existing draft of E2a report.

Delivery Dates
Draft Report: 9/30/2013
Final Report: 3/31/2014

REPORT O: CHARACTERIZATION OF BINDER DAMAGE RESISTANCE TO RUTTING

Included Work Elements/Subtasks
Work Element E1b: Binder Damage Resistance Characterization (DRC)
Subtask E1b-1: Rutting of Asphalt Binders
Subtask E1b-2: Feasibility of Determining Rheological and Fracture Properties of Asphalt Binders and Mastics Using Simple Indentation Tests
Work Element V3f: Validation of the AASHTO MP-19 Specifications and Improvements of the TP-70 Procedure

Status and Work Planned
Behind Schedule

Work Completed: Compilation of the final report progressed significantly in the past quarter. Work better defined the role of binder elasticity and aggregate structure on rutting resistance of asphalt mixtures through experimental and numerical simulation. This work will contribute significantly to the analysis and discussion of Report O.

Work Planned: Modeling efforts to define the role of binder elasticity and aggregate structure in mixture rutting performance will be finalized and included in the draft final report in the next quarter. Draft final report will be completed by the current deadline based on a synthesis of recent work.

Reasons for Delay: Additional time was needed to integrate findings from micro-mechanics analysis and imaging. This analysis is required to determine the relative contributions of binder and aggregate to rutting resistance. Final report deadline was extended to accommodate extended deadline for submittal of draft report.

Delivery Dates
Draft Report: 6/30/2013 (extended from 12/31/2012)
Final Report: 12/31/2013 (extended from 8/31/2013)

REPORT P: QUANTIFYING THE IMPACTS OF WARM MIX ASPHALT ON CONSTRUCTABILITY AND PERFORMANCE

Included Work Elements/Subtasks
Work Element E1c: Warm and Cold Mixes
Subtask E1c-1: Warm Mixes

Status and Work Planned
On Schedule

Work Completed: Procedure was developed to evaluate boundary lubrication through use of a Pin-on-Disk testing device adapted for the DSR. Results found that in addition to WMA additives, the surface roughness and mineralogy contributed significantly to coefficient of friction measurements and thus asphalt mixture workability. Due to the significance of mineralogy on WMA additive performance the concept of applying mastic viscosity to evaluate effects of WMA on workability was introduced in a lectern session at TRB. University of Nevada Reno continues work on a study comparing the mixture performance properties of field and laboratory produced mixes based on the materials sampled from the Manitoba field projects. These results were also presented at the 2013 TRB Conference. To prevent delays in submission of the draft final report the decision was made to submit the work related to development of mixing and compaction temperature guidelines approved in the ARC Yr. 6 work plan separately as a Technology Brief/NTIS Report.

Work Planned: Continue work on draft final report, including performance testing results collected by University of Nevada Reno. As requested by FHWA, prepare a summary of related WMA efforts funded by NCHRP for inclusion in the report.

Delivery Dates
Draft Report: 3/31/2013
Final Report: 10/31/2013

REPORT Q: IMPROVEMENT OF EMULSION CHARACTERIZATION AND MIXTURE DESIGN FOR COLD BITUMEN APPLICATIONS

Included Work Elements/Subtasks
Work Element E1c: Warm and Cold Mixes
Subtask E1c-2: Improvement of Emulsions' Characterization and Mixture Design for Cold Bitumen Applications
Work Element E3b: Development of PG Specification for Emulsions used in Surface Treatments, Cold Mixes, and Cold-In-Place Recycled Mixes

Status and Work Planned
On Schedule

Work Completed: The coating analysis procedure has been finalized and initial work has begun on compaction and curing procedures for CMA. A volumetric-based mix design framework has been established and a work plan to evaluate the framework has been finalized.

Evaluation of residue recovery methods including standard and non-standard methods was investigated. Initial results indicate that the recovery method can have a significant effect on the residue rheological properties. The proposed residue characterization framework was also applied to several emulsion residue samples.

Results from the chip seal aging study were summarized and presented at the annual TRB meeting and will be published in the TRR. Work continues by WRI on sampling emulsion residues from the field after 4 years in-service and characterizing their chemical properties and rheological properties using the 4mm Parallel Plate geometry in the DSR.

Work Planned: The volumetric design system proposed for CMA mixtures will be applied for several material types. It is expected that revisions to the design system will be proposed for next quarter.

Results will be correlated with mixture performance to propose practical limits on emulsion and mixture design properties. It is expected that the final report will include a 'straw-man' type framework for producing CMA mixtures using volumetric methods. UNR will continue to validate the proposed mix design approach for CIR mixes.

Suspend investigation of residue recovery methods pending establishment of standard procedures for alternative methods. Continue evaluation of emulsion residue performance properties for various preservation applications.

Delivery Dates
Draft Report: 9/30/2013
Final Report: 3/31/2014

REPORT R: STUDIES ON TIRE-PAVEMENT NOISE AND SKID RESPONSE

Included Work Elements/Subtasks
Work Element VP2a: Mixture Design to Enhance Safety and Reduce Noise of HMA

Status and Work Planned
Complete, awaiting further direction from WRI and FHWA.

Work Completed: Draft final report in Section 508 Format and a tech brief was submitted for review in December, 2011. WRI has indicated that this report will be finalized as an NTIS report and the 508 formatting is not needed.

Work Planned: Address any additional review comments. Complete any necessary formatting changes necessary for converting report to NTIS format.

Reasons for Delay: Deadline extended three months to address reviewer comments and convert report into NTIS format.

Delivery Dates
Draft Report: 12/31/2011 (Submitted)
Final Report: 6/30/2013, pending receipt of peer review comments and NTIS formatting guidelines.

REPORT S: MOLECULAR DYNAMICS RESULTS FOR MULTIPLE ASPHALT CHEMISTRIES

This report can be delivered in non-508 format.

Included Work Elements/Subtasks

Subtask F3a-1: *ab initio* Theories, Molecular Mechanics/Dynamics and Density Functional Theory Simulations of Asphalt Molecular Structure Interactions

Sub-subtask F3a-1.1. Specify desired asphalt compositions and chemistries for testing multiscale asphalt modeling effort (large cluster simulations) (URI, WRI)

Sub-subtask F3a-1.2. Develop algorithms and methods for directly linking molecular simulation outputs and phase field inputs (URI, NIST)

Sub-subtask F3a-1.3. Obtain temperature-dependent dynamics results for model asphalts that represent asphalts of different crude oil sources (URI)

Sub-subtask F3a-1.4. Simulate changes in asphalt dynamics after inducing representations of chemical and/or physical changes to a model asphalt (URI)

Subtask F3a-4. Overall integration for multiscale modeling (VT, URI, and WRI)

Subtask F3a-5. Experimental verification and validation (VT, URI, and WRI)

Status and Work Planned

Sub-subtask F3a-1.1. Specify desired asphalt compositions and chemistries for testing multiscale asphalt modeling effort (large cluster simulations) (URI, WRI)

On Schedule.

Compositions were identified in previous quarters. A publication that disseminates new proposed compositions for AAA-1, AAK-1, and AAM-1 will be submitted during January 2013.

Sub-subtask F3a-1.3. Obtain temperature-dependent dynamics results for model asphalts that represent asphalts of different crude oil sources (URI)

On Schedule

Work is progressing on conducting molecular simulations of model asphalts and analyzing the results to obtain physical insights and free energy parameters. Initial results were generated during the quarter for molecular simulation predictions of $|G^*|$ and phase angle δ from the spontaneous fluctuations in the stress tensor. Preliminary results were presented by the graduate student at the AIChE Annual meeting. The calculations have focused first on the new simulation composition of AAA-1 using elevated temperatures of 400, 443, and 533 K (260, 338, 500 ^{o}F). Ongoing efforts include analyzing these results using time-temperature superposition. Some $|G^*|$ and δ calculations have been done for prior model asphalt compositions.

Sub-subtask F3a-1.4. Simulate changes in asphalt dynamics after inducing representations of chemical and/or physical changes to a model asphalt (URI)

Slight delay during the past quarter.

Work to simulate additional asphalt systems continues to proceed more slowly than expected. Simulations have been initiated for multiple additional model asphalts using new compositions, though simulations at additional temperatures are required prior to full data analysis. The slowdown was initiated by a decision to have a new graduate student on the project initially focus their time on the complex modulus tool rather than on new simulations. The delay is a result of two factors. A new teaching load assigned to the PI slowed research progress significantly. Hurricane Sandy and a subsequent planned power outage also interfered with operating the computer cluster. New computer hardware will be obtained to speed the final calculations.

Sub-subtask F3a-1.2. Develop algorithms and methods for directly linking molecular simulation outputs and phase field inputs (URI)
Subtask F3a-4. Overall integration for multiscale modeling (VT, URI, and WRI)
Subtask F3a-5. Experimental verification and validation (VT, URI, and WRI)

Technical work - On Schedule. Decision about integrating reports – final decision delayed.

These Subtasks and Sub-subtasks constitute the ARC Model Deliverable for obtaining free energy from a molecular perspective. Developing models to interpret molecular simulations to parameterize free energy models is proceeding on schedule. The inputs for these calculations are the molecule positions, velocities, and stress fluctuations that are calculated in the detailed molecular simulations.

It is anticipated that the model for free energy will be a sequence of molecular simulations, interpretations, correlations, interpolations, and extrapolations that provide the free energy as a cumulative output. This involves much more complexity than is typically found in the representation of an asphalt model via an equation, a spreadsheet, or a simple computer program. It was intended that in the past quarters an idea would have been considered about incorporating the Model Deliverable into the contents of Report S. The discussions about integrating the report were again delayed because of the new teaching schedule. Incorporating the model into report S does seem to make sense at this time. The final decision will be made during the next quarter.

Report T is entitled “Progress Toward a Multi-scale Model of Asphalt Pavement- Including Test Methods for Model Input Parameters”. It is possible that that report will encompass Subtasks F3a-4 and F3a-5. This ambiguity will be resolved during the next quarter.

REPORT T: PROGRESS TOWARD A MULTI-SCALE MODEL OF ASPHALT PAVEMENT

Included work elements/subtasks
Work Element F3a: Phase-field modeling of crack interaction in asphalt binder
Subtask F3a-4.1 Implement of the phase field model into crack interaction
Subtask F3a-4.2 J-integral summation in crack interaction
Subtask F3a-4.3 Numerical simulation of crack interaction
Subtask F3a-4.4 Crack interaction experiment of asphalt binder

Status and Work Planned
On Schedule

At this moment, this research progress is on time according to the plan. Subtasks F3a 4.1-4.3 have been finished. Subtask F3a-4.4 of the asphalt crack interaction experiment will be finished in the next quarter.

In the state-of-the-art research of asphalt cracking, only the mode I cracking is paid enough attention by the researchers and the more realistic situation with crack interaction has not been well analyzed theoretically or experimentally. By using phase-field model, we can establish the whole crack interaction process and analyze the critical fracture stress and forthcoming crack interaction angle, path, etc.

Assume that there exists a macro crack and a micro crack as shown in Figure 1, set the anti-clockwise direction as the positive direction. According to the conservation law of *J*-integral, we have

$$J(\Gamma_\infty) + J(BC) + J(DE) + J(\Gamma_2) + J(ED) + J(\Gamma_1) + J(FA) = 0. \tag{1}$$

Note that integral over path DE is cancelled with the one on ED. Consider traction-free condition on the crack surfaces, we have $J(BC) = J(FA) = 0$ and thus equation (1) can be further derived as

$$J(\Gamma_\infty) = J(\Gamma_1) + J(\Gamma_2) \tag{2}$$

Where $J(\Gamma_\infty)$ is the *J*-integral from the remote stress field, $J(\Gamma_1)$ is the *J* integral from the macro-crack tip and $J(\Gamma_2)$ is the *J*-integral from the micro-crack tip. What should be mentioned here is that the position and mode of micro-crack Γ_2 does not affect the interaction itself but only the magnitude of the stress.

Figure 2 shows the crack propagation at different time instants using a simple crack interaction model. It can be clearly seen that the crack on the left propagates along the *x* direction while there is a diffuse interface between the crack phase and the intact phase. As the crack propagates, it interacts with the one on the right, which eventually leads to the specimen failure. Note that the microcrack is simplified as a horizontal crack.

Figure 3 shows the stress concentration at the crack interaction point as expected.

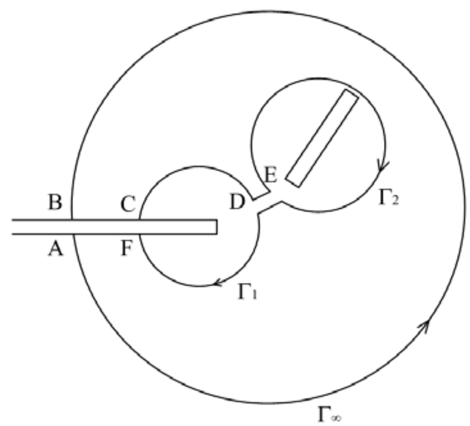


Figure 1. Contour plot of the crack interaction.

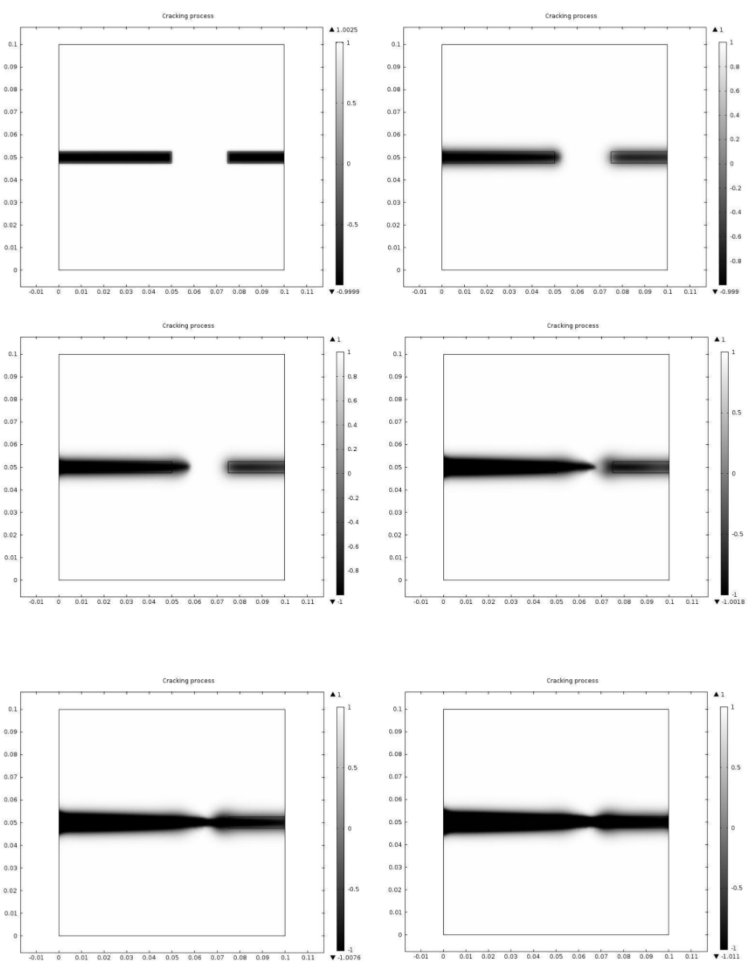


Figure 2. Crack interaction at different time instants.

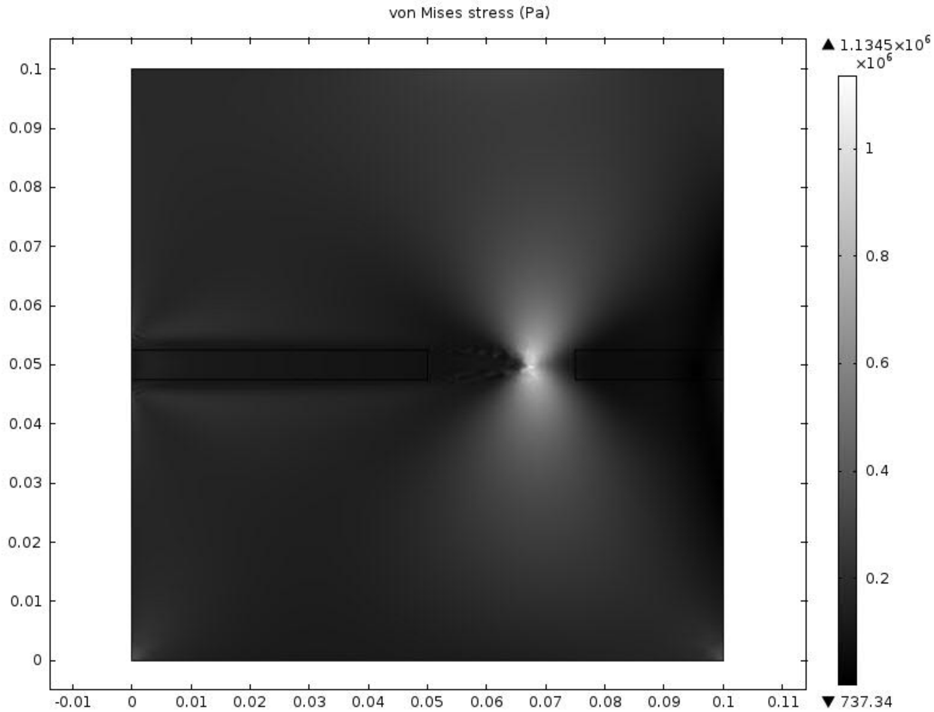


Figure 3. von Mises stress distribution at a given time instant.

REPORT U: DESIGN GUIDANCE FOR FATIGUE AND RUT RESISTANCE MIXTURES

Included Work Elements/Subtasks
Work Element E2e: Design Guidance for Fatigue and Rut Resistance Mixtures

Status and Work Planned
Behind schedule.

Work is progressing according to the year six work plan. All laboratory testing was completed this quarter. Analysis of the data and refinement of the four models is continuing: (1) Hirsch model for dynamic modulus, (2) resistivity rutting model, (3) reduced cycles fatigue model, and (4) permeability model. After discussions with FHWA it was decided that Report U would consist of two components: (1) research report submitted to NTIS thoroughly documenting the refinement of the four models, and (2) a Technical Brief demonstrating how the models can be used to improve during mixture design to improve the rutting and fatigue resistance of mixtures. Work on the NTIS report was initiated this quarter. The revised delivery date for the NTIS report is September 30, 2013.

Next quarter, data analysis and refinement of all four models will continue. Work on the NTIS report will continue.

REPORT V: CONTINUUM DAMAGE PERMANENT DEFORMATION ANALYSIS FOR ASPHALT MIXTURES

Included Work Elements/Subtasks
Work Element F2c: Mixture Testing Protocol (TAMU)
Work Element E1a: Analytical and Micro-Mechanics Models for Mechanical Behavior of Mixtures (TAMU)

Status and Work Planned
Status: on schedule.

In this quarter, a technical paper entitled "Characterization of Viscoplastic Yielding of Asphalt Concrete" was prepared and submitted to Journal of Construction and Materials for review.

Furthermore, work was performed to summarize the constitutive models, testing protocols, data analysis methods and processing programs, testing results and material properties developed and determined in all previous quarterly reports for the characterization of the permanent deformation of asphalt mixtures. The investigated properties of the ARC mixtures include the anisotropy, viscoelasticity, viscoplasticity and viscofracture. The investigated variables of the mixtures include two types of ARC asphalt binder (Valero and NuStar), two air void contents (4% and 7%) and three aging periods (0, 3, 6-month continuous aging at 60°C). The effects of each variable on the material properties of the mixtures were analyzed and discussed.

In addition, the draft of the final report (ARC Report V) has been initiated and several chapters of the final report were completed including: 1) Literature Review; and 2) Anisotropic Viscoelasticity of Undamaged Asphalt Mixtures. Work will be continued in finishing the writing of the final report in next quarter.

REPORT W: CHARACTERIZATION OF FATIGUE AND HEALING PROPERTIES OF ASPHALT MIXTURES

Included Work Elements/Subtasks
Work Element E1a: Analytical and Micro-Mechanics Models for Mechanical Behavior of Mixtures (TAMU)

Status and Work Planned
Status: on schedule.

The work under this work element is on schedule. Detailed methods and models are documented in Test Method and Model "Characterization of Fatigue and Healing Properties of Asphalt Mixtures" (No. 32) in the table of deliverables.

In the last quarter, the relationships between the fatigue resistance of asphalt mixtures and the modified Paris' Law parameters (A' and n') were studied. The fatigue resistance of asphalt mixtures is found to be measured by the value of n'. A smaller value of n' corresponds to better resistance of an asphalt mixture to fatigue cracking. Such an index is simple to use in terms of material comparison and selection for fatigue cracking. In order to find a similar index to measure the healing ability of asphalt mixtures, the characteristics of the healing curve were studied this quarter. Twenty types of asphalt mixtures were tested to verify that the index obtained from the healing curve can correctly represent the healing ability of different asphalt mixtures.

Healing curve of an asphalt mixture shows the relationship between the extent of healing and the rest time. The extent of healing is defined as the difference between the damage density at any time and the initial damage density before healing starts. It is observed from the healing curve that there is a rapid increase of the extent of healing at the beginning of the rest time. Then the change of the extent of healing gradually decreases as the rest time increases. Such characteristics of the healing curve can be described by three indexes: 1) short-term healing rate, which represents the healing speed of an asphalt mixture at the beginning of the rest time; 2) long-term healing rate, indicating the healing speed of the asphalt mixture after a long rest time; and 3) healing rate scale, which reflects the overall ability of the asphalt mixture to heal. Based on these three indexes, the extent of healing measured from the test can be predicted using a mathematical model with R-squared nearly 1.

To verify the accuracy of using the indexes from the healing curve as indicators of healing ability, these indexes are compared to evaluate the effect of asphalt binder, effect of air void content, and the effect of aging on twenty types of asphalt mixtures. The testing and analysis of the results include:

- Comparing AAD and AAM mixtures, which have the same aggregate, both the short-term healing rate and the healing rate scale of AAM mixtures are larger than those of AAD mixtures. This leads to the conclusion that the AAM mixtures have better healing ability than the AAD mixtures. Comparing Nustar and Valero mixtures, which have the same aggregate, the NuStar mixtures have better healing ability than Valero mixtures.

- Comparisons are performed on asphalt mixtures with 4% air void content and 7% air void content. It is found that the asphalt mixtures with 4% air void content always have better healing ability than those with 7% air void content, regardless the type of asphalt binder, aging, and temperature.
- The change of the healing ability due to the change of temperature is investigated by comparing the indexes at 10, 20, and 30°C, respectively. The results indicate that the temperature has significant influence on the healing ability of the asphalt mixtures: the healing ability is the highest at 30°C and it decreases rapidly when the temperature decreases; the healing of asphalt mixtures at 10°C is much slower and the extent is smaller.
- Comparisons are conducted on unaged and aged specimens for all AAD, AAM, NuStar, and Valero mixtures. There is a considerable reduction of the indexes from unaged asphalt mixtures to those aged. This fact suggests that the healing speed becomes smaller and smaller as the aging time increases.

The test results prove that the indexes obtained from the healing curve can be used as indicators of healing ability of different asphalt mixtures. In the next quarter, a further step will be taken to relate these healing indexes to fundamental material properties. It is expected that the healing behaviors can be predicted from rapid nondestructive tests on undamaged asphalt mixtures rather than through destructive tests.

REPORT X: CHARACTERIZATION OF FIELD CORES OF ASPHALT PAVEMENTS

Included Work Elements/Subtasks

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

Status and Work Planned

The work under this work element is on schedule. Detailed methods and models are documented in Test Method and Model "Characterization of Field Cores of Asphalt Pavements" in the Table of Deliverables.

In the previous quarters, the developed test protocol of field cores has been applied to field cores from Arizona and Yellowstone National Park. The analysis results show that this protocol is able to characterize the mixture stiffness gradient profiles in the field cores. In order to further examine its potential applicability, the test protocol for field cores was used on field cores taken from Farm-to-Market Road No. 973 (FM 973) in this quarter. These Texas field cores were taken from three sections of FM 973:

1. Section 1: hot mix asphalt (HMA);
2. Section 2: foamed warm mix asphalt (FWMA); and
3. Section 3: Evotherm warm mix asphalt (EWMA).

Each field core contains three different layers, which are separated before testing. The three layers are then cut into three rectangular specimens, which are tested nondestructively in the Direct Tension Test at 10°C and 20°C, sequentially.

Table 1 shows the stiffness gradient profile analysis for 10°C. The calculated results are summarized in table 1, and the stiffness profiles are illustrated in figures 1 and 2. In table 1, k is the ratio of the surface modulus to the bottom modulus and n is the exponent by which the modulus varies from bottom to top. Figure 1 shows the stiffness profiles for the top two layers of the HMA in Section 1 at 10°C; figure 2 shows the stiffness profiles for the FWMA at 10°C and 20°C. The results indicate that the protocol can reliably and repeatably generate the stiffness profiles of the Texas field cores at different locations and different temperatures.

Table 1. Stiffness gradient profile for Texas field cores.

ID	Temperature (C°)	n	k	Surface Modulus (psi)	Bottom Modulus (psi)
1-13-1	10	5.27	1.62	198000	122000
1-13-2	10	3.52	1.87	858000	457000
1-20-1	10	5.25	1.66	489000	294000
7-15-1	10	5.39	1.38	197000	273000
7-24-1	10	3.59	2.07	175000	362000
7-24-2	10	3.43	1.62	606000	986000
7-24-3	10	5.34	1.37	788000	1080000
8-24-2	10	5.39	1.38	445000	618000
8-24-3	10	5.27	1.34	763000	1030000

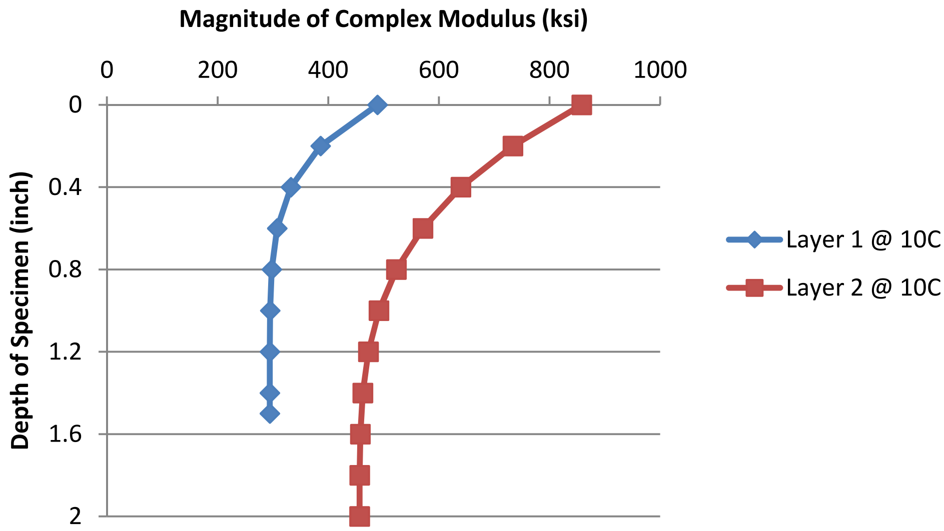


Figure 1. Complex moduli of different layers in HMA section.

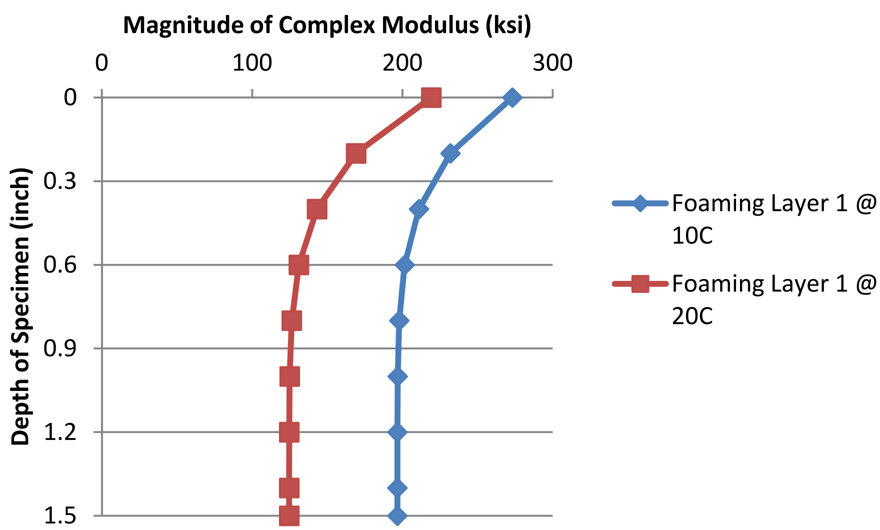


Figure 2. Complex moduli of FWMA layer 1 at different temperatures.

The work planned in next quarter includes the testing and analysis of the fracture properties of Texas field cores and YNP cores using the Overlay Tester and the Functionally Graded material (FGM) integrated finite element model.

REPORT Y: MODEL WATER VAPOR DIFFUSION IN PAVEMENT AND ITS EFFECTS ON THE PERFORMANCE OF ASPHALT MIXTURES

Included Work Elements/Subtasks
Work Element E1a: Analytical and Micro-Mechanics Models for Mechanical Behavior of Mixtures

Status and Work Planned
Status: on schedule.

In this quarter, more specimens were tested following the experimental testing plan. All the data are summarized in the following table:

Table 1. Summary of the fracture parameters for specimens fabricated with Nustar and Valero binder.

Aggregate	Binder Type	Specimens ID	Air Void (%)	Conditioning RH (%)	Fracture Parameters	
					n'	A'
Hanson Limestone	Nustar PG76-22	4_A0	8.05	0	3.23	4.38E-17
		5_A0	6.79	100	9.02	2.54E-42
		8_A0	7.82	100	10.99	7.25E-51
		9_A6	7.49	0	5.97	4.86E-29
		10_A6	7.64	0	5.15	1.74E-25
	Valero PG64-16	7_A0	7.54	0	2.96	6.83E-16
		8_A0	6.91	100	11.44	1.09E-52
		9_A0	7.35	100	10.52	1.06E-48
		11_A6	6.58	0	7.94	1.59E-37
		12_A6	7.37	0	8.12	2.56E-38

Table 1 shows that as the relative humidity conditioning increases to 100%, the fracture parameter n' tends to increase for both Nustar and Valero specimens, which indicates that the saturated vapor pressure in the specimens significantly decreases the fatigue resistance of the asphalt mix material. The modified Paris Law parameter A' tends to decrease as the relative humidity condition increases. This decrease is not adequate to offset the increase of n'. The testing results also indicate that the presence of moisture induces more fatigue damage than aging at 60°C for a period of six weeks. These results indicate that the presence of moisture in the asphalt due to vapor diffusion increases the fatigue cracking of asphalt mixes significantly.

In this quarter, the wind speed effect was considered in modeling the vapor diffusion process in pavement by using the Crank-Nicolson numerical method. The flux boundary condition, including wind speed at the pavement surface, was formulated as follows:

$$\frac{\partial u}{\partial x} = f(u)*(u_a - u_s) \tag{1}$$

Where $\frac{\partial u}{\partial x}$ = the rate of potential evaporation (PE); u_a = the suction in the air; u_s = the suction at the pavement surface; and $f(u)$ is a function which depends on the wind above the surface of the pavement and can be expressed as follows:

$$f(u) = h*(1+\alpha_m) \tag{2}$$

Where h = coefficient of vapor transfer at the boundary surface; and α_m = the mass exchange coefficient of water vapor due to the wind at surface. Specifically, Equation 3 indicates that the wind speed increases the water vapor mass exchange at the surface α_m:

$$\alpha_m = K\sqrt{\frac{V}{L}} \tag{3}$$

where V = the wind speed, m/sec; and L = the length over which the wind blows; the largest α_m occurs if the wind blows across the width of the highway, m. Based on the work done by Afanas'ev, the K can be expressed as:

$$K = 0.662\lambda_m (P_{rm})^{1/3} (\frac{1}{\upsilon})^{1/2} \tag{4}$$

where P_{rm} = Prandtl number for air; v = the kinematic viscosity of air, m^2/sec; and λ_m is considered as a constant at the air temperature of 20 °C and was taken as $2.54\times10^{-3} kg/(s^{-1}\cdot m^2)$.

Figure 1 shows that as the time after placement increases, the asphalt surface layer gradually wets up due to the moisture movement from the subgrade soil into the base course and then into the surface layer. The closer to the pavement surface, the lower is the relative humidity in the asphalt layer. The moisture builds up in the asphalt mixture at such a fast rate that the RH in the surface asphalt layer reaches 90% in approximately 90 days, and the RH level increases with time within the asphalt layer. These modeling results illustrate that the wind speed on the pavement surface will significantly increase the water vapor diffusion in pavement.

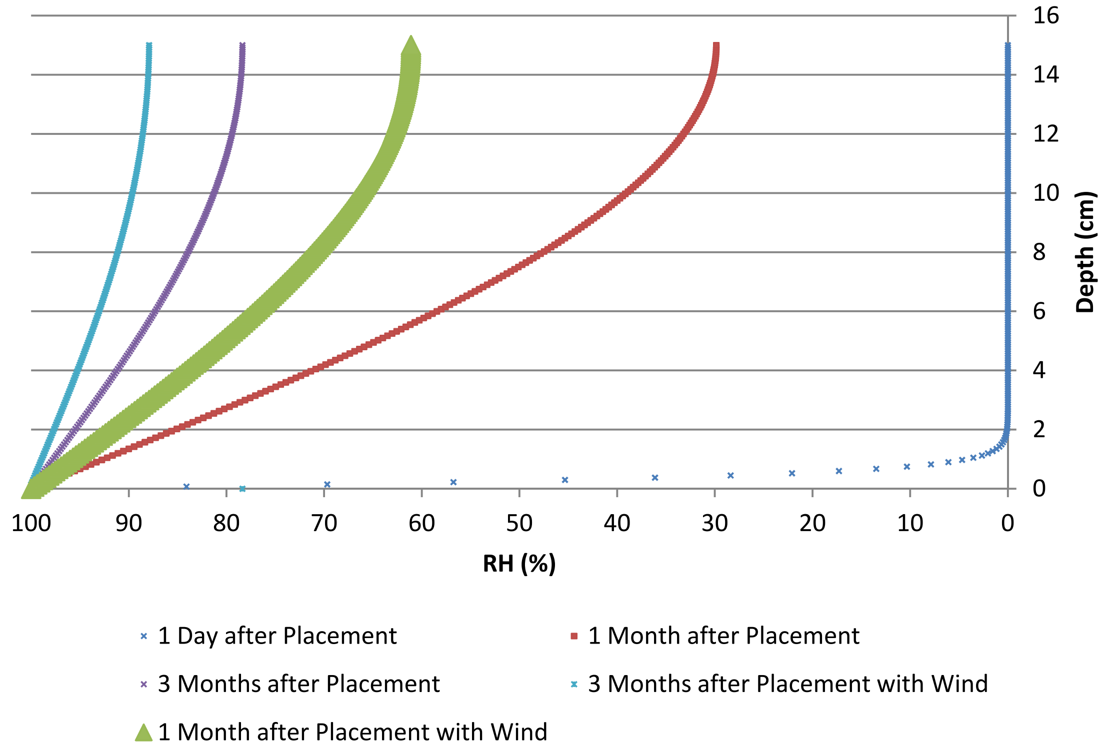


Figure 1. Wind speed effect on water vapor diffusion in pavement.

REPORT Z: EFFECT OF EXTRACTION METHODS ON THE PROPERTIES OF AGGREGATES IN RECLAIMED ASPHALT PAVEMENT

Included Work Elements/Subtasks
Work Element E2b: Design System for HMA Containing a High Percentage of RAP Materials

Status and Work Planned
On Schedule.

Part of the work in Work Element examined the effect of extraction method on RAP aggregate properties. A report on this part of the work is in the final stages of preparation in NTIS format. It is expected to be finished by March 1, 2013.

TEST METHODS

DRAFT AASHTO METHOD/PRACTICE: SIMPLIFIED CONTINUUM DAMAGE FATIGUE ANALYSIS FOR THE ASPHALT MIXTURE PERFORMANCE TESTER

Included Work Elements/Subtasks
Work Element E2e: Design Guidance for Fatigue and Rut Resistance Mixtures

Status and Work Planned
Behind schedule

Work is progressing according to the year six work plan. The geometric stress progression test without rest periods has worked well in characterizing damage to localization in eight different mixtures in Work Element E2e. Work continued on the development of an automated spreadsheet, much like Mastersolver, that can be used to reduce and analyze geometric stress progression test data collected with the Asphalt Mixture Performance Tester using reduced cycles analysis. An important component of the analysis is defining the damage tolerance of the mixture. The Fénix fracture energy test is being added to the procedure to determine the damage tolerance of the mixture.

The draft practice will be completed next quarter. The revised delivery date for the draft practice is March 31, 2013.

AASHTO METHOD: TEST METHODS FOR DETERMINING THE PARAMETERS OF MATERIAL MODELS IN PANDA

Included Work Elements/Subtasks:
Work Element V3c: Validation of PANDA

Status and Work Planned:

The laboratory tests needed to calibrate and validate PANDA for the first ARC Mixture are completed, and the data have been analyzed. The researchers have tested two specimens at a given loading condition, and they have conducted quality control on the data. A third specimen was added when the results of two replicates were not comparable. All the testing protocols necessary for the full calibration of validation of the PANDA model has been developed and used in the testing of ARC Mixture No. 1. Currently, the researchers are drafting these testing protocols in the format of AASHTO test procedures. In addition, the researchers have started in the laboratory tests needed to calibrate and validate PANDA for the second ARC Mixture.

TEST METHOD AND MODEL: CONTINUUM DAMAGE PERMANENT DEFORMATION ANALYSIS FOR ASPHALT MIXTURES

Included Work Elements/Subtasks
Work Element F2c: Mixture Testing Protocol (TAMU)
Work Element E1a: Analytical and Micro-mechanics Models for Mechanical Behavior of Mixtures (TAMU)

Status and Work Planned

References published:

Zhang, Y., Luo, R., and Lytton, R. L. (2013). "Mechanistic Modeling of Fracture in Asphalt Mixtures under Compressive Loading." *Journal of Materials in Civil Engineering*, American Society of Civil Engineers (ASCE), in press.

Zhang, Y., Luo, R., and Lytton, R. L. (2012). "Characterizing Permanent Deformation and Fracture of Asphalt Mixtures by Using Compressive Dynamic Modulus Tests." *Journal of Materials in Civil Engineering*, Vol. 24, No. 7, American Society of Civil Engineers (ASCE), pp. 898-906.

Zhang, Y., Luo, R., and Lytton, R. L. (2011). "Microstructure-Based Inherent Anisotropy of Asphalt Mixtures." *Journal of Materials in Civil Engineering*, Vol. 23, No. 10, American Society of Civil Engineers (ASCE), pp. 1473-1482.

Zhang, Y. (2012). "Anisotropic characterization of asphalt mixtures in compression." Ph.D. Dissertation, Texas A&M University, College Station, Texas, USA.

Test method document:

The test method document is under preparation, which will be referenced in and will be appendix to Report V "Continuum Damage Permanent Deformation Analysis for Asphalt Mixtures".

TEST METHOD AND MODEL: CHARACTERIZATION OF FATIGUE AND HEALING PROPERTIES OF ASPHALT MIXTURES

Included Work Elements/Subtasks

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

Status and Work Planned

References published:

Luo, X., Luo, R., and Lytton, R. L. (2013). "Modified Paris' Law to Predict Entire Crack Growth in Asphalt Mixtures." *Transportation Research Record: Journal of the Transportation Research Board,* Transportation Research Board of the National Academies, Washington, D.C., in press.

Luo, X., R. Luo, and R. L. Lytton. (2013). "Characterization of Asphalt Mixtures Using Controlled-Strain Repeated Direct Tension Test." *Journal of Materials in Civil Engineering*, American Society of Civil Engineers (ASCE), accepted for publication, available at http://ascelibrary.org/doi/pdf/10.1061/%28ASCE%29MT.1943-5533.0000586.

Luo, X., R. Luo, and R. L. Lytton. (2013). "Characterization of Fatigue Damage in Asphalt Mixtures Using Pseudo Strain Energy." *Journal of Materials in Civil Engineering*, American Society of Civil Engineers (ASCE), accepted for publication, available at http://cedb.asce.org/cgi/WWWdisplay.cgi?293976.

Luo, X., R. Luo, and R. L. Lytton. (2013). "An Energy-Based Mechanistic Approach to Characterize Crack Growth of Asphalt Mixtures." *Journal of Materials in Civil Engineering*, American Society of Civil Engineers (ASCE), accepted for publication, available at http://cedb.asce.org/cgi/WWWdisplay.cgi?294011.

Tong, Y., Luo, R., and Lytton, R. L. (2013). "Modeling Water Vapor Diffusion in Pavement and Its Influence on Fatigue Crack Growth if Fine Aggregate Mixture." *Transportation Research Record: Journal of Transportation Research Board*, National Research Council, Washington, D.C., in press.

Luo, X. (2012). "Characterization of Fatigue Cracking and Healing of Asphalt Mixtures." Ph.D. dissertation, Texas A&M University, College Station.

Tong, Y. (2013). "Modeling Water Vapor Diffusion in Pavement and Its Influence on the Fatigue Crack Growth of Asphalt Mixture". Ph.D. Dissertation. Texas A&M University, College Station, Texas.

Test method document:

The test method document is under preparation, which will be referenced in and will be appendix to Report W "Characterization of Fatigue and Healing Properties of Asphalt Mixtures".

TEST METHOD AND ANALYSIS PROGRAM: NONDESTRUCTIVE CHARACTERIZATION OF TENSILE VISCOELASTIC PROPERTIES OF UNDAMAGED ASPHALT MIXTURES

Included Work Elements/Subtasks

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

Status and Work Planned

References published:

Luo, R., and Lytton, R. L. (2010). "Characterization of the Tensile Viscoelastic Properties of an Undamaged Asphalt Mixture." *Journal of Transportation Engineering*, Vol. 136, No. 3, American Society of Civil Engineers (ASCE), pp. 173-180.

Test method document:

The test method document is under preparation, which will be referenced in and will be appendix to Report W "Characterization of Fatigue and Healing Properties of Asphalt Mixtures" and Report Y "Water Vapor Diffusion in Pavement and Its Effects on the Performance of Asphalt Mixtures".

TEST METHOD AND MODEL: CHARACTERIZATION OF FIELD CORES OF ASPHALT PAVEMENTS

Included Work Elements/Subtasks
Work Element E1a: Analytical and Micro-mechanics Models for Mechanical Behavior of Mixtures (TAMU)

Status and Work Planned

References published:

Koohi, Y., Luo, R., Lytton, R. L., and Scullion, T. (2013). “New Methodology to Find the Healing and Fracture Properties of Asphalt Mixes Using Overlay Tester.” *Journal of Materials in Civil Engineering*, in press.

Koohi, Y., Lawrence, J., Luo, R., and Lytton, R. L. (2012). “Complex Stiffness Gradient Estimation of Field-Aged Asphalt Concrete Layers Using the Direct Tension Test.” *Journal of Materials in Civil Engineering*, Vol. 24, No. 7, American Society of Civil Engineers (ASCE), pp.832-841.

Koohi, Y. (2012). "Analytical –Numerical Methodology to Measure Undamaged, Fracture and Healing Properties of Asphalt Mixtures." Ph.D. Dissertation, Texas A&M University, College Station, Texas, USA.

Test method document:

The test method document is under preparation, which will be referenced in and will be appendix to Report X “Characterization of Field Cores of Asphalt Pavements”.

TEST METHOD AND ANALYSIS PROGRAM: NONDESTRUCTIVE CHARACTERIZATION OF ANISOTROPIC VISCOELASTIC PROPERTIES OF UNDAMAGED ASPHALT MIXTURES UNDER COMPRESSIVE LOADING

Included Work Elements/Subtasks
Work Element F2c: Mixture Testing Protocol (TAMU)
Work Element E1a: Analytical and Micro-mechanics Models for Mechanical Behavior of Mixtures (TAMU)

Status and Work Planned

References Published:

Zhang, Y., Luo, R., and Lytton, R. L. (2012). "Anisotropic Viscoelastic Properties of Undamaged Asphalt Mixtures." *Journal of Transportation Engineering*, Vol. 138, No. 1, American Society of Civil Engineers (ASCE), pp. 75-89.

Zhang, Y. (2012). "Anisotropic characterization of asphalt mixtures in compression." Ph.D. Dissertation, Texas A&M University, College Station, Texas, USA.

Test method document:

The test method document is under preparation, which will be referenced in and will be appendix to Report V "Continuum Damage Permanent Deformation Analysis for Asphalt Mixtures".

DRAFT AASHTO PRACTICE: MIX DESIGN FOR COLD-IN-PLACE RECYCLING (CIR)

Included Work Elements/Subtasks
Work Element E1c-2: Improvement of Emulsion Characterization and Mixture Design for Cold Bitumen Applications

Status and Work Planned
On Schedule.

No CIR projects were identified last quarter. Work will continue to validate the proposed mix design approach for CIR mixes.

DRAFT AASHTO METHOD/PRACTICE: MIX DESIGN FOR COLD MIX ASPHALT

Included Work Elements/Subtasks
Work Element E1c: Warm and Cold Mixes
SubtaskE1c-2: Improvement of Emulsions' Characterization and Mixture Design for Cold Bitumen Applications
Subtask E1c2-Yr6-I: Protocol for Selecting Aggregates and Emulsions for CMA
Subtask E1c2-Yr6-II: Evaluation of CMA Laboratory Compaction Methods and Curing Conditions

Status and Work Planned
On Schedule

Work Completed: A volumetric-based mix design procedure was defined and an experimental plan to validate the framework was developed. The validation plan will focus on two aggregate sources using several gradations and emulsion formulations. As part of the mix design work began on the development of a curing procedure for CMA using confinement molds. It is anticipated that mix design and curing procedures used in combination will produce a design system capable of producing samples for volumetric and/or performance testing.

Work Planned: Work will focus on the further development of the curing and mix design procedures through execution of the experimental plan developed this quarter. It is anticipated that a preliminary data set related to compaction and volumetrics of CMA will be available by the end of the quarter.

Delivery Dates
Draft AASHTO Practice: 9/30/2013
Final AASHTO Practice: 3/31/2014

DRAFT AASHTO PRACTICE: EVALUATION OF RAP AGGREGATES

Included Work Elements/Subtasks
Work Element E2b: Design System for HMA Containing a High Percentage of RAP Materials
Subtask E2b-1: Develop a System to Evaluate the Properties of RAP Materials

Status and Work Planned
On Schedule.

The findings from the report entitled: "Effect of Extraction Methods on the Properties of Aggregates in Reclaimed Asphalt Pavement," were considered in the final recommendations of NCHRP 09-46 study completed by NCAT.

DRAFT AASHTO PRACTICE: IDENTIFICATION OF CRITICAL CONDITIONS FOR HMA MIXTURES

Included Work Elements/Subtasks
Work Element E2c: Critically Designed HMA Mixtures

Status and Work Planned
On schedule.

The following list describes the work items completed this quarter:

- A draft version of the AASHTO Standard Practice entitled "Determining the Asphalt Mixture Critical Conditions for Rutting Evaluation by Means of Dynamic Repeated Load Triaxial Test (RLT)" has been finalized.

The following list the work planned for next quarter:

- Submit the AASHTO Draft practice to FHWA for review and input.

DRAFT AASHTO METHOD: DETERMINING THERMAL CRACK PROPERTIES OF ASPHALT MIXTURES THROUGH MEASUREMENT OF THERMALLY INDUCED STRESS AND STRAIN

Included Work Elements/Subtasks
Work Element E2d: Thermal Cracking Resistant Mixes for Intermountain States
Subtask E2d-3: Identify an Evaluation and Testing System

Status and Work Planned
On Schedule

The following list describes the work items completed this quarter:

- Revisited The Uniaxial Stress and Strain Test (UTSST) draft AASHTO procedure to incorporate the Asphalt Thermal Cracking Analyzer (ATCA) procedure developed by University of Wisconsin-Madison.

The following list the work planned for next quarter:

- Testing control specimens to validate the approach presented to determine thermal visco-elastic properties of asphalt mixtures using ATCA device.
- Revise AASHTO draft procedure as needed to incorporate reviewers' comments.

DRAFT AASHTO METHOD/PRACTICE: DETERMINING ASPHALT BINDER BOND STRENGTH BY MEANS OF THE BITUMEN BOND STRENGTH TEST

Included Work Elements/Subtasks
Work Element M1a: Affinity of Asphalt to Aggregate

Status and Work Planned
Completed

Work Completed: The current standard AASHTO TP-91 was revised to include changes in the application temperature for the aggregate substrate to simulate mixing conditions. The suggested amount of fresh emulsion used in the test was changed to account for the water that evaporates after curing. Also, as failure in the BBS is not totally cohesive or adhesive, re-wording of the failure types are included in the revised standard (i.e., within asphalt binder and in asphalt-aggregate interface). To allow testing heavily modified binders, the revised standard suggests the use of piston F-4 instead of F-2 for higher loading capacity. Other revisions were made after feedback from users.

Work Planned: Submit revised standard to the FHWA Emulsion Task Force and Binder ETG.

Delivery Dates
Final Version of AASHTO TP-91: 3/31/2013

DRAFT AASHTO TEST METHOD: MEASUREMENT OF ASPHALT BINDER ELASTIC RECOVERY IN THE DYNAMIC SHEAR RHEOMETER (DSR)

Included Work Elements/Subtasks
Work Element F2a: Binder Tests and Effect of Composition

Status and Work Planned
Completed

Work Completed: Test procedure has been updated and combined with the DSR-Ductility method (following the BYET procedure) in AASHTO format. The AASHTO standard is intended to provide reliable alternatives for the standard elastic recovery and ductility tests using a DSR.

Work Scheduled: Submit test method to the Binder ETG and request time on the agenda to present in the May 2013 meeting. Propose changing name of this product to "Measurement of Asphalt Binder Elastic Recovery and Ductility in the Dynamic Shear Rheometer."

Reasons for Delay: Internal review of standard delayed submittal to early 2013. Draft is now complete and ready for submission.

Delivery Dates
Draft AASHTO Method: 1/31/2013 (extended from 12/31/2012)
Presentation at FHWA Binder ETG Meeting: 5/02/2013
Final AASHTO Method: 6/30/2013

AASHTO TEST METHOD: ESTIMATING FATIGUE RESISTANCE OF ASPHALT BINDERS USING THE LINEAR AMPLITUDE SWEEP

Included Work Elements/Subtasks
Work Element F2e: Verification of the Relationship between DSR Binder Fatigue Tests and Mixture Performance

Status and Work Planned
On Schedule (procedure completed, ruggedness on schedule)

Work Completed: Revised previously accepted AASHTO procedure to address limitations of DSR controls. Inter-laboratory ruggedness testing plan was completed. The modified test procedure, testing plan, and samples were distributed to the participating laboratories. The laboratories participating include: MTE Services, North Carolina State University, University of Wisconsin-Madison, and Utah DOT.

Work Planned: Ruggedness results will be analyzed over the next quarter in preparation for presenting an update at to the FHWA Binder ETG. AASHTO Procedure will be updated to include ruggedness results.

Delivery Dates
Submit Revised Draft AASHTO Method to ETG: Completed.
Presentation at FHWA Binder ETG Meeting: 5/02/2013
Final AASHTO Method: 6/30/2013

AASHTO TEST METHOD: BINDER YIELD ENERGY TEST (BYET)

Included Work Elements/Subtasks
Work Element F2e: Verification of the Relationship between DSR Binder Fatigue Tests and Mixture Performance

Status and Work Planned
Completed.

Work Completed: Previously submitted draft standard was revised and re-named as the DSR-Ductility procedure. This method has been combined with the DSR-Elastic Recovery AASHTO standard and will not be a separate deliverable. Draft AASHTO ER/Ductility in the DSR procedure was completed and is ready for submission.

Work Planned: None. All work will be reported under the product re-named, "Measurement of Asphalt Binder Elastic Recovery and Ductility in the Dynamic Shear Rheometer" standard previously reported on.

Delivery Dates
Completed, combined with ER-DSR test for one AASHTO procedure.

DRAFT AASHTO TEST METHOD: MEASUREMENT OF RIGDEN VOIDS FOR MINERAL FILLERS

Included Work Elements/Subtasks
Work Element F2e: Verification of the Relationship between DSR Binder Fatigue Tests and Mixture Performance

Status and Work Planned
Behind Schedule

Work Completed: Comments from the manufacturer regarding the previously submitted draft AASHTO procedure were addressed. A revised procedure was completed.

Work Planned: Submit draft AASHTO standard to FHWA and request time for presentation at the May 2013 ETG meeting.

Reasons for Delay: Delays were encountered in receiving feedback from the manufacturer. These delays were overcome and the product is complete.

Revised Delivery Dates
Draft AASHTO Method: Complete (1/31/2013).
Final AASHTO Method: 7/31/2013 (6 months after submission of draft). Will consult with FHWA on timing and review group.

DRAFT AASHTO TEST METHOD: MEASUREMENT OF ASPHALT BINDER LUBRICITY USING THE DYNAMIC SHEAR RHEOMETER (DSR)

<u>Included Work Elements/Subtasks</u>
Work Element E1c: Warm and Cold Mixes
Subtask E1c-1: Warm Mixes
Subtask E1c-1-Y6-I: Guideline for Determination of Mixing and Compaction Temperatures for Conventional HMA Mixes
Subtask E1c-1-Y6-II: Guideline for Determination of Acceptable WMA Production Temperatures

<u>Status and Work Planned</u>
On Schedule

Work Completed: Previously submitted TRB paper regarding use of the 4-Ball Lubricity Test to evaluate compactability for HMA and WMA was accepted for publication. M.S. Thesis related to development of a test to measure boundary lubrication was completed and accepted. Concept and outline for AASHTO standard based on these two efforts was completed.

Work Planned: Complete AASHTO standard and submit to FHWA. Standard will provide instruction for measuring lubricating properties of asphalt binders in both the hydrodynamic and boundary lubrication regimes.

<u>Delivery Dates</u>
Draft AASHTO Method: 3/31/2013
Final AASHTO Method: 9/30/2013 (6 months after date of initial submission)

DRAFT AASHTO METHOD/PRACTICE: PROCEDURE FOR EVALUATION OF COATING FOR COLD MIX ASPHALT

Included Work Elements/Subtasks
Work Element E1c: Warm and Cold Mixes
SubtaskE1c-2: Improvement of Emulsions' Characterization and Mixture Design for Cold Bitumen Applications
Subtask E1c2-Yr6-I:Protocol for Selecting Aggregates and Emulsions for CMA

Status and Work Planned
Behind Schedule

Work Completed: The proposed evaluation procedure was summarized in AASHTO format. The procedure includes evaluation of degree of particle coating using image analysis procedures and evaluation of quality of coating using a modified boiling test. The development and initial data for the procedure was summarized and presented at the Transportation Research Board annual meeting in January.

Work Planned: Conduct an experiment to identify the role of coating on mixture compaction and performance characteristics. Preliminary testing using a modified TSR procedure indicates that coating may influence the moisture susceptibility of CMA. Address internal review comments and submit finalized AASHTO draft standard.

Reason for Delay: Additional time was needed for internal review of the procedure prior to submission.

Delivery Dates
Draft AASHTO Method: 3/31/2013 – extended from 12/31/2012
Final AASHTO Standard: 9/30/2013 (6 months after initial submittal)

DRAFT AASHTO METHOD/PRACTICE: COLD MIX LABORATORY SPECIMEN PREPARATION USING MODIFIED SGC MOLDS

Included Work Elements/Subtasks
Work Element E1c: Warm and Cold Mixes
Subtask E1c-2: Improvement of Emulsions' Characterization and Mixture Design for Cold Bitumen Applications
Subtask E1c2-Yr6-II: Evaluation of CMA Laboratory Compaction Methods and Curing Conditions

Status and Work Planned
Behind Schedule

Work Completed: The use of confinement molds for sample curing was investigated. It appears sample curing can be expedited by using confinement at temperatures above ambient conditions. A work plan was finalized to evaluate the use of the SGC to produce CMA samples.

Work Planned: Execute work plan to define proper compaction and curing conditions for design of CMA. The research team will likely include this procedure as a subset for the complete CMA mix design procedure.

Reason for Delay: The "Development of a Coating Procedure for CMA" product required more time than expected, impeding the project of the CMA curing procedure. The coating test is nearing completion and efforts are being refocused.

Delivery Dates
Draft AASHTO Method: 6/30/2013 – extended from 12/31/2012
Final AASHTO Standard: 12/31/2013 (6 months after initial submittal)

DRAFT AASHTO TEST METHOD: RAP BINDER PG TRUE GRADE DETERMINATION

Included Work Elements/Subtasks
Work Element E2b: Design System for HMA Containing a High Percentage of RAP Materials

Status and Work Planned
Completed.

Work Completed: Submitted draft AASHTO standard and presented test procedure to the FHWA Mixtures ETG at the September 2012 meeting. No direct feedback has been received to date.

Work Planned: Continue efforts to establish external review and evaluation of the test procedure. Revise procedure based on external feedback and present progress at the May 2013 ETG meeting, if possible.

Delivery Dates
Draft AASHTO Test Method: Completed (9/30/2012)
Presentation at Mix ETG Meeting (if necessary): 4/30/2013.
Final AASHTO Test Method: 6/30/2013

AASHTO TEST METHOD: MEASUREMENT OF ASPHALT BINDER FRACTURE PROPERTIES USING THE SINGLE EDGED NOTCHED BENDING TEST

Included Work Elements/Subtasks
Work Element E2d: Thermal Cracking Resistant Mixes for Intermountain States

Status and Work Planned
Completed.

Work Completed: Finalized draft AASHTO standard and submitted to ETG.

Work Planned: Address comments from the review of ETG members and give a follow-up presentation at the May 2013 Binder ETG meeting if necessary.

Delivery Dates
Draft AASHTO Method: Completed (9/30/2012)
Presentation at Binder ETG Meeting (if necessary): 5/2/2013
Final AASHTO Test Method: 6/30/2013

DRAFT AASHTO TEST METHOD: TEST METHOD FOR MEASUREMENT OF THE GLASS TRANSITION TEMPERATURE OF ASPHALT BINDERS

Included Work Elements/Subtasks
Work Element E2d: Thermal Cracking Resistant Mixes for Intermountain States

Status and Work Planned
Completed

Work Completed: Completed draft AASHTO Standard. Document is ready for submission and presentation to FHWA Binder ETG.

Work Planned: Submit standard to the FHWA Binder ETG and request a presentation at May 2013 Binder ETG Meeting.

Reasons for Delay: Internal review of the standard extended into early 2013. Draft procedure is complete and was submitted to FHWA.

Delivery Dates
Draft AASHTO Test Method: Complete (1/31/2013) – extended from 12/31/2012
Presentation to Binder ETG (if necessary): 5/2/2013.
Final AASHTO Test Method: 6/30/2013

DRAFT AASHTO TEST METHOD: TEST METHOD FOR MEASUREMENT OF THE GLASS TRANSITION TEMPERATURE OF ASPHALT MIXTURES

Included Work Elements/Subtasks
Work Element E2d: Thermal Cracking Resistant Mixes for Intermountain States

Status and Work Planned
Behind Schedule

Work Completed: Combined test procedures developed by UW Madison and University of Nevada Reno to allow for evaluation of thermo-volumetric and fracture properties in the same test method. Completed preparation of draft AASHTO test procedure.

Work Planned: The draft standard is under final editing and will be submitted to the FHWA Mix ETG for review prior to the May 2013 meeting.

Reason for Delay: Additional time was needed to coordinate combination of the test procedures.

Revised Delivery Dates
Draft AASHTO Test Method: 3/31/2013 – extended from 12/31/2012
Presentation to Mix ETG (if necessary): 5/2/2013.
Final AASHTO Test Method: 6/30/2013

DRAFT AASHTO TEST METHOD/PRACTICE: ANALYSIS OF ASPHALT MIXTURE AGGREGATE STRUCTURE THROUGH USE OF PLANAR IMAGING ARC MODELS AND/OR SOFTWARE: IMAGE PROCESSING & ANALYSIS SYSTEM ($IPAS^2$)

Included Work Elements/Subtasks
Work Element E1b: Binder Damage Resistance Characterization (DRC)
SubtaskE1b-1: Rutting of Asphalt Binders

Status and Work Planned
On Schedule

Work Completed: Sensitivity analysis has been performed on the relation between indices measured using $IPAS^2$ (i.e., total proximity length, number of proximity zones, proximity orientation) and performance of mixtures. The existing AASHTO test method was updated to include new aggregate structure indices.

Work Planned: Finalize the AASHTO standard and submit to the FHWA Mixture ETG to be considered for inclusion on the agenda for the May meeting.

Delivery Dates
Draft AASHTO Method: 3/31/2013
Presentation to Mix ETG (if necessary): 4/30/2013
Final AASHTO Standard: 9/30/2013 (6 months after initial submittal)

DRAFT AASHTO METHOD/PRACTICE: DETERMINING THE RESISTIVE EFFORT OF ASPHALT MIXTURES DURING COMPACTION IN A GYRATORY COMPACTOR USING AN INTERNAL DEVICE

Included Work Elements/Subtasks
Work Element E1c: Warm and Cold Mixes
SubtaskE1c-1: Warm Mix Asphalt
Subtask E1c-2: Improvement of Emulsions' Characterization and Mixture Design for Cold Bitumen Applications

Status and Work Planned
Completed

Work Completed: The precision and bias data provided by Mathy Construction was analyzed and the research team has identified candidate labs to participate in inter-laboratory precision and bias testing. Proposed refinements to the ASTM standard have been presented to Troxler at the annual TRB meeting in January. The proposed refinements included minor alterations to the report and precision and bias sections of the standard.

Work Planned: The precision and bias testing will be completed and data analyzed for inclusion of precision and bias statement in standard.

Delivery Dates
Draft ASTM Standard: Complete
Finalize ASTM Standard to include Precision and Bias Statement: 3/31/2013

TEST METHOD AND ANALYSIS PROGRAM: SELF-CONSISTENT MICROMECHANICS MODELS OF ASPHALT MIXTURES

<u>Included Work Elements/Subtasks</u>
Work Element E1a: Analytical and Micro-mechanics Models for Mechanical Behavior of Mixtures (TAMU)

<u>Status and Work Planned</u>

References Published:

Luo, R., and Lytton, R. L. (2013). "Selective Absorption of Asphalt Binder by Limestone Aggregates in Asphalt Mixtures." *Journal of Materials in Civil Engineering*, American Society of Civil Engineers (ASCE), in press.

Luo, R., and Lytton, R. L. (2011). "Self-Consistent Micromechanics Models of an Asphalt Mixture." *Journal of Materials in Civil Engineering*, Vol. 23, No. 1, American Society of Civil Engineers (ASCE), pp. 49-55.

Test method document:

The test method document is under preparation, which will be referenced in and will be appendix to Report W "Characterization of Fatigue and Healing Properties of Asphalt Mixtures".

TEST METHOD AND ANALYSIS PROGRAM: RUTTING PREDICTION OF ASPHALT BINDER CONSIDERING STRESS-DEPENDENCE OF CREEP BEHAVIOR

<u>Status and Work Planned</u>

On Schedule - The AFM scanner has been repaired, and the AFM is now fully functional. Furthermore, materials and equipment necessary to complete the experimental analysis described in this phase of the work plan, such as specific binders, calibrated AFM tips, functionalized AFM tips, etc., have been ordered and are either prepared for testing or in route. Tasks 1 and 2 (described in the deliverables section) are being performed in conjunction with one another. The SARA [**S**aturates, napthene **A**romatics, Polar Aromatics (**R**esins), and **A**sphaltenes] fractions have been prepared for testing with yield fractions shown in Table F2d.1.

Table F2d.1. Asphalt blend details and resultant SARA fractions.

Blend No.	WRI Blend Code	Parent Asphalt	Blend Type	Resultant Fraction percent			
				Saturates	Aromatics	Polars	Asphaltenes
10086	WRI 1367-76-10	ARC BI0001	Asphaltene	14.5%	41.3%	18.8%	24.8%
10087	WRI 1367-76-9		Control	15.1%	43.0%	19.6%	21.8%
10088	WRI 1367-76-12		Saturate	20.4%	40.3%	18.4%	20.4%
10089	WRI 1367-76-14		Aromatic (Napthene)	13.1%	50.3%	17.1%	19.0%
10090	WRI 1367-76-16		Polar (Resin)	14.2%	40.3%	24.5%	20.4%
10091	WRI 1367-76-20	ARC BI0002	Asphaltene	14.1%	41.3%	24.0%	21.0%
10092	WRI 1367-76-18		Control	14.5%	42.7%	24.8%	18.2%
10093	WRI 1367-76-22		Saturate	19.9%	40.0%	23.2%	17.1%
10094	WRI 1367-76-24		Aromatic (Napthene)	12.4%	51.0%	21.2%	15.6%
10095	WRI 1367-76-26		Polar (Resin)	13.5%	39.5%	30.4%	16.9%

Tasks 1 and 2 are still on schedule to be completed for the following quarterly report (January 2013). Chemical Force Microscopy (CFM), depicted in figure F2d1, will commence in mid-October followed by Task 2 (Surface energy characterization of phase-specific asphalt microstructure).

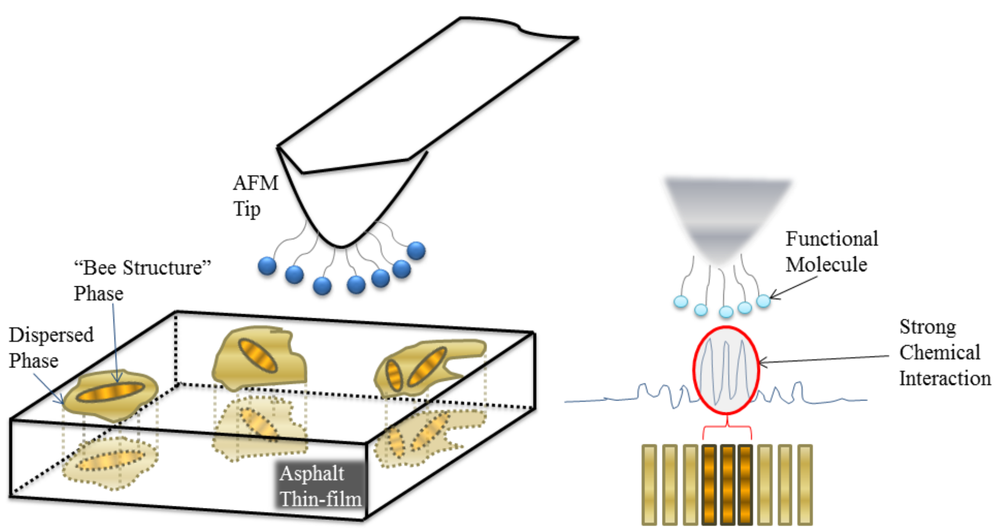


Figure F2d1. AFM mapping of surfaces with chemical contrast. By using the appropriate tip functionality, a specific surface image depicting chemical groups can be achieved based on the tip-surface interaction (Adapted from Nanocraft).

Proposed Grouping of Deliverables

Task 1 - The SARA preparation and analyses has commenced. SARA analyses will be performed using AFM to assess the impact of the different molecular asphalt components on the microstructure and micro-rheology of asphalt. The SARA analyses serves to validate and expand upon previous results presented for this work element as well as previous research performed by Pauli et al. (2003; 2009; 2011). The SARA samples have been prepared and will be tested using AFM beginning in August/September 2012. Chemical Force Microscopy (CFM) will also be implemented as part of the investigation to evaluate the relationship between AFM-depicted microstructure and chemical composition of asphalt.

Task 2 - Additional testing of PG 64-22 binder with 2.5% SBS (elastomer) and PG 64-22 with 2.5% 7686 (plastomer) as well as SHRP binder's AAB and AAD (aged and non-aged) will be performed as needed to validate the results presented in previous reports. Furthermore, the second step required to test the "susceptible phase interface" hypothesis involves measuring the surface energy of asphalt using AFM. As highlighted in this report, asphalt microstructure undergoes significant changes due to natural and synthetic modification processes. Furthermore, a decrease in asphalt cohesive bond energy with aging typically results in a reduced amount of work required (due to load or temperature) to propagate a crack in asphalt. These microstructural changes and characteristics are the basis for exploring parameters related to bond energy at the micro and nano scales. For instance, if a particular micro phase can be identified as having lower bond energy, then researchers can use this information to improve prediction models and enhance the properties of asphalt via existing and new synthetic modification processes. It will essentially provide a major step towards linking micro and nano properties of asphalt to the in-field performance of HMA. The key difference in previous methods and the proposed protocol to measure surface energy is that AFM will be used to measure surface energies of individual phases as opposed to random or grid-based surface energy measurements of the binder. This task will be performed in conjunction with Task 2. Testing will begin in August 2012.

DRAFT AASHTO METHOD: A METHOD TO DETERMINE SURFACE ROUGHNESS OF AGGREGATE AND FINES BASED ON AFM

Included Work Elements/Subtasks
M1b-2: Work of Adhesion at Nano-Scale using AFM

Status and Work Planned
Progress on this work element has been delayed due to an equipment problem. We expect a delay of up to six-months in order to accommodate the sharing of equipment between several work elements.

Preliminary development of this test method and proof-of-concept experiments have been completed. Additional testing designed to refine and improve this methodology has been delayed due to problems with the AFM instrument used in this study. This work can be completed using our metrology-equipped AFM, however, this instrument is already in use daily so we expect some delay will result from the need to share equipment.

DRAFT AASHTO METHOD: A METHOD TO DETERMINE DUCTILE-BRITTLE PROPERTIES VIA AFM

Included Work Elements/Subtasks
M1b-2: Work of Adhesion at Nano-Scale using AFM
M2a-2: Work of Cohesion at Nano-Scale using AFM

Status and Work Planned
On Schedule

Development of this test method will continue in the next quarter. Results of an AFM-based direct tension test are providing significant insight into the ductile-brittle properties of asphalt binders. Preliminary results show the effect of aging on these important parameters. A systematic study with a series of aged asphalts is currently underway.

DRAFT AASHTO METHOD: AFM-BASED MICRO/NANO-SCALE CYCLIC DIRECT TENSION TEST

<u>Included Work Elements/Subtasks</u>
M1b-2: Work of Adhesion at Nano-Scale using AFM
M2a-2: Work of Cohesion at Nano-Scale using AFM

<u>Status and Work Planned</u>
On Schedule

This test method is near completion. Aspects of this method will also be utilized in the development of "A Method to Determine Ductile-Brittle Properties via AFM." Results of this study show that rate-sensitive dissipated energy can be a significant component of the overall energy associated with asphalt fracture. To evaluate fracture energy of a visco-elastic solid, both temperature and separation rate must be considered to fully understand the system. Additional testing to validate and quantify this important concept continues.

DRAFT AASHTO METHOD/PRACTICE: MEASUREMENT AND TEXTURE SPECTRAL ANALYSIS OF PAVEMENT SURFACE PROFILES USING A LINEAR STATIONARY LASER PROFILER (SLP)

<u>Included Work Elements/Subtasks</u>
Work Element VP-2a: Mixture Design to Enhance Safety and Reduce Noise in HMA

<u>Status and Work Planned</u>
Completed

Work Completed: Procedure was submitted in AASHTO format for consideration to Mix ETG. The MIX ETG put review of this standard on hold until more pertinent issues have been resolved. The FHWA recommended that the VP2a final report be submitted as a NTIS report.

Work Planned: Due to the inclusion of the efforts of the RAP and WMA working groups into the Mix ETG, the committee secretary declined to review the offer to have the ETG provide feedback on the standard. The research team will work with FHWA to identify other working groups to provide feedback.

<u>Delivery Dates</u>

Draft AASHTO Method: Complete (9/30/2012)
Final AASHTO Standard: 3/31/2013 (6 months after initial submittal)

MODELS AND SOFTWARE

MODEL: HMA THERMAL STRESSES IN PAVEMENT

Included Work Elements/Subtasks
Work Element E2d: Thermal Cracking Resistant Mixes for Intermountain States

Status and Work Planned
On Schedule.

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

- Finalized the approach and working on the subroutine to predict the pavement temperature profile.
- Finalized the approach and working on the subroutine to predict asphalt pavement oxidation.
- Finalizing the approach and working on the subroutine to calculate the thermal build-up stress in pavement considering effect of aging and nonlinear thermal coefficient of contraction.

The following list the work planned for next quarter:

- Validate the developed software subroutine to predict temperature profile in asphalt layer using LTPP data.
- Validate the software subroutine to predict the carbonyl area growth as a function of time.
- Improving the subroutine software to calculate thermal build-up stress in pavement.

SOFTWARE: DYNAMIC MODEL FOR FLEXIBLE PAVEMENTS 3D-MOVE

Included Work Elements/Subtasks
Work Element VP3a: Pavement Response Model to Dynamic Loads

Status and Work Planned
On schedule.

The release of new version (Ver. 2.0) along with the preparation of Help Menu were the main focus of the last quarter. The revised version has been undergoing beta-testing by many student users at UNR. The Ver. 2.0 is almost ready for release and the release date is set for the first week of February 2013. The Help Menu includes five examples (Examples A – E) and these examples were chosen such that the user will be familiar with the capabilities and features of the *3D-Move Analysis*. The five examples are:

- Example A – Analysis of a pavement section (Three layers: HMA, Base and Subgrade) subjected to a dual tandem loading in static condition.
- Example B – Analysis of a pavement section (Three layers: HMA, Base and Subgrade) subjected to a dynamic load (Complex Young's Modulus, E*, calculated from Dynamic Modulus Data).
- Example C – Analysis of a pavement section (Three layers: HMA, Base and Subgrade) subjected to a dynamic load (Complex Young's Modulus, E*, calculated from Witczak equation).
- Example D – Performance analysis of a pavement section (Three layers: HMA, Base and Subgrade) based on NCHRP 1-37A Performance Model.
- Example E – Performance analysis of a pavement section (three layers: HMA, Base and Subgrade) based on VESYS Performance Model.

Maintained the 3D-move forum and assisted users with issues ranging from usage questions, concepts clarifications, and bugs.

The following list the work planned for next quarter:

- Release version (2.0) of the software.
- Maintain the 3D-move forum.
- Assist users with issues ranging from usage questions, concepts clarifications, and bugs.

MODEL: APPROACHES TO INTERPRET MD SIMULATION RESULTS AND EXPERIMENTAL DATA TO QUANTIFY THE COMPOSITION AND TEMPERATURE DEPENDENCE OF FREE ENERGY

Included Work Elements/Subtasks

Subtask F3a-1: *ab initio* Theories, Molecular Mechanics/Dynamics and Density Functional Theory Simulations of Asphalt Molecular Structure Interactions

Sub-subtask F3a-1.2. Develop algorithms and methods for directly linking molecular simulation outputs and phase field inputs (URI, NIST)

Subtask F3a-4. Overall integration for multiscale modeling (VT, URI, and WRI)

Subtask F3a-5. Experimental verification and validation (VT, URI, and WRI)

Status and Work Planned

Work - On Schedule. Report final decision – delayed by another quarter.

After the deliverables of the ARC were sorted into a smaller list, it was recognized that an effective way to provide the free energy model could be by incorporating it into Report S, "Molecular Dynamics Results for Multiple Asphalt Chemistries," which will describe molecular dynamics simulations of asphalts and their interpretations. Thus the progress towards the model is described in the Report S update. A decision was planned be made in the prior quarter about if combining these deliverables makes sense or if it is better for them to remain separate. This decision will be made in the upcoming quarter.

Ambiguity about if Subtask F3a-4 and F3a-5 belong in report S or report T will also be resolved during the quarter.

SOFTWARE: PANDA: PAVEMENT ANALYSIS USING A NONLINEAR DAMAGE APPROACH

<u>Included Work Elements/Subtasks</u>

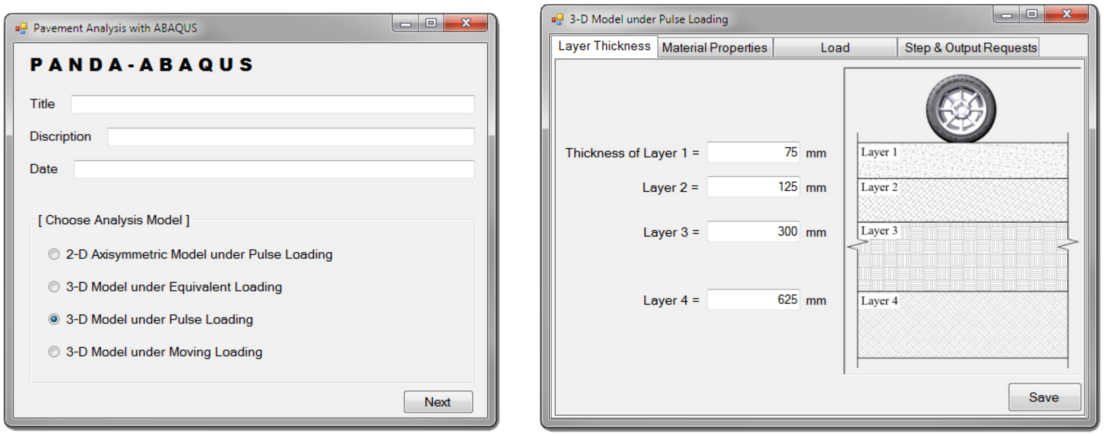
<u>Status and Work Planned</u>:

A user friendly interface has been created to facilitate the use of the PANDA model in Abaqus software. The interface customizes Abaqus for pavement engineering problems. Figure 1 schematically shows different modules developed as part of the PANDA-Abaqus user friendly interface. A shown in Figure 1, PANDA-Abaqus interface enables the pavement engineers to simulate and analyze the pavement responses subjected to traffic loading without the need to create the model directly in Abaqus software. As the same time, researchers will have access to Abaqus and materials subroutines if they choose to further develop the models.

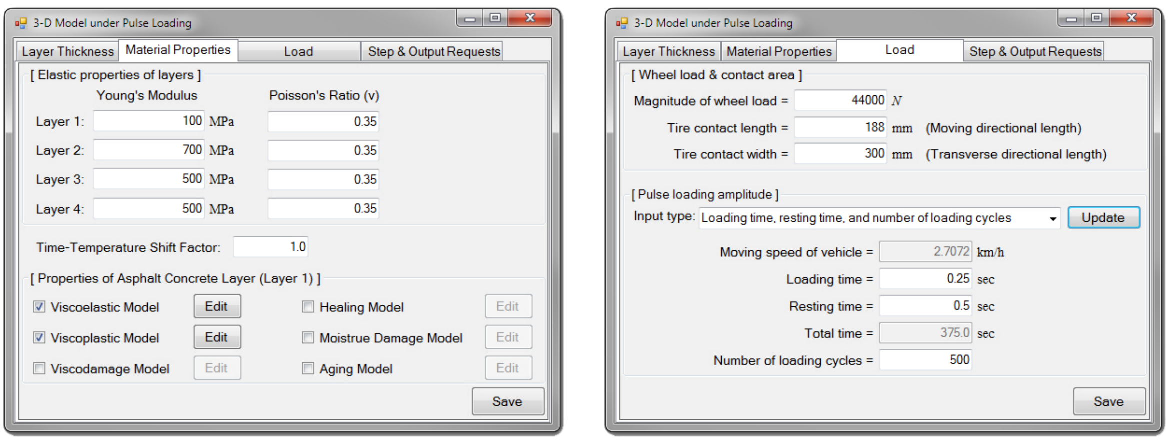
This interface has the following capabilities:

- includes a four-layered pavement system with the thickness of each layer is entered by the user;
- the user controls moving speed;
- asphalt concrete layer can be modeled as viscoelastic, viscoplastic-viscoplastic, or coupled viscoelastic-viscoplastic-viscodamage; while the other layers are modeled as elastic,
- the built-in models in Abaqus can also be used to model the supporting layers as plastic/viscoplastic materials.

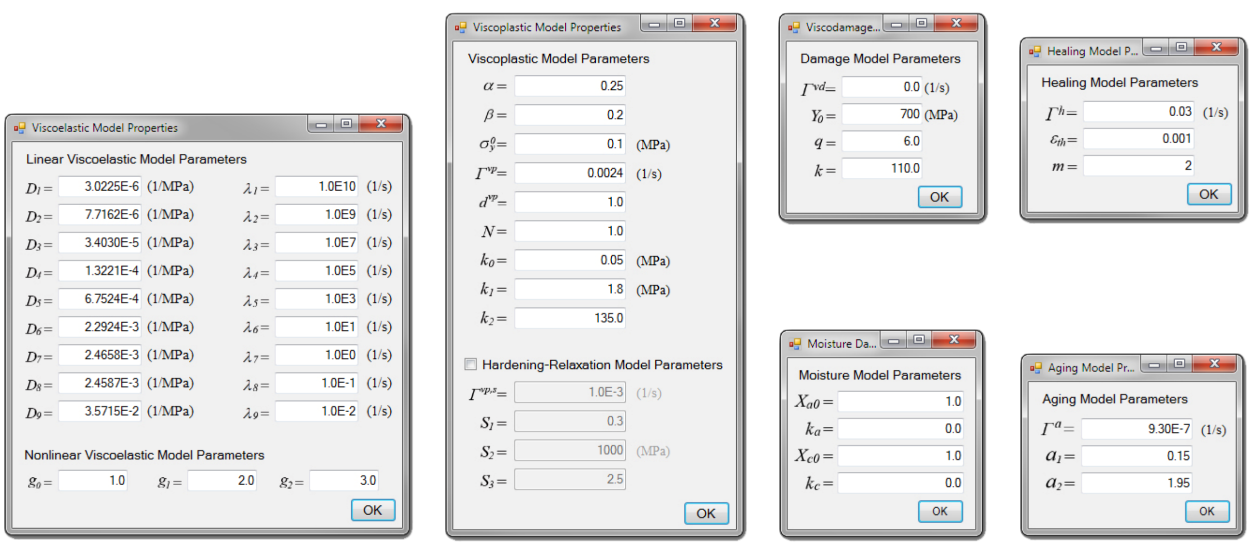
At this point, an alpha version of the PANDA standalone finite element software has been completed and is available for evaluation and future development. However, with the limited time and funding available before the conclusion of the ARC project, June of 2014, it has been necessary to take a structured assessment of the best allocation of the remaining time and fiscal resources. To that end we have decided that the prudent path is to address several key, remaining issues in lieu of continuing development of the standalone software. These issues include: (1) resolving the issue of saturation of the accumulation of plastic deformation that apparently occurs prematurely under certain conditions related to subgrade stiffness; (2) establish a methodology to successfully extrapolate to a realistic number of loading applications from the loading cycles that can be accomplished using the 3-D FEM analysis. A focus on these critical issues as well as “shakedown” validation of the rigor of the mechanics supporting PANDA and the validation of PANDA based on ALF experiments, the Vicksburg USACOE testing, and the Ohio test sections is deemed to be the most productive effort and provides the best chance toward development of a rigorous and uniquely sophisticated continuum damage model unparalleled in the area of asphalt materials and pavement technology.



(a-b) Modules to select different analysis modes and identify pavement structure.



(c-d) Moduled to enter layer properties, to select desired models, and contact stresses.



(e) Modules to enter model parameters based on the selected constitutive model

Figure 1. Schematic representation of the modules developed for the PANDA-Abaqus user friendly interface.

The focus has also shifted toward the development of a highly user-friendly interface between the constitutive PANDA model and the Abaqus FEM structural model. This interface will be graphically friendly and will allow the user to easily select pavement structures from a library and input material characterization input in a menu-driven way.

The focus of the current and future work is on the development of the graphical user-friendly interface (GUI) of PANDA. Also, moisture-induced damage and oxidative aging models that are part of the PANDA model will be integrated into the PANDA standalone finite element software.

PANDA Software

<u>Status and Work Planned</u>:

The work has been started on transferring the developed constitutive models that have been developed as part of the UMAT subroutine in Abaqus to the standalone PANDA finite element software. In this quarter, emphasize has been placed on checking PANDA using certain developed benchmark numerical examples. Moreover, the accuracy and speed of PANDA has been increased through the implementation of robust numerical algorithms. Therefore, at this stage of development, we have an alpha working PANDA that can be used to simulate various types of problems; plane stress, plane strain, axisymmetric, and three-dimensional problems with various levels of accuracy and computational time. The two-dimensional elements (i.e. the plane stress, plane strain, and axisymmetric) can be used to simulate two-dimensional pavement sections or various laboratory testing setups (e.g. dynamic modulus test, creep-recovery test, uniaxial tension/compression tests, cyclic stress/strain controlled tests, etc). On the other hand, the three-dimensional elements can be used to conduct more realistic pavement performance simulations.

Work is in progress of writing the installation and user manual of PANDA. Work is in progress in writing two chapters; the first on “Using PANDA” and the second on “Keywords” for writing the input file for PANDA. Also, the work has already been started in creating the graphical user-friendly interface (GUI) of PANDA.

OTHER RESEARCH ACTIVITIES

Subtask E2b-2: Compatibility of RAP and Virgin Binders

Status and Work Done This Quarter

Two chemically and physically different asphalts were RTFO-aged and then separately mixed with 15 and 50 percent of extracted RAP binders that were acquired from Manitoba and South Carolina RAP. A dynamic shear rheometer was used to measure the rheological properties of the blends at temperatures from -20 to 80°C. A part of the rheological results are reported in this quarter. The Christensen-Anderson (CA) model (Christensen and Anderson, 1992) was used to generate master curves with a reference temperature of 20°C and the rheological parameter, crossover frequency. The crossover frequency is defined as the frequency where G' is equal to G", or the elastic modulus is equivalent to the viscous modulus, or tan delta is 1. The higher the crossover frequency, the more viscous flow the material will demonstrate. The results show that addition of RAP binder to RTFO-aged asphalt reduces its viscous component (G") with an exponential decay form. When extracted RAP binder was added to RTFO-aged asphalt AAA-1, the viscous component was reduced more than when the same RAP binder was added to RTFO-aged asphalt AAC-1, indicating the RAP binder has more influence on asphalt AAA-1 than on asphalt AAC-1. Also, the extracted South Carolina RAP binder was shown to have more influence on both asphalts than that of the extracted Manitoba RAP binder.

The master curve data for complex modulus and phase angle were used to calculate the relaxation modulus via a prony series mathematical model for the samples described above. The prony series has been shown to provide more precise and mathematically efficient approach to calculate relaxation modulus for viscoelastic material than the other models (Ferry 1980). The prony series expression of the relaxation modulus is briefly described as follows:

$$G(t) = G_\infty + \sum_{i=1}^{n} G_i e^{-(t/\rho_i)}$$

Where: G_∞ = long-time equilibrium modulus
G_i = regression constants
ρ_i = relaxation time
n = number of dashpots in the model

Calculated relaxation modulus as a function of time plots for RTFO-aged asphalts AAA-1 and the blends with extracted RAP binders from Manitoba and South Carolina, suggest that addition of RAP binder into RTFO-aged asphalt reduces the relaxation properties. The data also show that the extracted South Carolina RAP binder reduces the relaxation properties more than that of the extracted Manitoba RAP binder. The plot of the slope of relaxation modulus versus time represents how the asphalt and RAP binder blends relax. The results of this analysis for these samples indicate that addition of extracted RAP binder to RTFO-aged asphalt increases the relaxation time. As more extracted RAP binder is added, the longer the relaxation time, i.e. the slower the material can relax at a given time. The results also show that the extracted South Carolina RAP binder has more effect on relaxation time than the extracted Manitoba RAP binder.

Work Planned Next Quarter

Solubility parameters based on the measurements from Automated Flocculation Titrimetry (AFT) for RTFO-aged asphalts and the blends with extracted RAP binders will be conducted. Rheological properties will be correlated to solubility parameters to investigate how compatibility properties relate to rheological properties with respect to different RAP binder contents. In addition, extensive rheological analyses on relaxation modulus and the slope of relaxation curves will be conducted to investigate how the relaxation modulus and the relaxation flow (slope of the relaxation curve) relate to field pavement performance.

A technical paper on the influence of RAP contents to chemical and rheological properties of neat asphalts will be prepared.

References

Christensen, Donald A., and D. A. Anderson. Interpretation of Dynamic Mechanical Test Data for Paving grade Asphalt, *Journal of the Association of Asphalt Paving Technologists*, Vol. 61, 1992, p. 67-116.

Ferry, John D. *Viscoelastic Properties of Polymers*, John Wiley & Sons, 1980.

Work Element E3a: Effects of Extenders and Alternative Binders on Performance

Work Done This Quarter

The feedback received from the survey distributed to the FHWA Binder ETG last quarter was used to select specific extender types and oils for use in the study. An experimental plan was developed that includes chemical, rheological, mechanical, thermal, and damage testing. The testing plan was executed on six of the extenders used in combination with two base binder types. Samples were sent to WRI to conduct the chemical analysis.

Work Planned Next Quarter

Efforts will continue on in executing the experimental plan established for E3a this quarter. It is anticipated that the rheological, thermal, and damage testing will be completed. The research team will coordinate with WRI to complete chemical testing by the end of 2013Q2.

Proposed Research Product and Timeline

Results will be added as a chapter to Report N: Guidelines for Selection of Modification Techniques
Due Date for Draft Report Submittal: 9/30/2013
Due Date for Final Report Submittal: 6/30/2014

Significant Problems, Issues and Potential Impact on Progress

None.

Work Element E3b: Development of a PG Specification for Emulsions used in Surface Treatments, Cold Mixes, and Cold-In-Place Recycled Mixes

Work Done This Quarter

A residue recovery procedure investigation was initiated to evaluate new concepts. Results indicate significant differences between procedures due to the effects of aging. The fresh emulsion characterization framework was extended to include several additional emulsion samples. Based on results, work is underway to finalize testing procedures.

The performance grading framework for emulsion residues was implemented on four materials commonly used for chip seals. The results of the chip seal raveling study were finalized for the unmodified emulsion and presented at the TRB annual meeting. Testing using a modified emulsion was completed and the results are current being summarized. Results of both efforts will be compared to the chip seal in-service aging work being conducted by WRI.

Work Planned Next Quarter

Evaluation of residue recovery methods will continue. The candidate test methods identified include the ASMT D7497 Method B and thin film recovery on a silicone substrate in the vacuum oven as proposed by Reinke. Work will continue on refining the fresh and residue characterization framework by applying the proposed tests to more emulsion samples. Work will also continue on characterizing emulsion residue properties.

Proposed Research Product and Timeline

Due Date for Draft Report Submittal: 9/30/2013
Due Date for Final Report Submittal: 6/30/2014

Significant Problems, Issues and Potential Impact on Progress

No significant problems were identified in this quarter.

Publications

- Moraes, R. Bahia, H. Effects of Curing and Oxidative Aging on Raveling in Emulsion Chip Seals. Accepted for publication in the Transportation Research Record. Presented at the 2013 Transportation Research Board Annual Meeting.
- Ling, C. Moraes, R. Swiertz, D. Bahia, H. Measuring Influence of Aggregate Coating on Workability and Moisture Susceptibility of Cold-Mix Asphalt. Accepted for publication in the Transportation Research Record. Presented at the 2013 Transportation Research Board Annual Meeting.

References

Reinke, G., Engber, S., Herlitzka, D., Evolution of Techniques Used for Obtaining Emulsion Residues at 60°C Using Thin Film Procedures and Test Methods Suited to the Limited Amount of Residue Obtained to Characterize the Recovered Binder, Presented at the ISAET Symposium, 2012.

Work Element E3c: Laboratory Assessment of Mixture Long Term Aging

Work Done This Quarter

A Ph.D. thesis project has been defined and is underway to define the critical properties of mineral aggregates affecting aging, through evaluation of asphalt mastics. Aging and extraction tests have been conducted on a number of mastics consisting of two base binders with very different asphaltene content and a number of fully characterized mineral aggregate fillers. Aging evaluation is underway using FTIR, dilatometric Tg measurements, and rheological assessment using the DSR.

Work Planned Next Quarter

Work plan testing needs to be completed over the next two quarters and used to develop either a long term mixture aging test using asphalt mastics, or modifying current binder aging models with practical aggregate specific factors to enable aging potential prediction. Team will collaborate with UNR on mixture and field validation of concepts using long term aged mixtures.

Proposed Research Product and Timeline

Results will be summarized in a final report titled: “Laboratory Assessment of Long Term Aging of Asphalt Mixtures” it is proposed this deliverable be labeled as “Report AA.”
Due Date for Draft Report Submittal: 9/30/2013
Due Date for Final Report Submittal: 6/30/2014

Significant Problems, Issues and Potential Impact on Progress

None.

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

<u>Work Done This Quarter</u>

No WMA monitoring was planned in this quarter.

<u>Work Planned Next Quarter</u>

No WMA monitoring is planned in the next quarter.

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

<u>Work Done This Quarter</u>

It was planned to sample construction materials from a new Arizona RAP project on SR 74. However, construction delays have changed the plans and sampling is now anticipated in early February 2013.

The Arizona sections constructed in 2001 were monitored in December 2012. These sections have four different crude source asphalts of PG 76-16. The sections are continuing to show increased distress. As might be expected, the longitudinal and transverse cracking is progressing into fatigue damage. There is also evidence that the pattern is moving toward block cracking.

The NCAT team has documented mix production and field construction in four field projects. Each project included two test sections. The first project was constructed on I-84 in Connecticut. The same mix design with approximately 20 percent RAP was used in this project. However, the mix paved in the control section was produced hot, and the mix used in the other section was produced warm using a foaming WMA technology. The second project was built on US 287 in Texas. The same mix design with 20% RAP and 5% RAS was used in this project. The mix was produced hot for the control section and produced warm with the Cecabase additive for the test section. The third field project was built on US 69 in Mississippi. Two different mix designs were used in this project. The mix paved in the control section used 15% RAP and that in the test section used 25% RAP. Both the mixes were produced warm with a foaming WMA technology. The fourth project was constructed on County Road 159 as part of the pavement preservation study at NCAT. The test mix used in this study was a 4.75 mm mix with 45% RAP used for a thin lift overlay.

The project team has been testing field cores and specimens prepared in the NCAT mobile lab at the plant sites and conducting mix design verification for preparing lab-mixed, lab-compacted specimens.

Work Planned Next Quarter

It is planned to sample construction materials on the Arizona RAP sections during the next quarter and install performance monitoring sections.

The NCAT team will continue testing the materials and specimens prepared for the four field sites and will identify field projects for evaluation this year.