Western Research INSTITUTE

Asphalt Research Consortium

Quarterly Technical Progress Report
July 1-September 30, 2012

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INTRODUCTION

This document is the Quarterly Report for the period of July 1 to September 30, 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 July 1 to September 30, 2012 is second 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	ARC Member	Draft Submittal Date	Final Submittal Date
Report A	Summary report on Moisture Damage (508 Report)	TAMU	12/30/2012	10/30/2013
Report B	Characterization of Fatigue Damage and Relevant Properties (508 Report)	TAMU	1/31/2013	10/30/2013
Report C	**PANDA:** Pavement Analysis using a Nonlinear Damage Approach (508 Report)	TAMU	3/30/2013	10/30/2013
Report D	Characterization of Asphalt Binders using Atomic Force Microscopy (Topical Report)	TAMU	3/30/2013	10/30/2013
Report E	Lattice Model and Continuum Damage to Fracture (Topical Report)	NCSU	12/30/2012	8/30/2013
Report F	Microstructure Cohesive Zone Modeling for Moisture Damage and Fatigue Cracking (Topical Report)	UNL	11/30/2012	8/30/2013
Report G	Design System for HMA Containing a High Percentage of RAP Material	UNR	12/31/2013	3/31/2014
Report H	Critically Designed HMA Mixtures	UNR	5/31/2013	11/30/2013
Report I	Thermal Cracking Resistant Mixes	UNR	8/31/2013	12/31/2013
Report J	Pavement Response Model to Dynamic Loads 3D Move	UNR	3/31/2013	9/30/2013
Report K	Development of Materials Database	UNR	6/30/2013	12/31/2013
Report L	Development and Validation of the Bitumen Bond Strength Test (BBS)	UWM	Completed 10/31/11	10/30/2012
Report M	Development of Test Procedures for Characterization of Asphalt Binder Fatigue and Healing	UWM	Completed 10/31/11	3/31/2013
Report N	Guideline for Selection of Modification Techniques	UWM	9/30/2013	6/30/2014
Report O	Characterization of Binder Damage Resistance to Rutting	UWM	12/31/2012	8/31/2013
Report P	Quantifying the Impacts of Warm Mix Asphalt on Constructability and Performance	UWM	3/31/2013	10/31/2013
Report Q	Improvement of Emulsion Characterization and Mixture Design for Cold Bitumen Applications	UWM	9/30/2013	6/30/2014
Report R	Studies on Tire-Pavement Noise and Skid Response	UWM	Completed 12/31/11	3/31/2013
Report S	Molecular dynamics results for multiple asphalt chemistries	URI	5/31/2013	12/31/2013
Report T	Progress Toward a Multi-scale Model of Asphalt Pavement- Including Test Methods for Model Input Parameters	WRI	5/31/2013	12/31/2013
Report U	Design Guidance for Fatigue and Rut Resistance Mixtures	AAT	12/31/2012	6/30/2013
Report V	Continuum Damage Permanent Deformation Analysis for Asphalt Mixtures (Topical Report)	TAMU		
Report W	Characterization of Fatigue and Healing Properties of Asphalt Mixtures (Topical Report)	TAMU		
Report X	Characterization of Field Cores of Asphalt Pavements (Topical Report)	TAMU		
Report Y	Water Vapor Diffusion in Pavement and Its Effects on the Performance of Asphalt Mixtures (Topical Report)	TAMU		

Deliverable	Description	ARC Member	Draft Submittal Date	Final Submittal Date
AASHTO Method	Simplified Continuum Damage Fatigue Analysis for the Asphalt Mixture Performance Tester	AAT	12/31/2012	6/30/2013
AASHTO Method	Wilhelmy Plate Test	TAMU	11/30/2012	
AASHTO Method	Universal Sorption Device	TAMU	11/30/2012	
AASHTO Method	Dynamic Mechanical Analysis	TAMU	11/30/2012	
ASTM Method	Automated Flocculation Titrimetric Analysis	WRI	Completed	
AASHTO Method	Determination of Polymer in Asphalt	WRI	Completed	
AASHTO Method	A Method for the Preparation of Specimens of Fine Aggregate Matrix of Asphalt Mixtures	TAMU	12/31/2012	
AASHTO Method	Measuring intrinsic healing characteristics of asphalt binders	TAMU/UT	12/31/2012	
AASHTO Method	Test Methods for Determining the Parameters of Material Models in PANDA (Pavement Analysis Using Nonlinear Damage Approach)	TAMU	11/30/2012	
Test Method & Model	Continuum Damage Permanent Deformation Analysis for Asphalt Mixtures	TAMU	11/30/2013	5/31/2014
Test Method & Model	Characterization of Fatigue and Healing Properties of Asphalt Mixtures	TAMU	10/31/2013	4/30/2014
Test Method Analysis Program	Nondestructive Characterization of Tensile Viscoelastic Properties of Undamaged Asphalt Mixtures	TAMU	Completed	
Test Method & Model	Characterization of Field Cores of Asphalt Pavements	TAMU	9/30/2013	3/31/2014
Test Method Analysis Program	Nondestructive Characterization of Anisotropic Viscoelastic Properties of Undamaged Asphalt Mixtures under Compressive Loading	TAMU	Completed	
AASHTO Practice	Mix Design for Cold-In-Place Recycling (CIR)	UNR	12/31/2013	
AASHTO Practice	Mix Design for Cold Mix Asphalt	UWM	9/30/2013	
AASHTO Practice	Evaluation of RAP Aggregates	UNR	12/31/2012	
AASHTO Practice	Identification of Critical Conditions for HMA mixtures	UNR	12/31/2012	
AASHTO Method	Thermal Stress Restrained Specimen Test (TSRST)	UNR	Completed 5/31/2012	
AASHTO Method	Determining Asphalt Binder Bond Strength by Means of the Bitumen Bond Strength Test (BBS)	UWM	Completed	12/31/2012 3/31/13 ETG
AASHTO Method	Measurement of Asphalt Binder Elastic Recovery in the Dynamic Shear Rheometer (DSR)	UWM	12/31/2012	4/30/2013
AASHTO Method	Estimating Fatigue Resistance of Asphalt Binders Using the Linear Amplitude Sweep	UWM	Completed	4/30/2013
AASHTO Method	Binder Yield Energy Test (BYET)	UWM	12/31/2012	
AASHTO Method	Measurement of Rigden Voids for fillers	UWM	12/31/2012	
AASHTO Method	Measurement of Asphalt Binder Lubricity Using the Dynamic Shear Rheometer (DSR)	UWM	3/31/2013	
AASHTO Method	Procedure for Evaluation of Coating for Cold Mix Asphalt	UWM	12/31/2012	
AASHTO Method	Cold Mix Laboratory Specimen Preparation Using Modified SGC Molds	UWM	12/31/2012	

Deliverable	Description	ARC Member	Draft Submittal Date	Final Submittal Date
AASHTO Method Software	RAP Binder PG True Grade Determination	UWM	Completed 9/30/2012	4/30/2013
AASHTO Method	Measurement of Asphalt Binder Fracture Properties Using the Single Edge Notch Bending Test	UWM	9/30/2012	4/30/2013
AASHTO Method	Test Method for Measurement of the Glass Transition Temperature of Asphalt Binders	UWM	12/31/2012	
AASHTO Method	Test Method for Measurement of the Glass Transition Temperature of Asphalt Mixtures	UWM	12/31/2012	
AASHTO Method Software	Analysis of Asphalt Mixture Aggregate Structure through Use of Planar Imaging and Image Processing & Analysis System (IPAS)	UWM	3/31/2013	
AASHTO Method	Determining the Resistive Effort of Asphalt Mixtures during Compaction in a Gyrator Compactor using an Internal Device	UWM	Completed	3/31/2013
AASHTO Method	Micromechanical Properties of Various Structural Components in Asphalt using Atomic Force Microscopy (AFM)	TAMU	3/1/2011	10/30/2013
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.	VT	4/30/2013	
AASHTO Method	Evaluate Healing using Continuum Damage Approach	TAMU/UT	12/30/2012	10/30/2013
Test Method & Analysis Program	Self-Consistent Micromechanics Models of Asphalt Mixtures	TAMU	Completed	
Test Method & Analysis Program	Rutting Prediction of Asphalt Binder Considering Stress-Dependence of Creep Behavior	TAMU	12/31/2012	
AASHTO Method	Method to determine surface roughness of aggregate and fines based on AFM	WRI	1/30/2013	
AASHTO Method	A method to determine ductile-brittle properties via AFM measurements	WRI	4/30/2013	
AASHTO Method	AFM-based micro/nano-scale cyclic direct tension test	WRI	3/31/2013	
AASHTO Method	Measurement and Texture Spectral Analysis of Pavement Surface Profiles Using a Linear Stationary Laser Profiler (SLP)	UWM	Completed 9/30/2012	
Model	HMA Thermal Stresses in Pavement	UNR	3/31/2014	
Software	Dynamic Model for Flexible Pavements 3D-Move	UNR	9/30/2013	
Model	Improved Oxygen and Thermal Transport Model of Binder Oxidation in Pavements	TAMU	10/31/2012	3/31/2013
Model	Pavement Air Voids Size Distribution Model for use in an Oxygen and Thermal Transport Model of Binder Oxidation in Pavements	TAMU	10/31/2012	3/31/2013
Model	Approaches to interpret MD simulation results and experimental data to quantify the composition and temperature dependence of free energy.	URI	3/31/2013	
Model and Software	Phase-Field Model of Asphalt Binder Fracture and COMSOL Code for Model	VT	1/31/2013	
Software	PANDA Software (Pavement Analysis using a Nonlinear Damage Approach)	TAMU	10/1/2013	

REPORTS

REPORT A: SUMMARY REPORT ON MOISTURE DAMAGE

Included Work Elements/Subtasks
Work Element / 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 needs to be reformatted as a chapter in Report A using 508 formatting guidelines. Procedures to measure diffusivity of water through asphalt binders and mortars will be in the Appendices to Report A.

The work that is described in the new topical reports W, X, and Y will also be relevant parts to Report A.

REPORT B: CHARACTERIZATION OF FATIGUE DAMAGE AND RELEVANT PROPERTIES

Included Work Elements/Subtasks

Work Element / 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. 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: Work is 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 applied to different modes of loading and other core ARC materials as discussed in the on-going technical research.

Work Element F1b: Viscoelastic Properties

Subtask F1b-1: Viscoelastic properties under cyclic loading

Status and Work Planned: The importance of characterizing damage evolution in a multi-axial stress state has been highlighted by several recent studies (Ozer et al. 2011; Wang and Al-Qadi 2010; Wang et al. 2011). During pervious quarters we have completed work on modeling the affect of multi-axial stress state on the properties of the asphalt binder. The model is now being implemented to asphalt mortar (FAM) specimens, albeit using a different experimental setup referred to as the Arcan apparatus. The ultimate goal is to investigate and establish the difference in damage evolution characteristics of the mortar when subjected to a multi-axial stress state. This will in turn be useful to improve prediction of top-down or near surface cracking in asphalt pavements.

Based on the computational modeling of FAM done in the previous quarter, a geometry for the FAM specimen was chosen to facilitate achieving a uniform stress across its cross-section. A custom-made punch has been fabricated to achieve the proper curvature and geometry at the ends of the test specimen. Visual Image Correlation (VIC) was set up and used for extracting the deformation data of the specimen under stress. The specimen being small, VIC plays a vital role for obtaining strain data as it can keep track of numerous points' displacement simultaneously.

Preparation of test specimens for this part of the research is complete. Two six-inch diameter FAM specimens were compacted using the core ARC materials. Test specimens from the SGC compacted FAM cylinders have been extracted and used for preliminary tests. The Arcan apparatus used for these tests enables us to test several multi-axial loading modes. Preliminary tests were performed to evaluate performance of VIC and the experimental setup in general (e.g. appropriate mounting of the test specimen in Arcan and calibration of the VIC). Figures F1b.1 and F1b.2 illustrate the Arcan set up and typical results using the VIC.

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 evaluate multi-axial stress effect on FAM made with ARC materials.

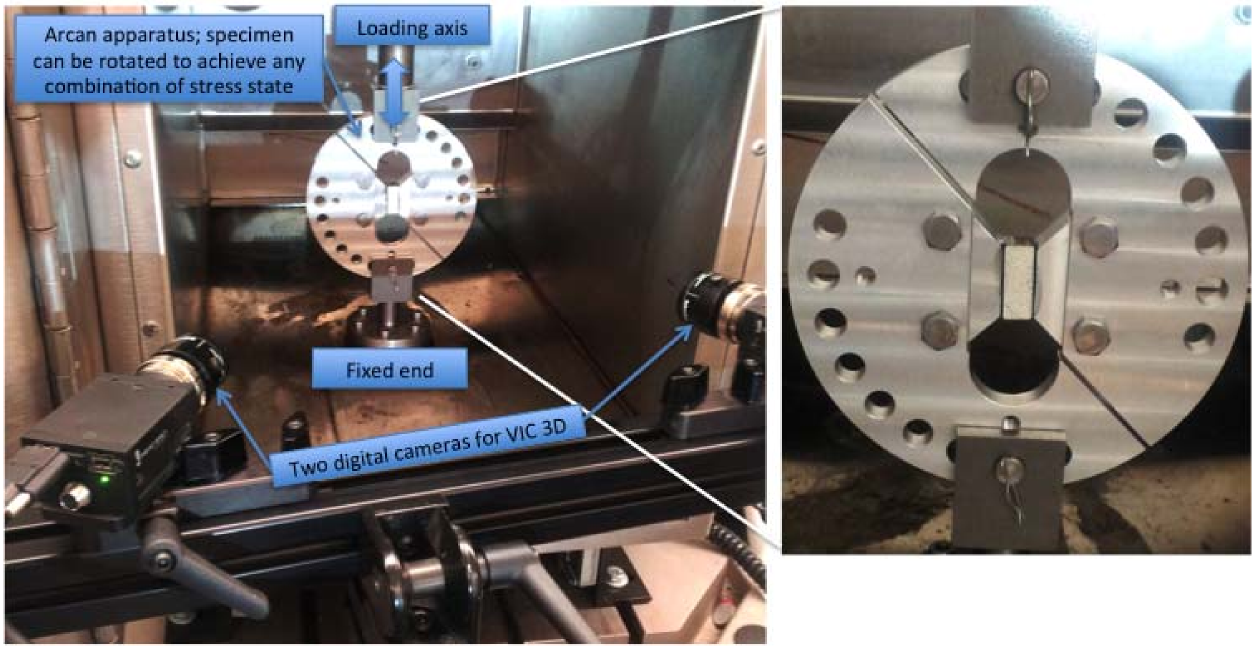

Figure F1b.1. Setup showing the VIC system to measure deformation in the test specimen in the Arcan apparatus.

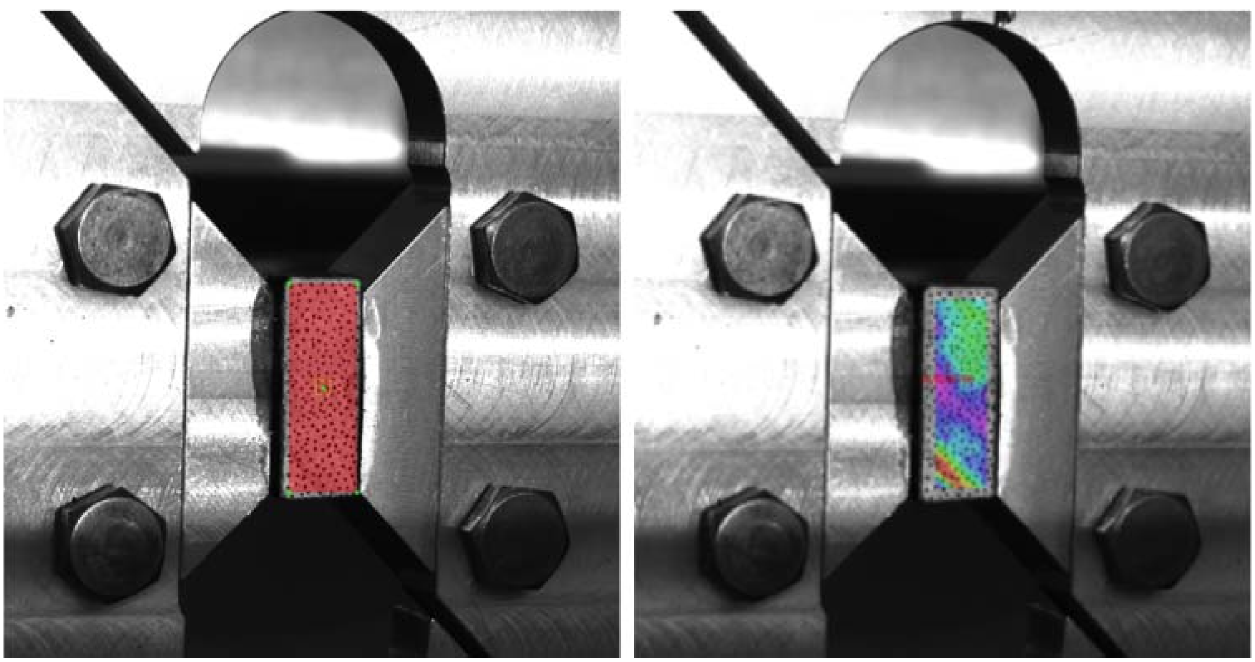

Figure F1b.2. VIC is used to measure the three dimensional strain field on an area of interest on the test specimen.

Work Element F1c: Material Properties: Aging

Subtasks 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. Last quarter we received aged ARC cores for comparison to model calculations. Specimens were received from the Arizona test sites. Volumetric testing was completed last quarter, but kinetics testing was not possible because the quantity of binder was insufficient for POV or PAV testing.

The civil engineering effort previously received cores from the Yellowstone National Park ("YNP") site and this quarter completed their planned testing. The cores are now ready for x-ray CT imaging, volumetric measurements (bulk specific gravity, accessible air voids, maximum theoretical specific gravity, and total air voids), and binder extraction and recovery.

This quarter we received binder from the YNP test site. We nearly completed a full POV test on the binder we received. The POV test included preparation of 90 binder aging trays. The tray samples were aged at atmospheric pressure at 5 different temperatures in POVs. The aged binder was tested for CA levels using FTIR, and tested for rheological properties using DSR. Two trays (lowest temp, 90 day aging time duplicates) are still being aged, and will be tested as soon as aging is complete.

We received binder from the YNP site, but did not receive any warm mix additives, or any loose mix from the warm mix asphalt. Therefore, our model validation work for the YNP site will be limited to the HMA section.

Work in the final quarters 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 section. We hope to perform x-ray CT on the YNP cores and are working with the civil engineering researchers to obtain these images. This will provide us with air void structure information to be used in our model. If we cannot have x-ray CT performed, we can estimate the properties, but our preference is to complete the x-ray CT. After this step, we will perform volumetric testing, as required, on the YNP cores, followed by extraction, recovery, and binder property measurement. We will complete our current YNP binder POV testing. 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.

Work also is proceeding on a final report on aging modeling and on incorporating the model into PANDA.

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

Status and Work Planned: In the previous quarter, we proposed using an improved single-specimen protocol in lieu of the previous multi-specimen protocol to measure the overall healing in asphalt composites using a dynamic shear rheometer (DSR). 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 previous protocol incorporates fatigue tests with the same duration of rest period introduced after different levels of damage for each specimen. Different test specimens are then used with different rest periods to obtain the overall healing as a function of the duration of the rest period and extent of damage. However, the new protocol incorporates a fatigue test with different durations of rest period introduced at multiple levels of damage on the same test specimen. Figure F1.d.1.a illustrates the typical results from this protocol. The results are analyzed to obtain the healing values based on a single curve without any rest period, as illustrated in Figure F1.d.1.b. The modified protocol thus reduces the number of test specimens required and simplifies the analysis to obtain the healing characterization of asphalt materials.

Using the limestone screenings smaller than 1.19 mm and PG 67-22 binder obtained from ARC, the Superpave gyratory compacted fine aggregate matrix (FAM) specimens with 12.25 mm diameter and 45 mm length were compacted. 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. Currently, the protocol is being validated by performing the multi-specimen tests using same damage level and different rest periods as well as same rest period and different damage levels.

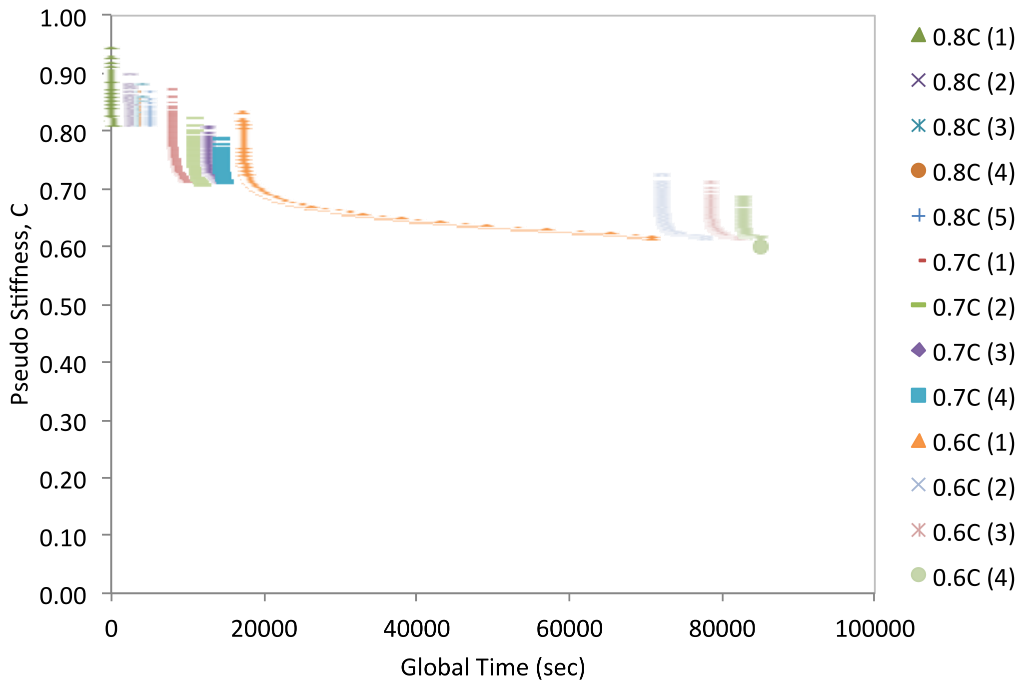

Figure F1d.1.a Typical results multiple combinations of rest period duration and damage level (Note: results shown are for qualitative reference only)

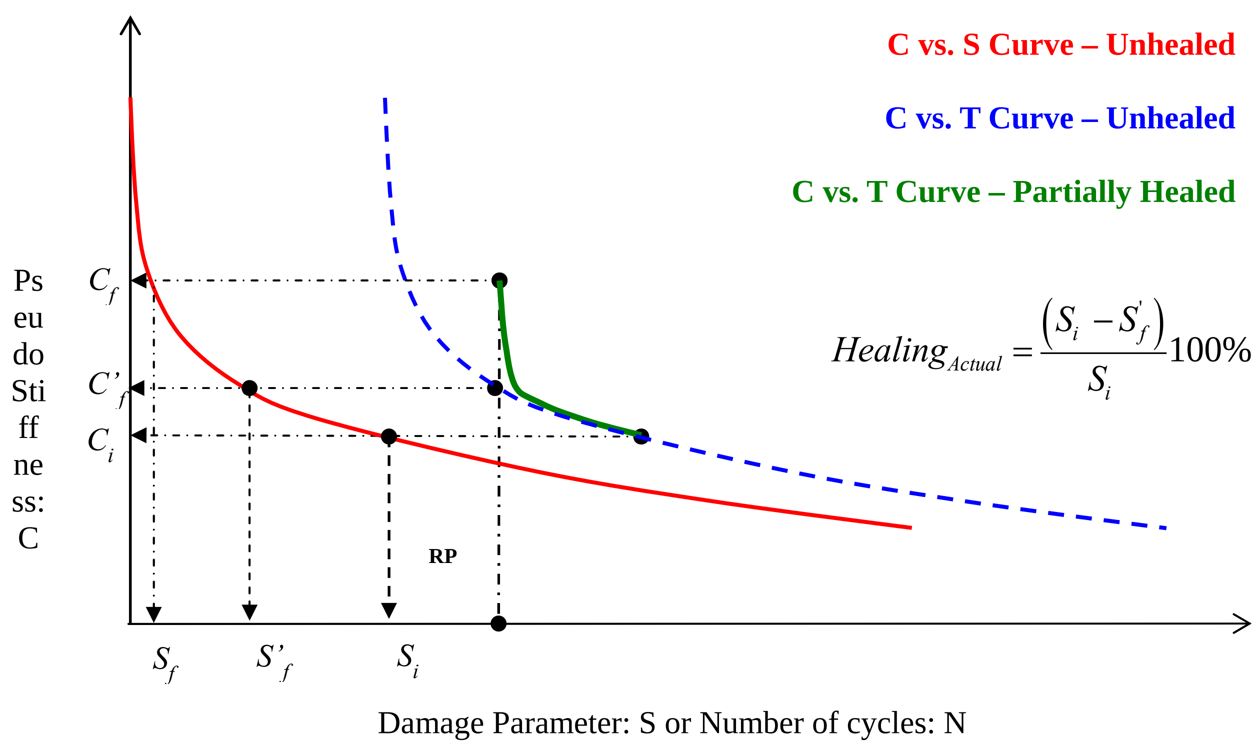

Figure F1d.1.b Analytical Method for determining the Healing values from C vs. T and C vs. S Curves

Significant Results

The healing values for the fine aggregate matrix (FAM) specimens (45 mm length, 12.25 mm diameter) obtained by performing the multi-step protocol for rest period and damage level at 10 Hz and 250,000 Pa are presented in Figure F1.d.2. The figure clearly manifests that the test specimens heal more after longer rest periods at the same level of damage and vice versa. Similarly, the test specimens heal more when the rest period is introduced at smaller level of damage when subjected to similar rest periods. Note that the analysis is based on the damage parameter from the continuum damage model and therefore ultimately is independent of the loading amplitude and frequency. This was verified earlier using different test specimens and will be verified again in upcoming work.

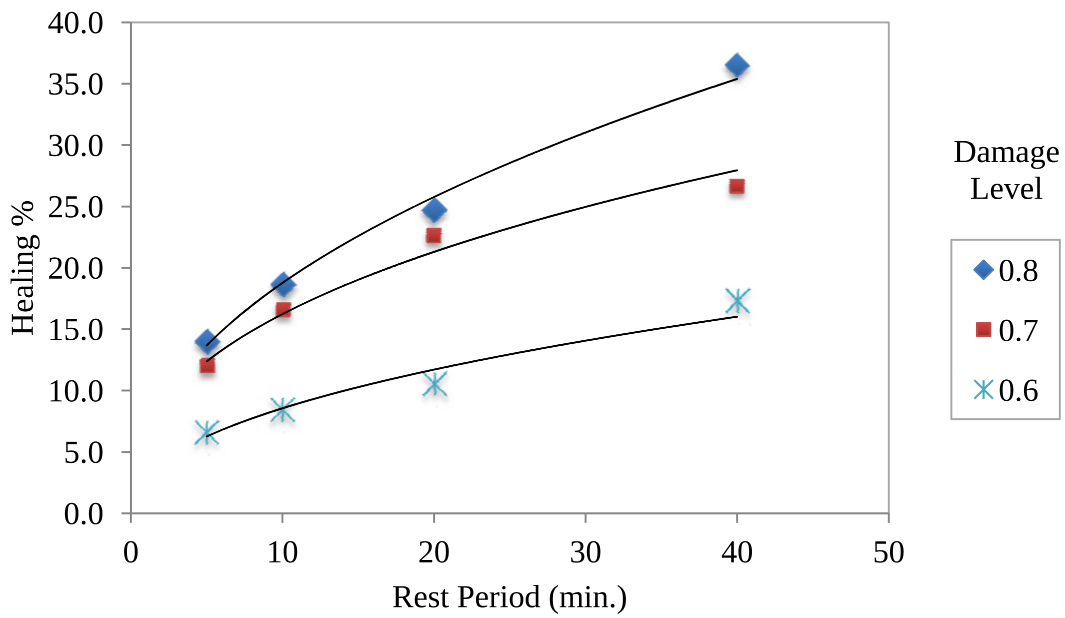

Figure F1d.2. Typical results from multiple combinations of rest period durations and damage levels (Materials: PG 67-22 binder and Limestone screenings < 1.19 mm; Geometry: 12.25mm diameter, 45 mm length; Loading: 250000 Pa, 10 Hz, 25°C)

The approach will be further validated by using at least one more mix design as well as tension-compression mode of loading, i.e., the second approach of characterizing healing mentioned in earlier report.

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: The work on this report is on schedule. All the constitutive equations that are necessary for predicting the thermo-hygro-chemo-mechanical properties of asphalt mixtures and the performance of asphalt pavements have already been incorporated into PANDA. Therefore, the mechanistic-based approach for integrating rutting, fatigue damage, micro-damage healing, moisture-induced damage, and oxidative aging has already been incorporated in the PANDA model. The developed models have been calibrated and validated against several experimental data including Nottingham data, Accelerated Loading Facility (ALF) data, and 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. The experiences from the validation and calibration efforts might require some improvements and changes in the constitutive models included in PANDA.

Moreover, 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. These tests include dynamic modulus test and repeated creep-recovery tests at various stress levels. The dynamic modulus test and the repeated creep-recovery test results have been analyzed to calibrate the linear and nonlinear viscoelastic models. Four of the eight mixtures will be used as part of the full-scale accelerated pavement testing. The focus will be placed on calibration of the viscoplastic component of PANDA against the repeated creep-recovery tests. Once calibrated, PANDA will be used to rank the rutting performance of full-scale accelerated pavement testing.

In addition to the testing conducted at the Waterways Experiment Station, PANDA will be validated against the results of the Ohio perpetual pavement sections. This task will be conducted jointly by Texas A&M and University of Illinois at Urbana-Champaign researchers. The instrumentation plan has been verified to make sure it can be used effectively to validate the PANDA. The experimental tests required for PANDA calibration has been provided. The focus of the future work will be on further validation of PANDA against the Ohio perpetual pavement sections.

Furthermore, user friendly interface has been created to facilitate the use of the PANDA model in Abaqus software. This 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. This interface has the following capabilities: it considers a four-layered system; thickness of each layer can be controlled by the user; moving speed can be controlled by the user; asphalt concrete layer can be modeled as viscoelastic, viscoplastic-viscoplastic, or coupled viscoelastic-viscoplastic-viscodamage; while the other layers are intended to be modeled as elastic, the built-in models in Abaqus can also be used to model the other layers as plastic/viscoplastic materials. The focus in the coming quarter will be placed on improving this interface.

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. A continuum-based model for the effect of the pore water pressure on crack evolution and propagation is currently being developed. 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 model will be evaluated for cases the 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 been requested 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.

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

Status and Work Planned: 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)].

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 focus is placed on further validating the micro-damage healing model against the ALF data on the control mixture as well as on the mixtures with modified binder.

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. 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 on 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," 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 under different temperatures. The testing on ARC Mix No. 1 is 95% completed. 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. 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) 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.

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. 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

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).

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-vsicoelastic, 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 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 (under review).

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 as well as Perzyna's viscoplastic model. This identification procedure is based on 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 aging data based on the dynamic modulus test has also been used for calibration and validation of the oxidative aging model.

Also, we have continued to carry out the ARC testing plan on the first asphalt mixture in compression. The data in tension are now available as provided by North Carolina State University. The data received from NCSU has been analyzed and processed for quality control purposes. The shortcomings have been reported and replicates have been requested when the test results were not consistent. The list of planned tests has been presented in the 6^{th} year work plan. Almost 95% of the planned testing on the first asphalt mixture is finished.

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. Four of the eight mixtures will be used as part of the full-scale accelerated pavement testing. The focus will be placed on calibration of the viscoplastic component of PANDA against the repeated creep-recovery tests. Once calibrated, PANDA will be used to rank the rutting performance of full-scale accelerated pavement testing.

PANDA will be validated against the results of the Ohio perpetual pavement sections. This task will be conducted jointly by Texas A&M and University of Illinois at Urbana-Champaign researchers. The instrumentation plan has been verified to make sure it can be used effectively to validate the PANDA. The experimental tests required for PANDA calibration has been provided. The focus of the future work will be on further validation of PANDA against the Ohio perpetual pavement sections.

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
Slightly behind schedule.

The AFM scanner repair took longer than expected, which has resulted in a slight interruption in testing; however, the delay is minor and testing is scheduled to commence in August, 2012. Tasks 1 and 2 will be performed in conjunction with one another. Results from Task 1 and/or Task 2 expected for next quarterly report (October 2012). Tasks 1 and 2 are scheduled to be completed for the following quarterly report (January 2013).

The second part of this work involves the characterization of nanoscale asphalt mechanical properties through the use the finite element method. Current work being completed includes the finalization and review of the ASCE Journal Paper Titled: "A Two Dimensional Finite Element Model of Atomic Force Microscope Indentation of Asphalt Thin Film" for submission. The next phase of this work includes considering plasticity of the asphalt thin film during the indentation process and incorporating it into the finite element analysis with both static and time dependent (creep) loading. A journal publication will be completed containing this work, which will give insight into more complex behavior under loading, and will serve as a validation for observed experimental phenomena such as strain hardening, and plastic deformation. Another publication for the upcoming TRB conference is also being prepared. This publication will contain details about static and time dependent indentation of asphalt thin film with elastic material model along with the effect of surface forces. It will also include future work covering more complex material models. The list of upcoming deliverables with status is listed in the table below.

Task 1 - Additional testing of PG 64-22 binder with 2.5% SBS (elastomer) and PG 64-22 with 2.5% 7686 (plastomer) will be performed as needed to validate the results presented in the previous report. 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.

Task 2 - The next step following the evaluation of the “susceptible phase interface” hypothesis is the SARA [**S**aturates, napthene **A**romatics, Polar Aromatics (**R**esins), and **A**sphaltenes] analyses. SARA analyses will be performed using AFM to assess the impact of the different molecular asphalt components on the microstructure and microrheology of asphalt. The SARA analyses serves to validate and expand on 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.

List of upcoming deliverables involving numerical analysis

Date	Deliverable	Description of Deliverable	Status of Deliverable
6/30/2012	**Journal Paper**	A Two Dimensional Finite Element Model of Atomic Force Microscope Indentation of Asphalt Thin Film	On Schedule
9/30/2012	**Journal Paper**	The Effects of Plasticity on Static and Time Dependent Loading of Asphalt Thin Film during Atomic Force Microscopy Indentation	On Schedule
1/1/2013	**TRB Paper**	A Numerical Model for the Atomic Force Microscopy Indentation of Asphalt with Adhesion	On Schedule

Asphalt Binder Microrheology and Microstructural Characterization

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

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.

Task 3 **–** The application of a dynamic load is useful in obtaining complex viscoleastic properties such as complex modulus, storage modulus, and loss modulus. These properties can then be used to indirectly calculate the creep compliance and the relaxation modulus of the individual phases previously examined. The current focus of this work is to apply a specified type of dynamic load to obtain complex viscoleastic properties of asphalt thin film. The focus of this work is to study the differences in complex viscoelastic properties of asphalt thin film between the different phases previously mentioned, and compare them to the values obtained during a creep nanoindentation test. A journal publication will be completed containing this work, which will give insight into more complex behavior under loading, and will serve as a method to numerically quantify the complex, storage, and loss modulus of the different microstructural phases in asphalt thin film. The list of upcoming deliverables with status is listed in the table below (table F2d.2).

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.

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: “A Two Dimensional Finite Element Model 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 the understanding the effect of plasticity on loading of asphalt thin film during nanoindentation. This work has been revised. The current focus of this work is to apply a specified type of dynamic load to obtain complex viscoleastic properties of asphalt thin film. The focus of this work is to study the differences in complex viscoelastic properties of asphalt thin film between the different phases previously mentioned. A journal publication will be completed containing this work, which will give insight into more complex behavior under loading, and will serve as a method to numerically quantify the complex, storage, and loss modulus of the different microstructural phases in asphalt thin film. The list of upcoming deliverables with status is listed in table F2d.2.

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	ARC BI0001	Control	15.1%	43.0%	19.6%	21.8%
10088	WRI 1367-76-12	ARC BI0001	Saturate	20.4%	40.3%	18.4%	20.4%
10089	WRI 1367-76-14	ARC BI0001	Aromatic (Napthene)	13.1%	50.3%	17.1%	19.0%
10090	WRI 1367-76-16	ARC BI0001	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	ARC BI0002	Control	14.5%	42.7%	24.8%	18.2%
10093	WRI 1367-76-22	ARC BI0002	Saturate	19.9%	40.0%	23.2%	17.1%
10094	WRI 1367-76-24	ARC BI0002	Aromatic (Napthene)	12.4%	51.0%	21.2%	15.6%
10095	WRI 1367-76-26	ARC BI0002	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 1, will commence in mid-October followed by Task 2 (Surface energy characterization of phase-specific asphalt microstructure).

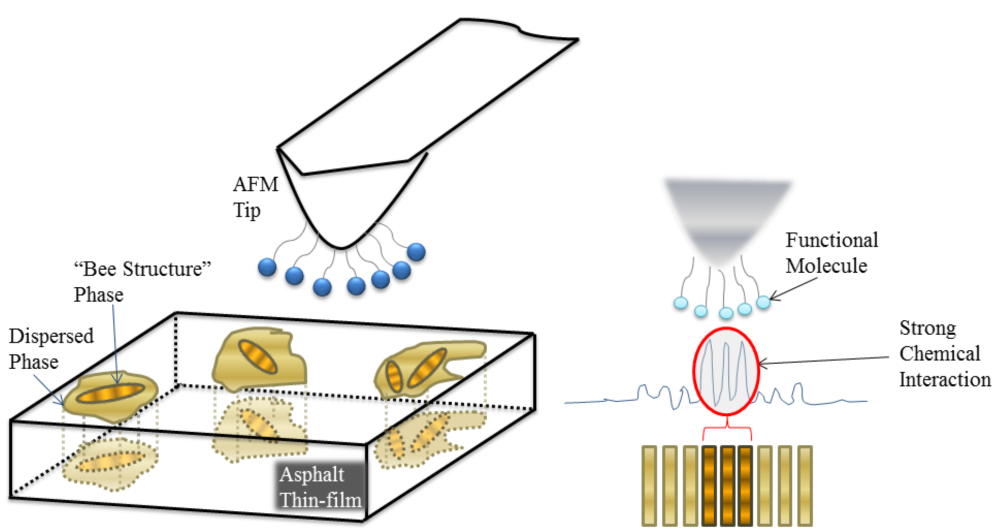

Figure F2d.1. AFM mapping of surfaces with chemical contrast. By using the appropriate tip functionality, a specific surface image depicting chemical groups can be achieved based on the tip-surface interaction. (Adapted from Nanocraft).

Table F2d.2. List of Deliverables and Status of Deliverables.

Date	Deliverable	Description of Deliverable	Status of Deliverable
11/30/2012	**Journal Paper**	A Two Dimensional Finite Element Model of Atomic Force Microscope Indentation of Asphalt Thin Film	Revised
2/30/2012	**Journal Paper**	Microstructural Viscoelastic Properties of Asphalt thin film measured using Nanoindentation	Revised
1/1/2013	**TRB Paper**	A Numerical Model for the Atomic Force Microscopy Indentation of Asphalt with Adhesion	On Schedule- Accepted for Presentation

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 (2011). 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 Underwood (2011) 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.

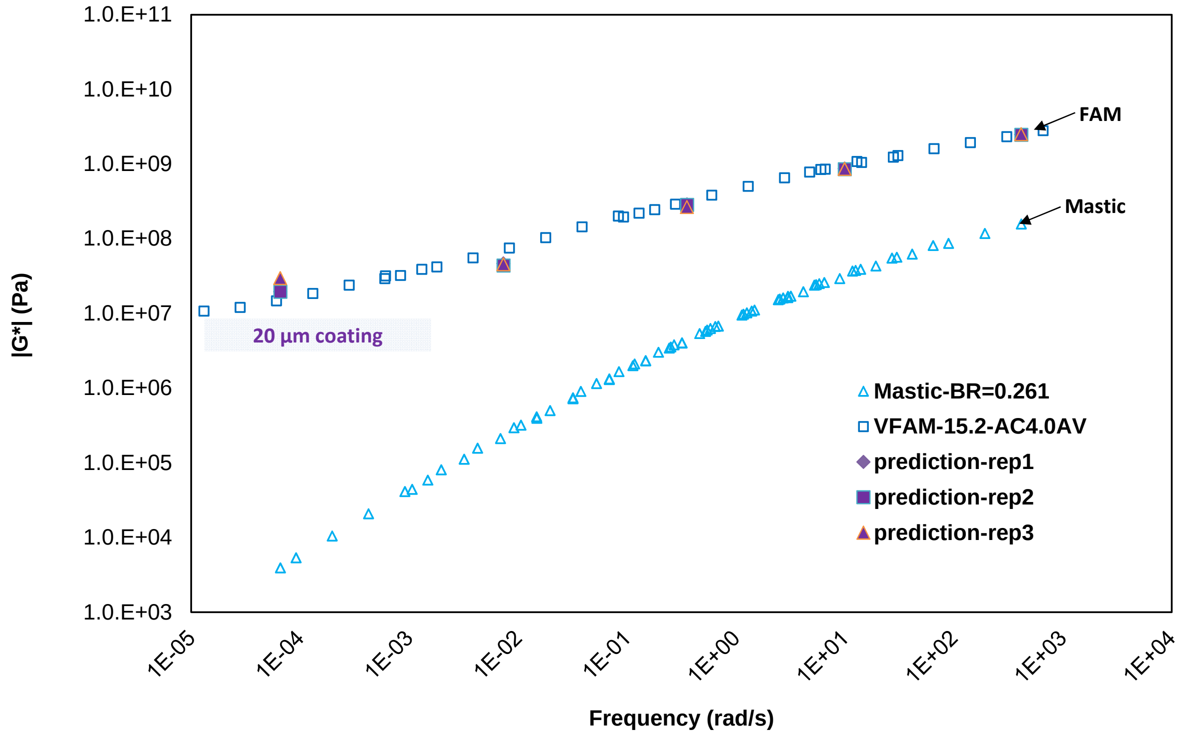

Figure 1. Dynamic modulus predictions for FAM from available mastic data.

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.

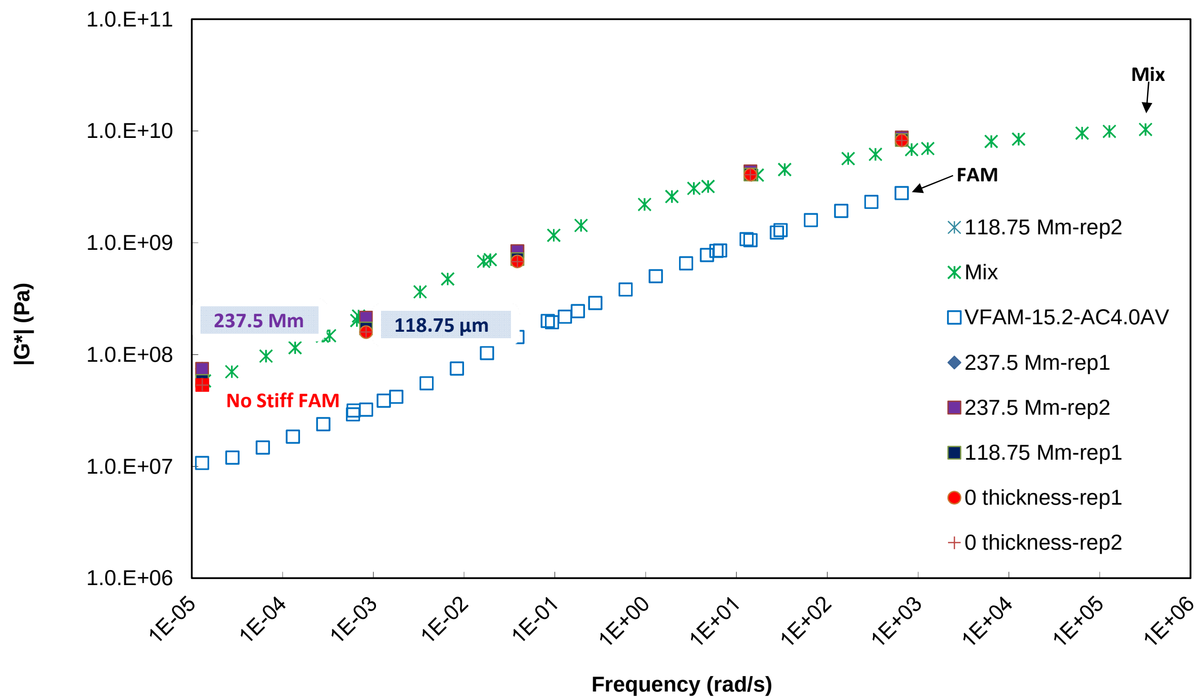

Figure 2. Dynamic modulus predictions for mix from available FAM data

References

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.

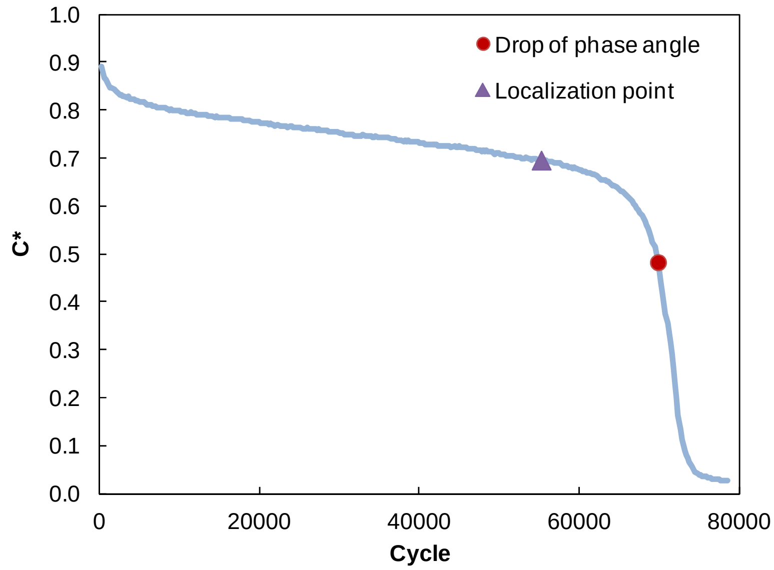

Figure 3. Schematic plot of failure point and localization point.

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.

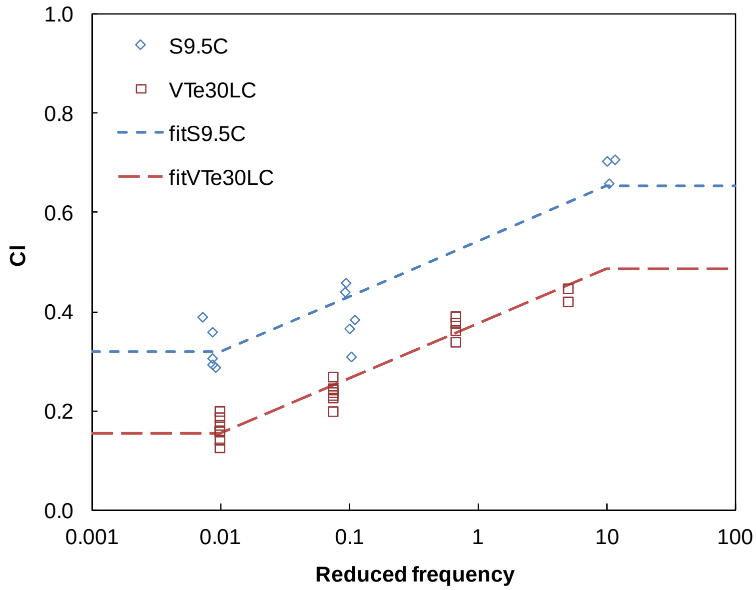

Figure 4. Development of localization envelope.

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.

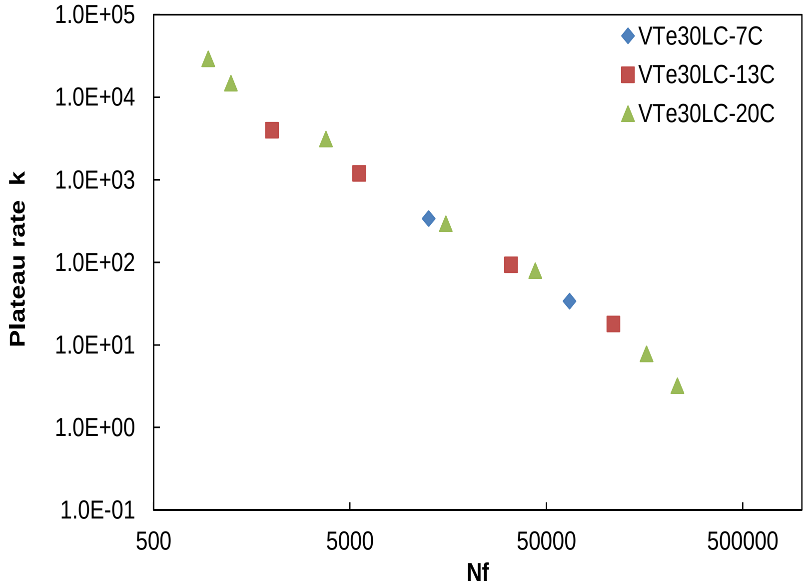

Figure 5 Relationship between plateau rate k and fatigue life N_f.

References

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:

- AASHTO Draft Procedure for blended binder continuous grading was submitted to the FHWA Asphalt Mixture and Construction Expert Task Group for review. The standard is being distributed to interested parties for ruggedness testing.
- A literature review regarding the specification of Dust Proportion (DP) for RAP mixtures has begun and an initial work plan for screening significant factors is in development. A thesis was submitted regarding the reinforcing effects of mastics; it is anticipated this thesis and NCHRP report 09-45 will be the basis of the work plan.
- Developed a plan for field test sections to evaluate HMA mixtures containing RAP in Arizona.
- Received the high RAP content mixtures from University of New Hampshire for uniaxial thermal stress and strain test (UTSST).

The following list the work planned for next quarter:

- Conduct a literature review regarding fractionation procedures for RAP materials. It is anticipated that an informal survey will be conducted with industry producers as the construction season ends.
- Ruggedness and expanding database for continuous grade procedure, inclusive of different RAP and RAS sources.
- Conduct the uniaxial thermal stress and strain test (UTSST) on the high RAP content mixtures from University of New Hampshire.

- Sample field mixtures from the Arizona RAP field sections. Anticipated construction date is November 12, 2012.

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 two mixtures from WesTrack, two mixtures from local projects in Reno, Nevada, and one mixture from the US95 highway in Las Vegas, Nevada.
- Five mixtures from the MnRoad test facility have been collected for further validation of the FN approach.
- Dr. Bonaquist presented the findings of the study at the FHWA Asphalt Mixture and Construction Expert Task Group meeting in Minneapolis, Minnesota, September 26, 2012.

The following list the work planned for next quarter:

- Validate the findings of the FN study using the MnRoad mixtures.
- Assess the use of AMPT to determine the critical conditions of an asphalt mixture.
- Submit a draft version of Report H to FHWA for review and feedback.

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).
- 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 70% of the binder aging and testing have been completed thus far.
- 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 are being prepared and aged at 85°C. Half of these mixtures have been prepared and are undergoing their respective aging for 0.5, 1, and 3 month durations. Some of the 0.5 month sample are out of the oven are in the process of being tested. The other half of this data set is being prepared and should begin aging relatively soon.
- Preparation of the direct tension test specimens for polymer-modified asphalt mixtures.
- Performing UTSST test for the polymer-modified asphalt mixtures 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.
- Prepared and submitted two papers for presentation and publication at the upcoming 2013 TRB annual meeting in Washington DC.

The following list the work planned for next quarter:

- 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 polymer-modified asphalt mixtures and various aged mixtures.
- Evaluate the relationship between the mixture and binder viscoelastic properties as a function of aging.

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 several chapters of the report. Work will continue on the report.

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 describes the work items completed or in progress this quarter:

- Report Upload and File Management Subsystem.
- Multi-factor Properties – Creation and Measure Assignment:
  - Multi-factor property creation.
  - Multi-factor measure assignment.
  - Property decoupling.
- Changes / Enhancements to Validation Site Implementation.
- Changes / Enhancements to the Batch Viewer Form.
- Creation of Preliminary Reports.
- Prototype of Public User Interface:
  - Search engine.
  - Selection engine.
  - Execution engine.
  - Custom query engine.
- Role Viewer.
- General Bug Fixes.
- Prepared and submitted the QC/QA plans and protocols.

The following list the work planned for next quarter:

- Create file renaming tool for WRI and other ARC users.
- Complete the infrastructure and user interface to approve measures for test runs.
- Complete the report to display qualitative properties in addition to the report to display quantitative properties.
- Create 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.
- Complete work on property name decoupling.

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

Work Completed: Report has been revised to include justification for revisions to the AASHTO standard, address the importance of testing substrate (e.g., rock, glass, or metal), and demonstrate the effect of the stiffness of the binder and aging on the bond strength. Two new sections were included in the report, one to present bond strength results for mastics and another presenting a ruggedness testing plan for further development of the procedure.

Work Planned: Finish addressing comments submitted by the reviewers and finalize the report.

Reasons for Delay: Justifying the recommended revisions to the AASHTO standard test procedure and addressing reviewer comments took longer than anticipated. Completion of the report is imminent, final version will be submitted in early 2012Q4 to FHWA.

Revised Delivery Dates
Draft Deadline: 10/30/11 (Submitted)
Final Report Deadline: 10/30/2012 (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

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 Deadline: 10/30/11 (Submitted)
Final Report Deadline: Tentative: 3/31/2013, assumes review comments received by 12/31/12 (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.

Work Planned: The report will be combined with Work Element E3a: Effects of Extenders and Alternative Binders on Performance. This is a new task that was established in the ARC Year 6 work plan, technical work is still ongoing.

Delivery Dates
Draft Deadline: 9/30/2013
Final Report Deadline: 6/30/2014

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
On Schedule

Work Completed: Work for subtask E1b-2 (indentation test procedure) has been completed and report chapters have been drafted. Although industry feedback was not directly received on white papers discussing modification to the current MSCR AASHTO standards, results and recommendations were included in the report and summarized in the discussion of MSCR test protocols at the FHWA Binder ETG meeting held in September 2012.

Work Planned: Modeling efforts to define the role of binder elasticity in mixture rutting performance will continue. Draft final report will be completed by the current deadline based on a synthesis of recent work and an MS theses related to the subtasks mentioned above.

Delivery Dates
Draft Deadline: 12/31/2012
Final Report Deadline: 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: Applied different tribology measurement devices to investigate the impact of aggregate surface type and texture on asphalt binder coefficient of friction. Results will be included in the final report as a means to evaluate potential applications of the Asphalt Lubricity Test. Work began on evaluating revised guidelines for selection of mixing and compaction temperatures by establishing by applying existing test methods to evaluate the effects of asphalt binder viscosity on the quality of aggregate coating. Mixes have been prepared with WMA additives and various levels of RAP binder replacement to assess the how the combination of reduced temperatures and binder replacement levels impact workability and performance. UNR continues to test and summarized data from the Manitoba field sections.

Work Planned: Continue progress on remaining work tasks and incorporate new findings and results from UNR in draft final report. Establish a working draft of the final report with the expectation of submitting by the March, 2013 deadline.

Delivery Dates
Draft Deadline: 3/31/2013
Final Report Deadline: 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: A literature review focused on the field compaction and volumetrics of CMA was completed and a preliminary procedure for producing CMA specimens to meet volumetric criteria was established. A method to evaluate aggregate coating in CMA was finalized and applied for a wide range of mix design variables including aggregate source, emulsion type, aggregate gradation, aggregate moisture content, and emulsion content.

A framework for fresh emulsion characterization was proposed. The framework is based on testing of seven emulsions including slow, medium, rapid, and quick setting types. Polymer modification was used for several of the emulsions. Residue has been recovered but has not been tested at the time of reporting. A chip seal late-raveling study is ongoing that is expected to provide critical emulsion properties leading to raveling distresses in chip seals after extended aging (field service).

Work Planned: The volumetric design system proposed for CMA mixtures will be applied for several material types. 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.

The previously completed emulsion residue testing framework will be applied to the residues collected last quarter to assess variation in properties due to emulsion type, modifier, and chemistry. Results of the chip seal raveling study will be summarized.

Delivery Dates
Draft Deadline: 9/30/2013
Final Report Deadline: 6/30/2014

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
Behind Schedule

Work Completed: Draft final report in Section 508 Format and a tech brief was submitted for review in December, 2011.

Work Planned: Address review comments and finalize report.

Reasons for Delay: Comments on the final report have not yet been received. It is anticipated that upon receipt of comments, approximately 2 months will be necessary to submit final report.

Delivery Dates
Draft Deadline: 12/31/2011 (Submitted)
Final Report Deadline: Tentatively 3/31/13, pending receipt of final report comments.

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-3. Overall integration for multiscale modeling (VT, URI, and WRI)

Subtask F3a-4. 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 continues to move near completion.

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. Work during the quarter continued to apply a method for converting calculations of spontaneous stress fluctuations from past simulations into predictions of frequency-dependent complex modulus |G*| and phase angle □. Interpretations were continued for new model asphalt system AAA-1 but are not yet complete. Applying the method was started but not completed for earlier model asphalt systems that were simulated previously; this will enable comparisons of chemical effects.

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

On Schedule.

Work to simulate additional asphalt systems continues to proceed more slowly than expected but remains on schedule. 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. Additional PI and graduate student time is being devoted to the simulations, though a new teaching load that was assigned to the PI is impeding progress during the semester. New computer hardware will also speed the calculations.

Sub-subtask F3a-1.2. Develop algorithms and methods for directly linking molecular simulation outputs and phase field inputs (URI)
Subtask F3a-3. Overall integration for multiscale modeling (VT, URI, and WRI)
Subtask F3a-4. Experimental verification and validation (VT, URI, and WRI)

Technical work - On Schedule. Decision about integrating reports – delayed by 1 quarter.

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 quarter an idea would have been considered about incorporating the Model Deliverable into the contents of Report S. This was delayed due to personal circumstances that arose during the quarter and to a new teaching load for Greenfield. The decision will be made during the next quarter.

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

Included work elements/subtasks

Subtask F3a-2: Phase-field modeling of crack propagation in asphalt binder

- Sub-Subtask F3a-2.5. Simulations of crack propagation under mode II loading and mixed-mode loading
  - Sub-Subtask F3a-2.5.1: Formulation of Allen-Cahn Phase-field model for mixed-mode cracking
  - Sub-Sub-Subtask F3a-2.5.2. Determination of J-integral in mixed-mode cracking
  - Sub-Sub-Subtask F3a-2.5.3. Verification of mixed-mode J-integral in Phase-field model
  - Sub-Sub-Subtask F3a-2.5.4. Phase-field simulation of mixed-mode cracking
  - Sub-Sub-Subtask F3a-2.5.5. Experimental verification of phase-field simulation of mixed-mode cracking

Status and Work Planned

On Schedule

At this moment, this research progress is on time according to the plan. Sub-Subtasks F3a 2.5.1-F3a 2.5.4 have been finished. Sub-Subtask F3a-2.5.5 will be finished in the next quarter.

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

On Schedule

Work is progressing according to the year six work plan. Laboratory testing for the Hirsch model refinements and the resistivity model refinements has been completed. Also permeability data has been obtained from various publications for the permeability model refinements. Analysis of the data for these three models is underway. For the fatigue model refinements, the geometric stress progression tests with and without rest periods has been completed and data analysis is underway. Dr. Christensen reported on the geometric stress progression test at the Mixtures Expert Task group meeting in September. Approximately 75 percent of the Fénix fracture energy tests has been completed.

Next quarter, the remaining Fénix fracture energy tests be completed. Data analysis for refinement of all four models 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.

Data analyses and model verifications were continued in this quarter on the processing of the testing data to determine the viscoplastic and viscofracture material properties of the two tested ARC asphalt mixtures: 1) NHL (Nustar binder and Hanson limestone) and 2) VHL (Valero binder and Hanson limestone). Combined with the material properties determined in Work Elements F2c and E1a documented in the previous quarterly reports, all of the data analysis and model verification work were completed and the draft of the final report (ARC Report V) has been initiated in this quarter. Details of the achievements made in this quarter are summarized as follows:

1) Determination of Viscoplastic and Viscofracture Material Properties of ARC Mixtures
To obtain the viscoplastic and viscofracture material properties of the ARC asphalt mixtures, testing data analyses were performed on the lab-mixed-lab-compacted (LMLC) ARC asphalt mixtures which were fabricated with 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 viscoplastic model's parameters determined for the ARC asphalt mixtures in this quarter included viscosity-related Perzyna's coefficient (Γ), rate dependent Perzyna's parameter (N), and the coefficient of the rate effect factor in the viscoplastic yield surface (κ_3). The anisotropic viscofracture model's parameters determined for the ARC asphalt mixtures included flow number (N_f), crack speed index (η), the anisotropic J-integral Paris' law's coefficients for the axial damage density (A_1 and n_1) and the radial damage density (A_2 and n_2). These parameters were used in the constitutive models for the viscoplastic and viscofracture characterization of the asphalt mixtures, part of which (e.g., Γ and N) also can be used as the input parameters of the PANDA program.

2) Draft of Final Report
A draft of the ARC final report (Report V, Continuum damage permanent deformation analysis for asphalt mixtures) was initiated in this quarter to summarize the developed mechanistic models, testing protocol, testing results of ARC asphalt mixtures and the data processing program in the characterization of the asphalt mixtures in compression including anisotropy, viscoelasticity, viscoplasticity and viscofracture.

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.

In the last quarter, the fatigue properties and fatigue resistance of all ARC asphalt mixtures have been obtained by analyzing the data of the controlled-strain repeated direct tension (RDT) tests using the energy-based mechanistic approach. As a continuation of characterizing fatigue and healing properties of asphalt mixtures, two tasks are accomplished in this quarter: 1) identify the relationship between the fatigue resistance of asphalt mixtures and the modified Paris' law parameters (A' and n'); and 2) investigate the recovery behaviors of asphalt mixtures in order to characterize healing of asphalt mixtures during the rest period.

In order to find the relationship between the fatigue resistance of asphalt mixtures and the modified Paris' law parameters, a statistical regression analysis is first conducted on A' and n' of all ARC asphalt mixtures obtained in the last quarter. The high R-square statistic indicates a high correlation between A' and n'. Based on this finding, a sensitivity analysis is conducted to understand how the damage density behaves in response to changes of A' and n'. The results of the sensitivity analysis suggest that n' can be used directly to compare the damage density of different asphalt mixtures. The rank of n' is in accord with the resistance of the material to fatigue cracking. It can be used solely in material comparison and selection in terms of fatigue cracking, and a smaller value of n' is preferred.

The recovery behaviors of all ARC asphalt mixtures are investigated using the creep and step-loading recovery (CSR) test that is introduced in previous quarterly reports. As the driving force of recovery, the internal stresses of all ARC asphalt mixtures are measured in the recovery phase of the CSR test, and used to define the recovery modulus. To fully understand the characteristics of the recovery modulus, the effects of loading level, temperature, and aging are studied and the following findings are made:

- The recovery modulus of undamaged asphalt mixtures does not change with the change of the loading level as long as the loading is nondestructive, but it becomes different when the loading is destructive.
- The recovery modulus of an asphalt mixture decreases with the increase of the air void content given that all the other conditions remain the same.
- The recovery modulus of an asphalt mixture is dependent on temperature in this way: it increases as the temperature decreases and vice versa.
- The recovery modulus of an asphalt mixture becomes larger as the aging period increases.

Based on the findings on the recovery properties of asphalt mixtures, the healing properties of all ARC asphalt mixtures will be studied in the next quarter in terms of healing rates and healing scale. In addition, the healing characteristics of all asphalt mixtures will be investigated as they are affected by different types of asphalt binder, different air void contents, different aging periods, and different temperatures.

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
Status: on schedule.

In this quarter, the field specimens from the Yellowstone National Park (YNP) were tested and analyzed using the test protocol of field cores. The construction sites were built in September 2007 so these cores are 4 years old. The cores were cut to construction lifts and first tested using the Direct Tension Test protocol for field specimens. The stiffness gradient profiles for these sections were calculated for 10°C and 20°C degrees.

Results of the stiffness gradient calculation for YNP cores

Table 1 shows the stiffness gradient profile analysis for 10°C and 20°C degrees. As shown in Table 1, the analyses were not completed for many sections at 20°C because especially the bottom lift is a coarse graded weak mixture. The outputs from 20°C and 30°C degrees still can be used to get the average stiffness calculations but the test duration for these sections are not long enough to provide sufficient data for the stiffness gradient profile calculations.

Table 1. Stiffness gradient profile for Yellowstone park sections.

ID	Lift	Location	Temperature (C°)	n	k	Surface Modulus(psi)	Bottom Modulus(psi)
1-2A	Bottom	W/P	10	4.706	4.35	396459	91140
1-2A	Bottom	W/P	20	-	-	-	-
1-2A	Bottom	Shoulder	10	4.04	2.26	116428	51517
1-2A	Bottom	Shoulder	20	3.49	1.82	53364	29321
1-2A	Top	W/P	10	3.78	2.46	382234	155380
1-2A	Top	W/P	20	3.8	2.24	145770	65076
1-2A	Top	Shoulder	10	5.4	1.37	252285	184150
1-2A	Top	Shoulder	20	-	-	-	-
1-3A	Bottom	W/P	10	3.74	1.52	284179	186960
1-3A	Bottom	W/P	20	5.35	1.47	176870	120320
1-3A	Bottom	Shoulder	10	3.77	2.15	101338	47134
1-3A	Bottom	Shoulder	20	-	-	-	-
1-3A	Top	W/P	10	3.59	2.72	452363	166310
1-3A	Top	W/P	20	-	-	-	-
1-3A	Top	Shoulder	10	-	-	-	-
1-3A	Top	Shoulder	20	-	-	-	-

Figure 1 shows the stiffness profiles for a wheel path section at 10°C and 20°C.In general, results indicate that the bottom lift of these sections are very weak and the wheel path has been aged more than the shoulder. Figure 2 shows the stiffness profiles for the wheel path and shoulder from the same section in the road. The results from the stiffness profile show a higher rate of aging in the wheel path compared to shoulder sections.

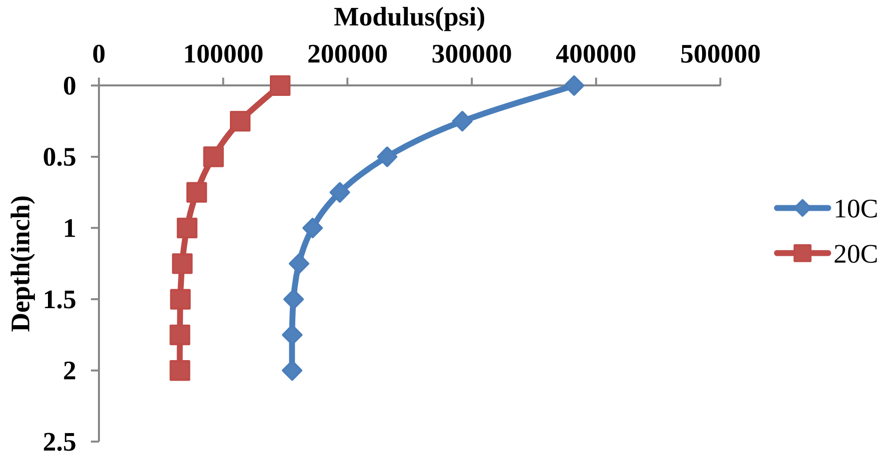

Figure 1. The stiffness gradient profiles for 1-2A, top lift at wheel path.

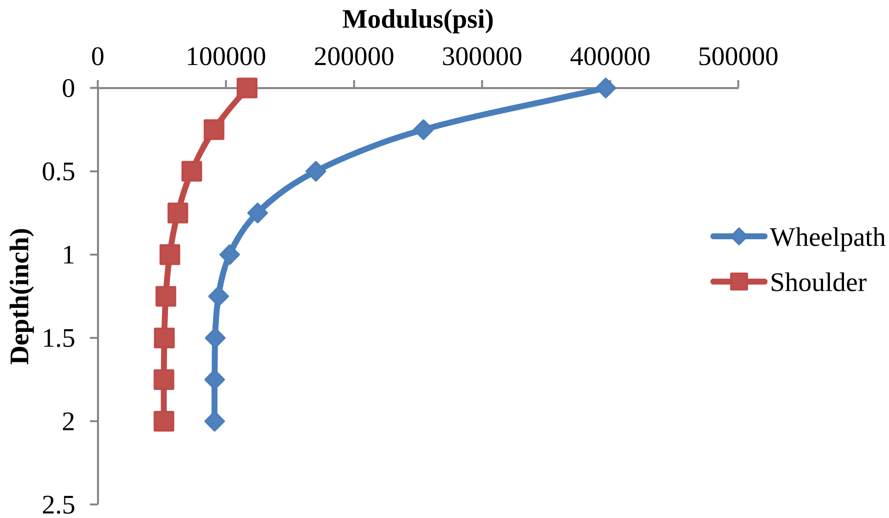

Figure 2. The stiffness gradient profiles for wheel path versus shoulder.

The work planned in next quarter includes the testing and analysis of the fracture and healing properties of YNP cores using OT test and the FGM integrated finite element model. In addition, the mixture stiffness gradient results will be compared to the binder extraction test results, to find the possible correlations.

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, an implicit numerical method was adopted to model the water vapor diffusion in the pavement layers. As discussed in the previous quarterly report, the diffusion process in pavement is governed by a parabolic partial differential diffusion equation controlled by a single diffusivity coefficient, D:

$$\frac{\partial u}{\partial t} = D\frac{\partial^2 u}{\partial x^2} \tag{1}$$

where u is the suction at the specified depth of pavement on a logarithmic scale, pF; D = water vapor diffusion coefficient of the asphalt mixture, mm^2/sec.

The major problem in the previous modeling using the approximate solution method is the two different boundary condition assumption. Therefore, a numerical method was adopted to improve the previous models. Crank-Nicholson is a popular method for solving parabolic equations because it is unconditionally stable and second order accurate. The simplest and well known implicit Crank-Nicholson scheme is obtained by a combination of the forward time differencing and an averaging over time at the second order centered space derivative operator. It is based on a central difference in space and the trapezoidal rule in time, giving second-order convergence in time.

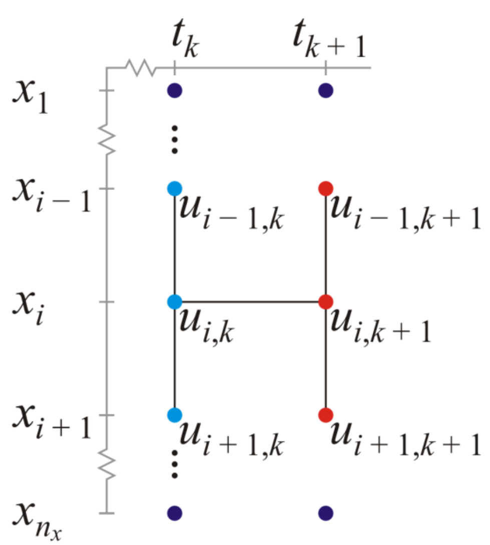

Figure 1. Schematic illustration of Crank-Nicholson Method.

Given the general diffusion equation formulated as equation 1, the finite-difference equation can be generated using schemes shown in the Figure 1. as follows:

$$2u_{i,k+1} = 2u_{i,k} + \frac{D\Delta t}{h^2}\left(u_{i-1,k} - 2u_{i,k} + u_{i+1,k}\right) + \frac{D\Delta t}{h^2}\left(u_{i-1,k+1} - 2u_{i,k+1} + u_{i+1,k+1}\right) \tag{2}$$

where h = the distance step upward from the subgrade soil to the surface of the HMA layer, cm; and Δt = time steps for this scheme, sec.

Let $r = \frac{\kappa\Delta t}{h^2}$, equation 2 can be reformulated as follows by removing all unknowns to the left and all knowns to the right:

$$-ru_{i-1,k+1} + 2(r+1)u_{i,k+1} - ru_{i+1,k+1} = 2u_{i,k} + r\left(u_{i-1,k} - 2u_{i,k} + u_{i+1,k}\right) \tag{3}$$

Since there are n-2 unknowns, therefore this requires setting up a system of n-2 linear equations to solve. Combining all the equations, this can be written in the form Mx = b as follows:

$$\begin{pmatrix} 2(1+r) & -r & & & & \\ -r & 2(1+r) & -r & & & \\ & -r & 2(1+r) & \ddots & & \\ & & \ddots & \ddots & -r & \\ & & & -r & 2(1+r) & -r \\ & & & & -r & 2(1+r) \end{pmatrix} \begin{pmatrix} u_{2,k+1} \\ u_{3,k+1} \\ u_{4,k+1} \\ \vdots \\ u_{n_x-2,k+1} \\ u_{n_x-1,k+1} \end{pmatrix} = \begin{pmatrix} 2u_{2,k} + r\left(u_{1,k} - 2u_{2,k} + u_{3,k}\right) + ra_{\text{bndry}}\left(t_{k+1}\right) \\ 2u_{3,k} + r\left(u_{2,k} - 2u_{3,k} + u_{4,k}\right) \\ 2u_{4,k} + r\left(u_{3,k} - 2u_{4,k} + u_{5,k}\right) \\ \vdots \\ 2u_{n_x-2,k} + r\left(u_{n_x-3,k} - 2u_{n_x-2,k} + u_{n_x-1,k}\right) \\ 2u_{n_x-1,k} + r\left(u_{n_x-2,k} - 2u_{n_x-1,k} + u_{n_x,k}\right) + rb_{\text{bndry}}\left(t_{k+1}\right) \end{pmatrix} \tag{4}$$

For the convenience of programming, Equation 5 can be further simplified as follows:

$$\begin{pmatrix} 2u_{2,k} + r\left(u_{1,k} - 2u_{2,k} + u_{3,k}\right) + ra_{\text{bndry}}\left(t_{\ell+1}\right) \\ 2u_{3,k} + r\left(u_{2,k} - 2u_{3,k} + u_{4,k}\right) \\ 2u_{4,k} + r\left(u_{3,k} - 2u_{4,k} + u_{5,k}\right) \\ \vdots \\ 2u_{n_x-2,k} + r\left(u_{n_x-3,k} - 2u_{n_x-2,k} + u_{n_x-1,k}\right) \\ 2u_{n_x-1,k} + r\left(u_{n_x-2,k} - 2u_{n_x-1,k} + u_{n_x,k}\right) + rb_{\text{bndry}}\left(t_{\ell+1}\right) \end{pmatrix} = 2\begin{pmatrix} u_{2,k} \\ u_{3,k} \\ u_{4,k} \\ \vdots \\ u_{n_x-2,k} \\ u_{n_x-1,k} \end{pmatrix} + r\begin{pmatrix} u_{1,k} - 2u_{2,k} + u_{3,k} \\ u_{2,k} - 2u_{3,k} + u_{4,k} \\ u_{3,k} - 2u_{4,k} + u_{5,k} \\ \vdots \\ u_{n_x-3,k} - 2u_{n_x-2,k} + u_{n_x-1,k} \\ u_{n_x-2,k} - 2u_{n_x-1,k} + u_{n_x,k} \end{pmatrix} + \begin{pmatrix} ra_{\text{bndry}}\left(t_{k+1}\right) \\ \\ \vdots \\ \\ rb_{\text{bndry}}\left(t_{k+1}\right) \end{pmatrix} \tag{5}$$

Boundary conditions are set as follows:

1. $u\left(x = d, t\right) = u_d$
2. $\frac{\partial u}{\partial x}\left(x = 0, t\right) = 0$

where u_d = is the suction in the granular base material, which is a constant.

Thus, given the initial state at time t_1, we create a system of equations with k = 1 to solve for $u_{2,2}$ through $u_{n_x-1,2}$. By applying the same theory to the following time and spatial steps, all the unknowns as shown in the schematic illustration figure 2 can be solved.

$u_{\text{init}}(x_1)$	$a_{\text{bndry}}(t_2)$	$a_{\text{bndry}}(t_3)$	$a_{\text{bndry}}(t_4)$	$a_{\text{bndry}}(t_5)$	$a_{\text{bndry}}(t_6)$	$a_{\text{bndry}}(t_7)$	$a_{\text{bndry}}(t_8)$	$a_{\text{bndry}}(t_9)$	$a_{\text{bndry}}(t_{10})$	$a_{\text{bndry}}(t_{11})$	$a_{\text{bndry}}(t_{12})$
$u_{\text{init}}(x_2)$	?	?	?	?	?	?	?	?	?	?	?
$u_{\text{init}}(x_3)$	?	?	?	?	?	?	?	?	?	?	?
$u_{\text{init}}(x_4)$	?	?	?	?	?	?	?	?	?	?	?
$u_{\text{init}}(x_5)$	?	?	?	?	?	?	?	?	?	?	?
$u_{\text{init}}(x_6)$	?	?	?	?	?	?	?	?	?	?	?
$u_{\text{init}}(x_7)$	?	?	?	?	?	?	?	?	?	?	?
$u_{\text{init}}(x_8)$	?	?	?	?	?	?	?	?	?	?	?
$u_{\text{init}}(x_9)$	$b_{\text{bndry}}(t_2)$	$b_{\text{bndry}}(t_3)$	$b_{\text{bndry}}(t_4)$	$b_{\text{bndry}}(t_5)$	$b_{\text{bndry}}(t_6)$	$b_{\text{bndry}}(t_7)$	$b_{\text{bndry}}(t_8)$	$b_{\text{bndry}}(t_9)$	$b_{\text{bndry}}(t_{10})$	$b_{\text{bndry}}(t_{11})$	$b_{\text{bndry}}(t_{12})$

Figure 2. Schematic illustration of solving sequence.

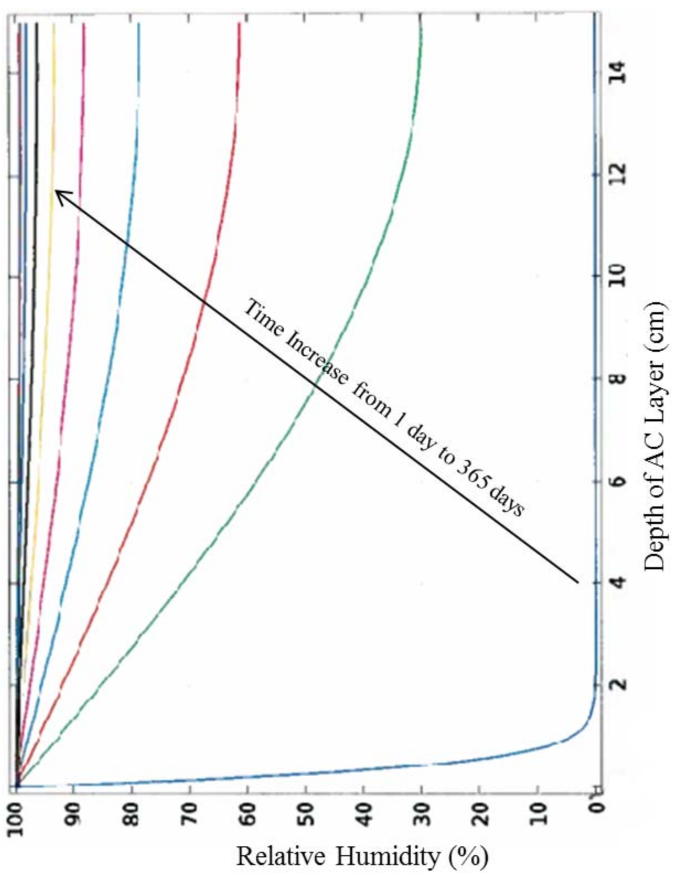

Figure 3. Moisture vapor diffusion in pavement.

The final results are plotted in figure 3, as service time increases, the asphalt surface layer gradually wets up after placement 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 96% in approximately 180 days, and this RH level remains within the asphalt layer. These modeling results illustrate that the pavement surface layer attains nearly saturation vapor pressure within a relatively short period of 180 days.

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
On 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 is underway to develop 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.

Next quarter, the development of the automated spreadsheet should be substantially complete. Upon its completion, the test method that was submitted earlier will be revised.

AASHTO METHODS: WILHELMY PLATE TEST, UNIVERSAL SORPTION DEVICE, DYNAMIC MECHANICAL ANALYSIS, AND METHOD FOR THE PREPARATION OF SPECIMENS OF FINE AGGREGATE MATRIX OF ASPHALT MIXTURES

Included Work Elements/Subtasks
Work Element/Subtask F1a: Cohesive and Adhesive Properties

Status and Work Planned

The protocols for the Wilhelmy Plate test, the Universal Sorption Device, and Dynamic Mechanical Analysis have been developed and are being finalized in AASHTO format. They will be submitted for consideration by the end of November 2012.

The Method for Preparation of Specimens of Fine Aggregate Matrix of Asphalt Mixtures will be submitted in AASHTO format by the end of December 2012.

ASTM METHOD: AUTOMATED FLOCCULATION TITRIMETRIC ANALYSIS

Included Work Element/Subtasks

None.

Status and Work Planned

Completed as an ASTM Standard. Full title is: ASTM D6703-07, Standard Test Method for Automated Heithaus Titrimetry.

DRAFT AASHTO METHOD: DETERMINATION OF POLYMER IN ASPHALT

Included Work Elements/Subtasks

None.

Status and Work Planned

Completed and submitted for AASHTO review.

DRAFT AASHTO METHOD: MEASURING INTRINSIC HEALING CHARACTERISTICS OF ASPHALT BINDERS

Included Work Elements/Subtasks
F1d.

Status and Work Planned

Details of this test procedure are documented in a Master's thesis. A standalone version will be edited and presented in the AASHTO format.

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

<u>Included Work Elements/Subtasks</u>
Work Element V3c: Validation of PANDA

<u>Status and Work Planned</u>

The laboratory tests needed to calibrate and validate PANDA for the ARC Mixture No. 1 are 95% 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. The focus of the coming quarter will be in drafting these testing protocols in the format of AASHTO test procedures. Drafts of these test protocols will be developed by February 2013. In addition, more emphasis will be placed on the development of a systematic procedure for the identification of the PANDA model parameters.

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. (2012). "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*, 24(7), 898-906.

Zhang, Y., Luo, R., and Lytton, R. L. (2011). "Microstructure-based inherent anisotropy of asphalt mixtures." *Journal of Materials in Civil Engineering*, 23(10), 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 in the AASHTO format will be initiated at the conclusion of this portion of the draft of the Final Report V.

FHWA delivery to be determined.

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., R. Luo, and R. L. Lytton. (2012). "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. (2012). "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. (2012). "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., under review.

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 draft of the test method document in the AASHTO format will be initiated at the conclusion of the analysis of:

1) The healing rates and healing scales of asphalt mixtures as they are affected by different types of asphalt binder, air void contents, aging periods, and temperatures; and
2) The scales and the moisture damage and aging tests with fine aggregate mixtures.

FHWA delivery to be determined.

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:

Testing and data analysis of undamaged properties of fine aggregate mixtures and their fatigue as affected by moisture, aging and air voids is currently ongoing. At the conclusion of this testing and analysis phase, a draft document of the test method(s) will be initiated.

FHWA delivery to be determined.

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

<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:

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., Luo, R., Lytton, R. L., and Scullion, T. (2012). “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. (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:

Testing of field cores is currently ongoing. At the conclusion of testing and data analysis phase of this work element a draft of test method document in AASHTO format will be initiated.

FHWA delivery to be determined.

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:

Testing and data analysis of undamaged asphalt mixtures in compression is now complete and a draft of this portion of the Final Report V is initiated. Upon the completion of this draft final report, a draft of the test method document will be initiated.

FHWA delivery to be determined.

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.

The paper entitled: "Mix Design of Cold-in-Place Recycling" was presented at the ISAP: "2nd International Symposium on Asphalt Pavements & Environment," conference meeting that was held on October 1-3, 2012 in Fortaleza, Brazil. The comments and feedbacks from the conference will be considered in the work plan.

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
Subtask E1c-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: Literature review on existing mix design and compaction methods was completed. Experimental plan to develop laboratory methods to estimate coating of CMA and identify the factors affecting aggregate coating for several aggregate-emulsion systems was executed. A volumetric mix design framework has been established and is being applied to several emulsion-aggregate systems.

Work Planned: Work will focus on development and evaluation of a mix design procedure to evaluate the volumetric and performance properties of CMA. Specific tasks include: definition of compaction and curing procedures for sample preparation and establishing volumetric limits for selection of optimum fluids content. The final mix design procedure will be implemented to measure performance properties of CMA, results will be used to identify critical performance properties and establish design limits.

Delivery Dates
Estimated Completion Date: 9/30/2013

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:

- Started the writing of the draft AASHTO practice.
- Revised the original version of Report H.

The following list describes the work planned for next quarter:

- Complete the writing of the draft AASHTO practice and submit to FHWA.

DRAFT AASHTO METHOD: THERMAL STRESS RESTRAINED SPECIMEN TEST (TSRST)

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:

- Submitted the AASHTO draft procedure entitled “Determining Thermal Visco-Elastic Properties of Asphalt Mixtures Using the Uniaxial Thermal Stress and Strain Test (UTSST).”
- Presented a summary of the AASHTO standard procedure at the FHWA Asphalt Mixture and Construction Expert Task Group meeting in Minneapolis, Minnesota, September 26, 2012.

The following list the work planned for next quarter:

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

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
Behind Schedule

Work Completed: The current standard was revised to include requirements to control the temperature of the aggregate substrate prior to application of the binder. Other minor revisions were also made. An experimental plan for ruggedness testing was developed. All revisions made relate to application of the BBS test for hot-applied binders.

Work Planned: Execute ruggedness testing plan and revise standard accordingly. Apply a similar approach to improve the procedure for evaluating the curing of emulsions provided in the current standard (AASHTO TP-91). Status was changed from "complete" to "behind schedule" based on the need to revise the standard and conduct ruggedness testing for emulsions and hot applied binders.

Reasons for Delay: Continued use of BBS test for both hot-applied binders and fresh emulsions identified opportunities to improve the test procedure. Ruggedness testing for both materials is also necessary to promote future implementation of the test. The revised timeline allows for the possibility of presenting the revised procedure to the FHWA Binder ETG and Emulsion Task Force in spring of 2013.

Delivery Dates
Draft Standard: Complete
Revised Standard and Ruggedness Testing – Hot Applied Binders: 12/31/2012.
Revised Standard and Ruggedness Testing – Fresh Emulsions: 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
On Schedule

Work Completed: Work continued on writing the test procedure in AASHTO format. The test is intended for use as a surrogate to the conventional elastic recovery test that is conducted in a ductility bath test

Work Scheduled: Complete test procedure and combine with Binder Yield Energy Test (BYTE) method and DSR-Ductility Test method. Submit test method to the Binder ETG and present in the April 2013 meeting.

Delivery Dates
Submit Draft Standard to Binder ETG: 12/31/2012
Presentation at ETG Meeting: 4/30/2013

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
Completed

Work Completed: Internal ruggedness test results were analyzed and used to revise the LAS procedure. The modified procedure was presented to the ETG in September 2012 for review. Based on ETG recommendations testing plans for internal and intra-laboratory ruggedness testing were developed to allow for further evaluation of the revised testing procedure.

Work Planned: Intra-laboratory ruggedness samples will be distributed and progress will be monitored through the next quarter. Feedback will be used to finalize testing procedure. Results will be presented to Binder ETG in April 2013 meeting.

Delivery Dates
Submit Revised AASHTO Procedure to ETG: Completed.
Complete Ruggedness Testing: 12/31/2012
Present Progress and final procedure to the Binder ETG: 4/30/2013.

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
On Schedule

Work Completed: Draft standard of procedure is under development and will be completed next quarter.

Work Planned: Draft AASHTO procedure will be completed and combined with DSR-Elastic Recovery and DSR-Ductility tests. The procedure will be submitted to the Binder ETG for review and discussion in the April 2013 meeting.

Delivery Dates
Deliver draft standard to FHWA Binder ETG: 12/31/2012.
Present combined standard to ETG for endorsement to submit to AASHTO: 4/30/2013.

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: A draft AASHTO procedure was completed and submitted to the equipment manufacturer. Feedback from the manufacturer was received and is currently being incorporated into the test procedure. Based on the specifications provided in the standard the manufacturer has produced a prototype device that will be piloted by the UW team.

Work Planned: Complete revisions to test procedure based on feedback from the equipment manufacturer and submit to the FHWA Binder ETG. Timing of submittal will be based on priority established in the Yr-6 ARC Work Plan.

Reasons for Delay: Delays were encountered in receiving feedback from the manufacturer, comments have been received and the standard will be finalized next quarter.

Revised Delivery Dates
Complete AASHTO Standard: 12/31/2012.
Deliver to FHWA Binder ETG: TBD

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

Included Work Elements/Subtasks
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

Status and Work Planned
On Schedule

Work Completed: Submitted a paper to TRB identifying the factors contributing to the change in asphalt mixture workability due to use of lower compaction temperatures. The paper also identified the conditions under which the coefficient of friction measured by the lubricity test has most impact and identified deficiencies in the test procedure. Other tribology testing devices were used to measure the impact of aggregate surface and texture on lubricating properties of conventional binders and those modified with WMA additives.

Work Planned: Begin work on summarizing test procedure in AASHTO format.

Delivery Dates
Completion of AASHTO Standard: 3/31/2013

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

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

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

Work Completed: Coating procedure for CMA was finalized and applied for two aggregate mineralogies and two emulsion chemistries. The experimental design included three gradations, three moisture conditions, and three emulsion contents. Findings were summarized in a paper submitted to TRB for the 2013 annual meeting.

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. Summarize test procedure in AASHTO format and identify appropriate committee to submit for review. No priority ranking was provided by the ETG in the ARC Yr. 6 work plan. The research team will consider submitting to the FHWA Mix ETG or the FHWA Emulsion Task Force.

<u>Delivery Dates</u>
Completion Date: 12/31/2012

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
On Schedule

Work Completed: The use of perforated molds were deemed successful in producing samples for volumetric and performance evaluation.

Work Planned: Execute work plan to define proper curing conditions for design of CMA. All sample preparation will be completed using the perforated molds. Summarize procedure in AASHTO format. The research team will consider combining this procedure with CMA mix design procedure.

Delivery Dates
Completion Date: 12/31/2012

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
Complete

Work Completed: Submitted draft AASHTO standard and presented test procedure to the FHWA Mixtures ETG at the September 2012 meeting.

Work Planned: Coordinate with Mix ETG RAP subcommittee to establish external review and evaluation of the test procedure. Revise procedure based on external feedback and present progress at the April 2013 ETG meeting.

Delivery Dates
Test Procedure in AASHTO Format: Submitted.
Present Revised Procedure to ETG: 4/30/2013.

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
On Schedule

Work Completed: A draft AASHTO standard and a Technical Brief describing the procedure and application of the SENB test were completed. A presentation was given to FHWA Binder ETG at the September 2012 meeting to introduce the test method and solicit review and comment on the test procedure. The research team also developed an experimental plan to evaluate the ruggedness of the test procedure.

Work Planned: Address comments from reviewers of the standard and complete ruggedness testing.

Delivery Dates
Test Procedure in AASHTO Format: Complete
Present results of ruggedness testing and revised procedure to Binder ETG: 4/30/2013.

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
On Schedule

Work Completed: Work began on drafting the standard test procedure in AASHTO format. Adjustments were made to the hardware used in the testing device to improve ease of use and repeatability.

Work Planned: Complete hardware adjustments and finish draft AASHTO standard. Submit standard to the FHWA Binder ETG. Timing of submittal will be based on other completed standards and the ETG priority defined in ARC Yr. 6 Work Plan.

Delivery Dates
Completion Date: 12/31/2012
Submission and Presentation to FHWA Binder ETG: TBD

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
On Schedule

Work Completed: Draft AASHTO test procedure was completed.

Work Planned: Contact University of Nevada Reno to explore the possibility of combining this procedure with the TSRST test they have developed. After a decision is made regarding how to proceed, the draft standard will be submitted to the FHWA Mix ETG for review prior to the April 2013 meeting.

Delivery Dates
Completion Date: 12/31/2012

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)
Subtask E1b-1: Rutting of Asphalt Binders

Status and Work Planned
On Schedule

Work Completed: The $iPas^2$ software was modified to include the capability to measure the average film thickness of asphalt mortar between the contact zones of aggregates. Due to the limitations of the planar imaging tool, for this analysis mortar is defined as asphalt binder plus aggregates passing the 1.18 mm sieve. This modification was made based on recent research that established a relationship between development of aggregate structure and mortar viscosity.

Work Planned: Summarize the measurement and analysis procedure for characterization of the aggregate structure through use of planar imaging in AASHTO format. Present results and contribution to the current state of practice to the FHWA Mixture ETG. Work is also planned to verify the use of 2-D imaging through comparison to 3-D x-ray scanned images of asphalt mixture samples.

Delivery Dates
Completion Date: 3/31/2013

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
Subtask E1c-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: A standard was submitted to ASTM and assigned to committee D4-20. The GPDA device was developed and data analysis automated. The research team is currently working with Mathy Construction to develop a laboratory based precision and bias statement.

Work Planned: The precision and bias testing will be completed and data analyzed for inclusion of precision and bias statement in standard. The next ASTM meeting is December 2012.

Delivery Dates
Finalize ASTM Standard: 3/31/2013

TEST 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

On-Going Technical Research
Sub-subtask F3a-1.2. Develop algorithms and methods for directly linking molecular simulation outputs and phase field inputs (URI, VT)
Sub-Subtask F3a-2.5: Simulations of crack propagation under mode II loading and mixed-mode loading

Subtask F3a-3. Overall integration for multiscale modeling (VT, URI, and WRI)
Subtask F3a-4. Experimental verification and validation (VT, URI, and WRI)
Sub-Subtask F3a-4.1. Molecular mechanics simulations of asphalt-aggregate interfaces (VT)
Sub-Subtask F3a-4.2. Modeling of fatigue behavior at atomic scale (VT)
Sub-Subtask F3a-4.3. Modeling of moisture damage (VT)
Sub-Subtask F3a-4.4. ab initio Calculations of Asphalt Molecular Structures and Correlation to Experimental Physico-Chemical Properties of SHRP Asphalts (WRI-TUDelft)

Efforts are currently focused on simulations of mode II cracking. After completion of model validation by mode I and model II cracks, efforts will focus on crack propagation under mixed-mode loading, which is closer to the real pavement situation. The numerical results will be compared with available experiments.

DRAFT AASHTO METHOD: EVALUATE HEALING USING CONTINUUM DAMAGE APPROACH

Included Work Elements/Subtasks
Work element F1d.

Status and Work Planned

Verification tests for this procedure are currently under way and on schedule. We expect to have a draft of the test procedure next quarter.

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. (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.

Luo, R., and Lytton, R. L. (2012). "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.

Test method document:

The test method requires a determination of the effect of absorbed asphalt on the viscoelastic properties of the aggregate. Other relevant tests are being conducted on fine aggregate mixtures. The tests on columns of aggregate soaked in asphalt are underway. At the conclusion of these tests and data analysis, a draft of the test method document will be initiated.

FHWA delivery to be determined.

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

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

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

Preliminary development of this test method and proof-of-concept experiments have been completed. Additional testing designed to refine and improve this methodology will continue in the next quarter

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 planned.

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

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

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 is currently under way.

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

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

Status and Work Planned
Completed

Work Completed: Summarized measurement and analysis method for use of linear stationary laser profiler (SLP) to analyze the surface texture of laboratory and field compacted samples of asphalt mixtures. Procedure was submitted in AASHTO format for consideration to Mix ETG.

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.

Delivery Dates
Completion Date: 9/30/2012

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:

- Conducted a literature review to evaluate feasibility of the TCModel, ILLI-TC model to be adopted and improved to include the findings from this work element.
- Continued the modeling effort for improving the temperature profile prediction subroutine
- Continued working on the subroutine to predict asphalt pavement oxidation.
- Conducted several meetings between UNR and UWM teams to discuss the various components of the thermal stress analysis tool.

The following list the work planned for next quarter:

- Validate the developed software subroutine to predict temperature profile in asphalt layer using LTPP data.
- Complete and validate the software subroutine to predict the carbonyl area growth as a function of time.
- Work on the uniaxial continuum model software to calculate thermal 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 following list describes the work items completed or in progress this quarter:

- Debugging technical errors of the new version (2.0).
    - Version 2.0 was beta-tested under a variety of conditions to find compilation and other errors. All of them have been fixed.
- Developed the User Guide, which includes Help Menu along with five worked examples to help the user. This 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 worked examples lead the user through a series of steps so that the user becomes familiar with all aspects of the steps associated with the input.
- Included the principal stresses and strains responses in the output.

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-3. Overall integration for multiscale modeling (VT, URI, and WRI)

Subtask F3a-4. Experimental verification and validation (VT, URI, and WRI)

Status and Work Planned

Work progress-On Schedule. Report decision – delayed by one 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.

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

MODEL: PHASE FIELD MODEL OF ASPHALT BINDER FRACTURE
SOFTWARE: COMSOL CODE FOR PHASE FIELD MODEL OF ASPHALT BINDER FRACTURE

In the state-of-the-art research of asphalt cracking, the single mode cracking, especially the Mode I cracking, has been studied by many researchers. However, there is a lack of theoretical and experimental research on mixed-mode cracking, which is more reasonable and realistic than pure modes. In this research, the phase-field method is adopted to solve the complex mixed-mode cracking of asphalt.

In phase-field model, the potential energy can be denoted by $\boldsymbol{\Psi} = \boldsymbol{\Psi}(\phi, \varepsilon_{ij}, x_i)$, where the variables in the brackets are phase field variable, stain tensor, and spatial coordinates. This potential energy gives the generalized Eshelby tensor

$$\boldsymbol{b} = \boldsymbol{\Psi}\mathbf{1} - \nabla\mathbf{u}^{\mathrm{T}}\sigma - \frac{\partial\boldsymbol{\Psi}}{\partial\nabla\phi}\nabla\phi, \tag{1}$$

which can be divided into an elastic part

$$\boldsymbol{b}^{el} = ((\frac{E(\phi)}{2(1+\nu)}(\frac{\nu}{1-2\nu}(\varepsilon_{ii})^2 + \varepsilon_{ik}\varepsilon_{ik}))\delta_{ij} - \nabla\mathbf{u}^{\mathrm{T}} \cdot \boldsymbol{\sigma} \tag{2}$$

and a surface part

$$\boldsymbol{b}^{gr} = \left(\frac{\lambda}{4\epsilon^2}(1-\phi)^2(1+\phi)^2 + \frac{1}{2}\lambda|\nabla\phi|^2\right)\delta_{ij} - \frac{\partial\boldsymbol{\Psi}}{\partial\nabla\phi} \cdot \nabla\phi. \tag{3}$$

For a straight crack, a contour integral of the Eshelby tensor along a closed curve that encloses the crack tip leads to the crack propagation criterion in phase-field calculations:

$$J = \int_{\partial\Omega} \boldsymbol{e_1} \cdot \boldsymbol{b}^{el} \cdot \boldsymbol{n}\, ds \geq 2\gamma. \tag{4}$$

Here $\boldsymbol{e_1}$ is the unit vector in the crack direction, $\boldsymbol{n}$ is the unit normal to the closed curve, and γ is the surface tension in the phase-field model. Apparently, this criterion is consistent with the Griffith theory.

Figure 1 gives the mixed-mode crack propagation at different time instants and figure 2 shows that there is a stress concentration at the crack tip. In the region near the crack tip, the von Mises stress is much larger than that in the intact regions in front of the crack. Immediately above and below the crack, the stress is much lower than the average since the elastic energy has been released to create new fracture surface area.

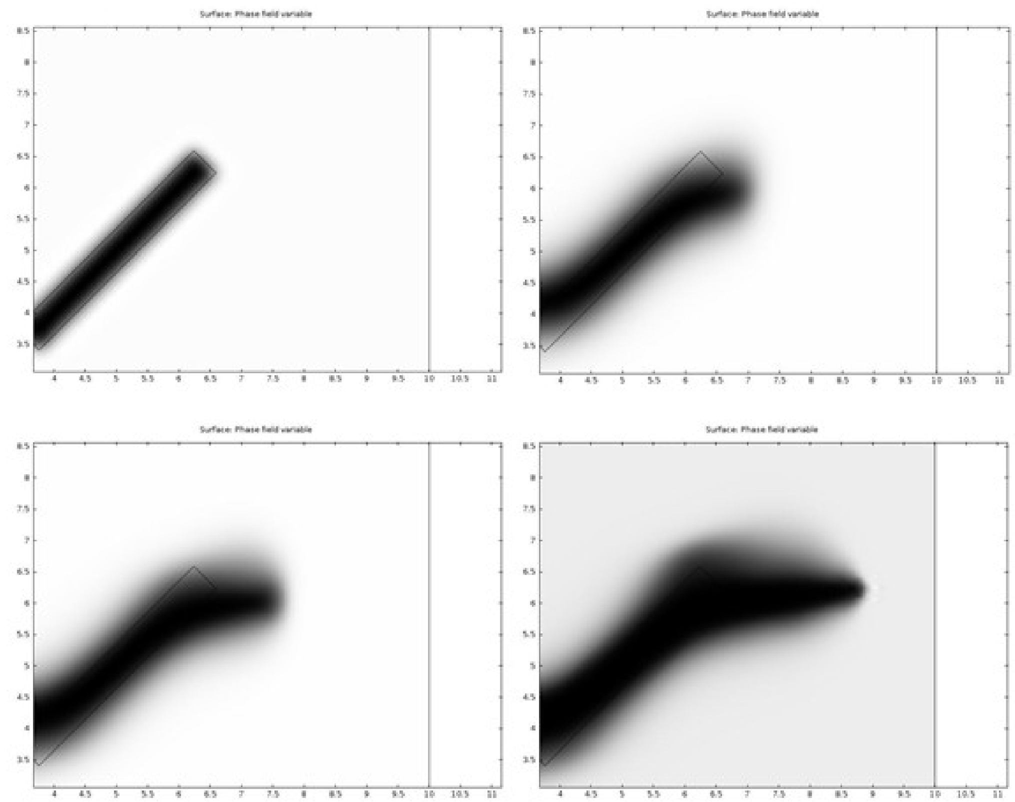

Figure 1. Magnified view of crack propagation. The material is under a tensile stress in the vertical direction.

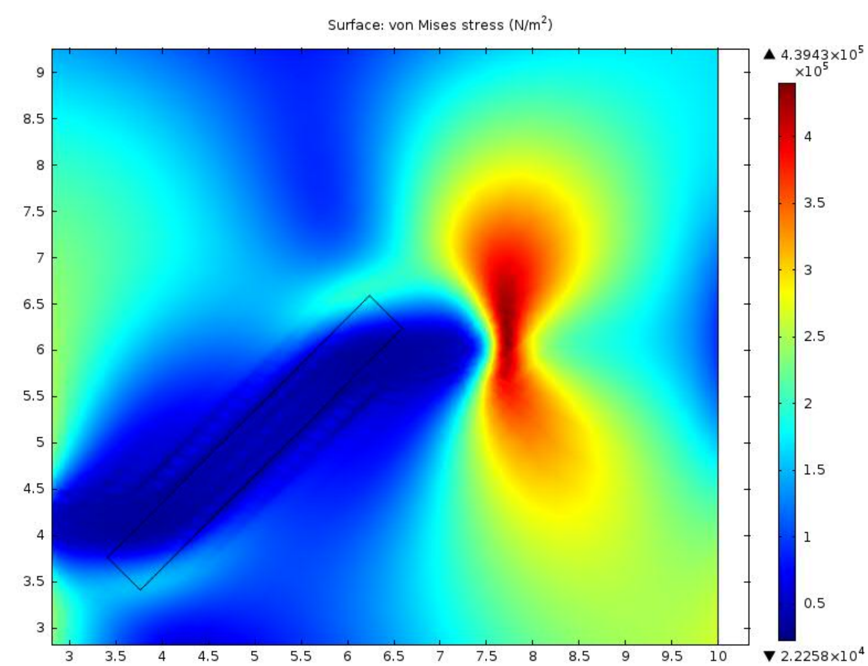

Figure 2. A typical distribution of von Mises stress at the crack tip.

SOFTWARE: PANDA: PAVEMENT ANALYSIS USING A NONLINEAR DAMAGE APPROACH

Included Work Elements/Subtasks

Status and Work Planned

There are two main products of the PANDA model; the PANDA-Abaqus subroutine and the PANDA standalone finite element software. The PANDA-Abaqus subroutine is complete and is currently under testing for removing any errors and bugs and for increasing its computational efficiency. User friendly interface has been created for PANDA-Abaqus. This 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. The simulations can be conducted in both 2D and 3D modes. This interface has the following capabilities: it considers a four-layered system; thickness of each layer can be controlled by the user; moving speed can be controlled by the user; asphalt concrete layer can be modeled as viscoelastic, viscoplastic-viscoplastic, or coupled viscoelastic-viscoplastic-viscodamage; while the other layers are intended to be modeled as elastic, the built-in models in Abaqus can also be used to model the other layers as plastic/viscoplastic materials. The focus will be placed on improving this interface.

At this point, an alpha version of the PANDA standalone finite element software is available. 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

Status and Work Planned

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

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

Work Done This Quarter

The blending mechanisms of oil extenders with asphalt was investigated through advanced TG measurements systems using the Modulated Differential Scanning Calorimetry (MDSC), as well as rheological tests. Mixture samples have been prepared using oil modification and will be evaluated using newly developed Asphalt Thermal Cracking Analyzer (ATCA) test method in next quarter. A request for input was prepared and distributed at the FHWA Binder ETG meeting to identify the most promising and important types of extender oils. Based on ETG feedback aromatic/parraffinic oil, waste oil, and tall oil pitch were identified as extenders to be included in this subtask.

Work Planned Next Quarter

Efforts will continue in finalizing blending mechanism and procedure. Mixture performance tests will be conducted to assess advantages and disadvantages, as well as possible implications to compactability and coating. Tests using gel permeation chromatography (GPC) will be conducted to investigate the chemical nature of oil extender effect. The scope of study will be expanded based on the high priority extender oils identified by the ETG.

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 Recycle Mixes

Work Done This Quarter

The evaporative thin film residue recovery study was postponed pending further review of the literature and consultation with industry. A framework for fresh emulsion characterization was proposed and implemented to evaluate of seven emulsions including slow, medium, rapid, and quick setting types. Field sections using these emulsions have been constructed. Many of the emulsions used included polymer modification. Residue has been recovered but has not been tested at the time of reporting. Test methods include a developmental ‘three-step-shear’ viscosity test using the Brookfield RV (see publications), a modified storage stability test, and a curing and compatibility test using the Bitumen Bond Strength (BBS) test. Initial work to correlate the fresh binder properties with coating in CMA using emulsion rheological properties (viscosity, etc.) has also begun. It is anticipated that the fresh binder testing will be coupled with residue characterization to produce a specification framework similar to the traditional Superpave PG tables for hot binder.

A chip seal raveling study is ongoing that is expected to provide critical emulsion properties leading to raveling distresses in fresh chip seals and after extended aging (field service). Initial results indicate that aggregate-emulsion bond strength development as measured with the BBS dictates early chip loss while strain tolerance (determined using the linear amplitude sweep test) is highly correlated with late raveling in the chip seals. Two emulsion types have been evaluated including one modified (CRS-2P).

Work Planned Next Quarter

Residue testing of the aforementioned emulsions will be completed with several candidate test methods and aging conditions. Based on discussion with industry and state agencies evaluation of residue recovery methods will resume. The candidate test methods identified include the ASMT D7497 Method B and thin film recovery on an aluminum substrate in the vacuum oven. Field assessment of the emulsion performance will be correlated to residue and fresh emulsion properties to identify critical response parameters. Similarly, emulsions used for CMA will be evaluated using the proposed specification system and critical properties will be identified through correlation with performance testing.

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.

Work Element E3c: Laboratory Assessment of Mixture Long Term Aging

Work Done This Quarter

A number of possible mechanisms for effects of mineral filler on long term aging have been identified this quarter based on the analysis of experimental data using DSR and BBS tests and literature review. The scope of a PhD thesis was defined to investigate these mechanisms further through analysis of effect of aging on chemical-physical interaction of aggregate mineral filler using BET testing and other chemical/physical analysis tools.

Work Planned Next Quarter

Results of advanced study of aggregate mineral filler and asphalt interactions during aging will be used to expand current binder aging models to include effect of aggregate and used to develop a simple laboratory long term aging procedure using mastics at UW. Mixture and field performance data from UNR will be used to substantiate conclusions and formulate possible mixture aging mechanisms.

Proposed Research Product and Timeline

Results will be summarized in a final report titled: "Laboratory Assessment of Long Term Aging of Asphalt Mixtures"
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

Work Done This Quarter

Monitoring of the Manitoba WMA sections was conducted in August 2012. The Yellowstone WMA sections were monitored in September 2012. It was noted that sometime during the summer the Yellowstone maintenance department placed a chip seal on 5 of the 9 monitoring sections. This effectively ends the performance monitoring of the Yellowstone sections.

Work Planned Next Quarter

No WMA monitoring is planned in the next quarter.

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

Work Done This Quarter

The Manitoba RAP sections and the Minnesota asphalt source sections were monitored in August 2012.

The ARC, Ohio DOT, and Ohio University collaborated to place new experiments on LTPP SPS-1, SPS-2, SPS-8, and SPS-9 sections that were reconstructed or rehabilitated on U.S. 23 in Delaware County in September 2012. Some of the sections were reconstructed as perpetual pavement sections with significant instrumentation and material sampling for calibration of PANDA. The SPS-9 sections were rehabilitated using two different binder sources (from different crudes/blends) in the mill and fill construction. The construction milled and filled 1 ¾ inches using two different source asphalts from Shelly Materials (contractor) and NuStar Paulsboro. Both asphalts were PG 70-22 modified asphalts. The Ohio DOT required that foaming technology be used in production of the mix but the actual temperature of mixing and compaction is still to be determined from the construction sheets. Ohio University personnel sampled construction materials for the ARC on the sections where two sources were used whereas personnel from the University of Illinois sampled materials from the perpetual pavement sections.

Personnel from WRI traveled to Ohio in late September to prepare and ship the sampled materials from both the crude source and perpetual pavement sections. Most of the shipped material was sent to the LTPP Materials Library in Sparks, Nevada.

Also during the quarter, discussions continued with Arizona DOT on placing new RAP sections in Arizona using asphalts from two different crude sources. The project identified is on SR 74 just north of the Phoenix metro area. The project will contain two hot-mix sections using the different asphalt sources; two 20% RAP sections (one from each source); and two 30% RAP sections (one from each source. Construction is expected in the late fall 2012. A pre-construction meeting is planned for October 17, 2012.

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. It is also planned to monitor the Arizona sections placed in 2001.