Asphalt Research Consortium

Quarterly Technical Progress Report
January 1-March 31, 2013

April 2013

Prepared for
Federal Highway Administration
Contract No. DTFH61-07-H-00009

By
Western Research Institute
Texas A&M University
University of Wisconsin-Madison
University of Nevada-Reno
Advanced Asphalt Technologies
National Center for Asphalt Technology

www.westernresearch.org
www.ARC.unr.edu

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INTRODUCTION

This document is the Quarterly Report for the period of January 1 to March 31, 2013 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 January 1 to March 31, 2013 is the fourth quarter of the Year 6 contract year. Reviewers may want to reference the previous Annual Work Plans and many other documents that are posted on the ARC website, www.ARC.unr.edu. The more detailed information about the research such as approaches to test method development, data collection, and analyses will be reported in research publications as part of the deliverables.

SUPPORT OF FHWA AND DOT STRATEGIC GOALS

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

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

Deliverable	Description	Draft Delivery Date	Final Delivery Date	ARC Partner	Staff Assignment	Notes
Summary Report	Comprehensive Summary Report (Level 1) (Report summarizing all work elements in significant detail to provide a single source documentation of ARC accomplishments)	4/30/2013	12/15/2013	TAMU	All	Reference level 2 and 3 deliverables for details
Report A	Summary report on Moisture Damage (Level 2)	1/31/2013	9/30/2013	TAMU	Masad	Sent to FHWA for review, Reference level 3 deliverables for details
Report B	Characterization of Fatigue Damage and Relevant Properties (Level 2)	5/31/2013	10/31/2013	TAMU	Bhasin	Reference level 2 and 3 deliverables
Report C	PANDA: Pavement Analysis using a Nonlinear Damage Approach (Level 2)	5/31/2013	11/30/2013	TAMU	Darabi	Summary of PANDA methodology including descriptions of methods for indentifying model parameters

Deliverable	Description	Draft Delivery Date	Final Delivery Date	ARC Partner	Staff Assignment	Notes
Report D	Characterization of Asphalt Binders using Atomic Force Microscopy (Level 2)	5/31/2013	10/31/2013	TAMU	Little	Summary report on methodology for characterizing the phases of asphalt binder with description of composite implications
Report E	Lattice Model and Continuum Damage to Fracture (Level 2)	5/31/2013	9/30/2013	NCSU	R. Kim	Comprehensive report on lattice model
Report F	Microstructure Cohesive Zone Modeling for Moisture Damage and Fatigue Cracking (Level 2)	1/31/2013	8/31/2013	UNL	Y.R. Kim	Sent to FHWA for review, Comprehensive report on cohesive zone model
Report G	Design System for HMA Containing a High Percentage of RAP Material	12/31/2013	3/31/2014	UNR	Sebaaly Hajj	
Report H	Critically Designed HMA Mixtures	5/31/2013	11/30/2013	UNR	Hajj Sebaaly	Comprehensive report describing the developed mechanistic-based approach for critically designed mixtures
Report I	Thermal Cracking Resistant Mixes	8/31/2013	12/31/2013	UNR	Hajj Sebaaly	

Deliverable	Description	Draft Delivery Date	Final Delivery Date	ARC Partner	Staff Assignment	Notes
Report J	Pavement Response Model to Dynamic Loads 3D Move	9/30/2013	12/31/2013	UNR	Hajj Sebaaly	Delayed. Research team focused on addressing and solving the various bugs reported by the users for newly released Ver. 2 of the software
Report K	Development of Materials Database including Data Quality Act Compliance	6/30/2013	12/31/2013	UNR	Hajj Ekedahl	
Report L	Development and Validation of the Bitumen Bond Strength Test (BBS)	Completed 10/31/11	6/30/2013	UWM	Hanz	Extended to incorporate new information from NCHRP 9-50
Report M	Development of Test Procedures for Characterization of Asphalt Binder Fatigue and Healing	Completed 10/31/11	6/30/2013	UWM	Tabatabaee	Final pending receipt of peer review comments
Report N	Guideline for Selection of Modification Techniques	9/30/2013	3/31/2014	UWM	Tabatabaee	On schedule
Report O	Characterization of Binder Damage Resistance to Rutting	6/30/2013	12/31/2013	UWM	Tabatabaee	On schedule
Report P	Quantifying the Impacts of Warm Mix Asphalt on Constructability and Performance	9/31/2013	12/31/2013	UWM	Hanz	Draft extended 6 months
Report Q	Improvement of Emulsion Characterization and Mixture Design for Cold Bitumen Applications	9/30/2013	3/31/2014	UWM	Hanz	On schedule
Report R	Studies on Tire-Pavement Noise and Skid Response	Completed 12/31/11	6/30/2013	UWM	Roohi	On schedule

Deliverable	Description	Draft Delivery Date	Final Delivery Date	ARC Partner	Staff Assignment	Notes
Report S	Molecular dynamics results for multiple asphalt chemistries	5/31/2013	12/31/2013	URI	Greenfield	
Report T	Progress Toward a Multi-scale Model of Asphalt Pavement- Including Test Methods for Model Input Parameters	9/30/2013	3/31/2014	WRI	Pauli	Delayed because of Delft finite element work
Report U	Design Guidance for Fatigue and Rut Resistance Mixtures	9/30/2013	3/31/2014	AAT	Bonaquist Christensen	NTIS format report with Technical Brief
Report V	Continuum Damage Permanent Deformation Analysis for Asphalt Mixtures (Level 2)	5/31/2013	10/31/2013	TAMU	Lytton/Luo	Reference appropriate level 3 deliverables
Report W	Characterization of Fatigue and Healing Properties of Asphalt Mixtures (Level 2)	5/31/2013	10/31/2013	TAMU	Lytton/Luo	Reference appropriate level 3 deliverables
Report X	Characterization of Field Cores of Asphalt Pavements (Level 2)	5/31/2013	10/31/2013	TAMU	Lytton/Luo	Reference appropriate level 3 deliverables
Report Y	Water Vapor Diffusion in Pavement and Its Effects on the Performance of Asphalt Mixtures (Level 2)	5/31/2013	11/30/2013	TAMU	Lytton/Luo	Reference appropriate level 3 deliverables
Report Z	Effect of Extraction Methods on the Properties of Aggregates in Reclaimed Asphalt Pavement (NTIS format)	Completed 3/1/2013		UNR	Hajj Sebaaly	Final pending receipt of peer review comments
AASHTO Method	Simplified Continuum Damage Fatigue Analysis for the Asphalt Mixture Performance Tester	5/31/2013	9/30/2013	AAT	Bonaquist Christensen	Development documented in Report U

Deliverable	Description	Draft Delivery Date	Final Delivery Date	ARC Partner	Staff Assignment	Notes
AASHTO Method	Wilhelmy Plate Test (Level 3)	1/31/2013	6/30/2013	TAMU	Bhasin	Sent to FHWA for review, Referenced in Reports A & B
AASHTO Method	Universal Sorption Device (Level 3)	1/31/2013	6/30/2013	TAMU	Bhasin	Sent to FHWA for review, Referenced in Reports A & B
AASHTO Method	Dynamic Mechanical Analysis (Level 3)	1/31/2013	6/30/2013	TAMU	Kassem	Sent to FHWA for review, Referenced in Reports A & B
ASTM Method	Automated Flocculation Titrimetric Analysis	Completed		WRI	Pauli	ASTM D-6703
AASHTO Method	Determination of Polymer in Asphalt	Completed		WRI	Harnsberger	
AASHTO Method	A Method for the Preparation of Specimens of Fine Aggregate Matrix of Asphalt Mixtures (Level 3)	1/31/2013	6/30/2013	TAMU	Kassem	Sent to FHWA for review, Referenced in Reports A & B
AASHTO Method	Measuring intrinsic healing characteristics of asphalt binders	1/31/2013	6/30/2013	TAMU/ UT	Bhasin	Sent to FHWA for review, Referenced in Report B
AASHTO Method	Test Methods for Determining the Parameters of Material Models in PANDA (Pavement Analysis Using Nonlinear Damage Approach) (Level 3)	5/31/2013	7/31/2013	TAMU	Kassem Darabi	Referenced in Report C
Test Method & Model	Continuum Damage Permanent Deformation Analysis for Asphalt Mixtures (Level 3)	5/31/2013	10/31/2013	TAMU	Lytton/Luo	Referenced in Report V

Deliverable	Description	Draft Delivery Date	Final Delivery Date	ARC Partner	Staff Assignment	Notes
Test Method & Model	Characterization of Fatigue and Healing Properties of Asphalt Mixtures (Level 3)	5/31/2013	9/30/2013	TAMU	Lytton/Luo	Referenced in Report W
Test Method Analysis Program	Nondestructive Characterization of Tensile Viscoelastic Properties of Undamaged Asphalt Mixtures (Level 3)	5/31/2013	10/31/2013	TAMU	Lytton/Luo	Referenced in Reports W & Y
Test Method & Model	Characterization of Field Cores of Asphalt Pavements (Level 3)	5/31/2013	10/31/2013	TAMU	Lytton/Luo	Referenced in Reports W & X
Test Method Analysis Program	Nondestructive Characterization of Anisotropic Viscoelastic Properties of Undamaged Asphalt Mixtures under Compressive Loading (Level 3)	5/31/2013	10/31/2013	TAMU	Lytton/Luo	Referenced in Report V
AASHTO Practice	Mix Design for Cold-In-Place Recycling (CIR)	12/31/2013		UNR	Sebaaly Hajj	Detailed in Report Q
AASHTO Practice	Mix Design for Cold Mix Asphalt	9/30/2013	3/31/2014	UWM	Hanz	On schedule
AASHTO Practice	Evaluation of RAP Aggregates	12/31/2012		UNR	Sebaaly	Detailed in Report G
AASHTO Practice	Identification of Critical Conditions for HMA mixtures	5/31/2013		UNR	Hajj Sebaaly	Detailed in Report H
AASHTO Method	Determining Thermal Crack Properties of Asphalt Mixtures Through Measurement of Thermally Induced Stress and Strain	Completed 5/31/2012		UNR	Hajj Velasquez	Detailed in Report I
AASHTO Method	Determining Asphalt Binder Bond Strength by Means of the Bitumen Bond Strength Test (BBS)	Completed	6/30/13	UWM	Hanz	Includes minimum of 3 months external peer review
AASHTO Method	Measurement of Asphalt Binder Elastic Recovery in the Dynamic Shear Rheometer (DSR)	Completed 1/31/2013	6/30/2013	UWM	Tabatabaee	On schedule

Deliverable	Description	Draft Delivery Date	Final Delivery Date	ARC Partner	Staff Assignment	Notes
AASHTO Method	Estimating Fatigue Resistance of Asphalt Binders Using the Linear Amplitude Sweep (LAS)	Completed	6/30/2013	UWM	Tabatabaee	On schedule
AASHTO Method	Binder Yield Energy Test (BYET)	Completed 1/31/2013	Complete	UWM	Tabatabaee	Combine with ER-DSR, BYET
AASHTO Method	Measurement of Rigden Voids for fillers	Completed 1/31/2013	6/30/2013	UWM	Roohi	Pending review comments
AASHTO Method	Measurement of Asphalt Binder Lubricity Using the Dynamic Shear Rheometer (DSR)	6/30/2013	12/31/2013	UWM	Hanz	Draft and final extended 3 months
AASHTO Method	Procedure for Evaluation of Coating for Cold Mix Asphalt	4/30/2013	9/30/2013	UWM	Hanz	Submission pending
AASHTO Method	Cold Mix Laboratory Specimen Preparation Using Modified SGC Molds	6/30/2013	12/31/2013	UWM	Hanz	Draft extended 6 months
AASHTO Method Software	RAP Binder PG True Grade Determination	Completed 9/30/2012	6/30/2013	UWM	Hanz	Action pending ETG comments
AASHTO Method	Measurement of Asphalt Binder Fracture Properties Using the Single Edge Notch Bending Test	Completed 9/30/2012	6/30/2013	UWM	Tabatabaee	Action pending ETG comments
AASHTO Method	Test Method for Measurement of the Glass Transition Temperature of Asphalt Binders	Completed 1/31/2013	6/30/2013	UWM	Tabatabaee	Action pending FHWA/ETG comments
AASHTO Method	Test Method for Measurement of the Glass Transition Temperature of Asphalt Mixtures	4/30/2013	6/30/2013	UWM	Tabatabaee	Combined with UNR TSRST procedure
AASHTO Method Software	Analysis of Asphalt Mixture Aggregate Structure through Use of Planar Imaging and Image Processing & Analysis System (IPAS)	4/30/2013	9/30/2013	UWM	Roohi	Submission pending

Deliverable	Description	Draft Delivery Date	Final Delivery Date	ARC Partner	Staff Assignment	Notes
AASHTO Method	Determining the Resistive Effort of Asphalt Mixtures during Compaction in a Gyrator Compactor using an Internal Device	Completed ASTM	9/30/2013 P&B testing	UWM	Hanz	ASTM Standard approved
AASHTO Method	Micromechanical Properties of Various Structural Components in Asphalt using Atomic Force Microscopy (AFM) (Level 3)	3/31/2013	8/31/2013	TAMU	Little	Sent to FHWA for review, Referenced in Report D
AASHTO Method	Test Method for Fatigue of Binder and Mastics: A cyclic direct tension test that can provide direct evaluation of fatigue for binder and mastic. It can also provide model validation and model parameter inputs.	4/30/2013	10/31/2013	VT	Wang	
AASHTO Method	Evaluate Healing using Continuum Damage Approach (Level 3)	5/31/2013	8/31/2013	TAMU/ UT	Bhasin	Appendix in Report B
Test Method & Analysis Program	Self-Consistent Micromechanics Models of Asphalt Mixtures (Level 3)	5/31/2013	10/31/2013	TAMU	Lytton/Luo	Referenced in Report W
AASHTO Method & Analysis Program	Rutting Prediction of Asphalt Binder Considering Stress-Dependence of Creep Behavior (Level 3)	5/31/2013	9/30/2013	TAMU	Little	References to Dissertation & journal papers
AASHTO Method	Method to determine surface roughness of aggregate and fines based on AFM	9/30/2013	4/30/2014	WRI	Grimes	Will be subject of Tech. Pub.
AASHTO Method	A method to determine ductile-brittle properties via AFM measurements	9/30/2013	11/30/2013	WRI	Grimes	Will be subject of Tech. Pub.
AASHTO Method	AFM-based micro/nano-scale cyclic direct tension test	4/30/2013	10/31/2013	WRI	Grimes	Will be subject of Tech. Pub.

Deliverable	Description	Draft Delivery Date	Final Delivery Date	ARC Partner	Staff Assignment	Notes
AASHTO Method	Measurement and Texture Spectral Analysis of Pavement Surface Profiles Using a Linear Stationary Laser Profiler (SLP)	Completed 9/30/2012	3/31/2013	UWM	Roohi	Pending FHWA review
Model	HMA Thermal Stresses in Pavement	3/31/2014		UNR	Hajj	Detailed in Report I
Software	Dynamic Model for Flexible Pavements 3D-Move	9/30/2013		UNR	Hajj Siddharthan	Detailed in Report J
Model & Test Method	Improved Oxygen and Thermal Transport Model of Binder Oxidation in Pavements (Level 3)	5/31/2013	10/31/2013	TAMU	Glover	Part of Report B & Summary Report References to Dissertations and Journal Papers
Model & Test Method	Pavement Air Voids Size Distribution Model for use in an Oxygen and Thermal Transport Model of Binder Oxidation in Pavements (Level 3)	5/31/2013	10/31/2013	TAMU	Glover	Part of Report B & Summary Report References to Dissertations and Journal Papers
Model	Approaches to interpret MD simulation results and experimental data to quantify the composition and temperature dependence of free energy.	3/31/2013		URI	Greenfield	Detailed in Report S
Model and Software	Phase-Field Model of Asphalt Binder Fracture and COMSOL Code for Model	9/30/2013	3/31/2014	VT	Wang	Detailed in Report T
Software	PANDA Software (Pavement Analysis using a Nonlinear Damage Approach)	12/31/2013	6/20/2014	TAMU	Sun-Myung Kim	
Model and Software	Lattice Micromechanical for Virtual Testing of Asphalt Concrete in Tension	3/31/2013	9/30/2014	NCSU	Richard Kim	Detailed in Report E

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.

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

Status and Work Planned:
On schedule.

As mentioned in the previous quarter, the developed viscoelastic characterization (VEC) test protocol can be applied to characterize stiffness variations in field cores by the stiffness gradient profile. In this quarter, the VEC test was conducted on 8 field specimens from Yellowstone National Park (YNP), which have been aged for four years. The field cores are collected from both shoulder and wheel-path of the two sections of YNP, which are the Advera warm mix asphalt (AWMA) section labeled as 1-2, and the Sasobit warm mix asphalt (SWMA) section labeled as 1-3. Each field core contains both top and bottom layers, which were separated before testing. The field cores were cut into two rectangular specimens and then were used for the Direct Tension Test at 10°C and 20°C, respectively.

Table 1 summarizes the results of the stiffness gradient calculation for YNP field specimens. According to the results in table 1, the stiffness gradient profiles for each specimen are generated as shown in figures 1 to 4. The results of the stiffness gradient profiles can be used to characterize field cores as functionally graded material (FGM) in finite element models.

Table 1. Stiffness gradient profile for YNP field specimens.

Specimen ID	Temperature (°C)	n	k	Bottom Modulus (ksi)	Surface Modulus (ksi)
1-2B-Top-WP	10	4.08	2.27	301	684
1-2B-Bot-WP	10	4.11	1.76	213	374
1-2B-Top-S	10	4.94	2.09	311	651
1-2B-Bot-S	10	3.92	1.64	231	379
1-3B-Top-WP	10	4.28	1.70	321	546
1-3B-Bot-WP	10	4.90	1.35	271	364
1-3B-Top-S	10	4.90	1.89	251	476
1-3B-Bot-S	10	4.93	1.65	195	322
1-2B-Top-WP	20	4.09	2.01	221	444
1-2B-Bot-WP	20	3.74	1.66	144	239
1-2B-Top-S	20	4.13	2.31	203	469
1-2B-Bot-S	20	4.15	1.83	147	270
1-3B-Top-WP	20	4.10	2.05	200	410
1-3B-Bot-WP	20	3.80	1.64	150	245
1-3B-Top-S	20	4.21	2.34	148	346
1-3B-Bot-S	20	4.34	1.52	139	211

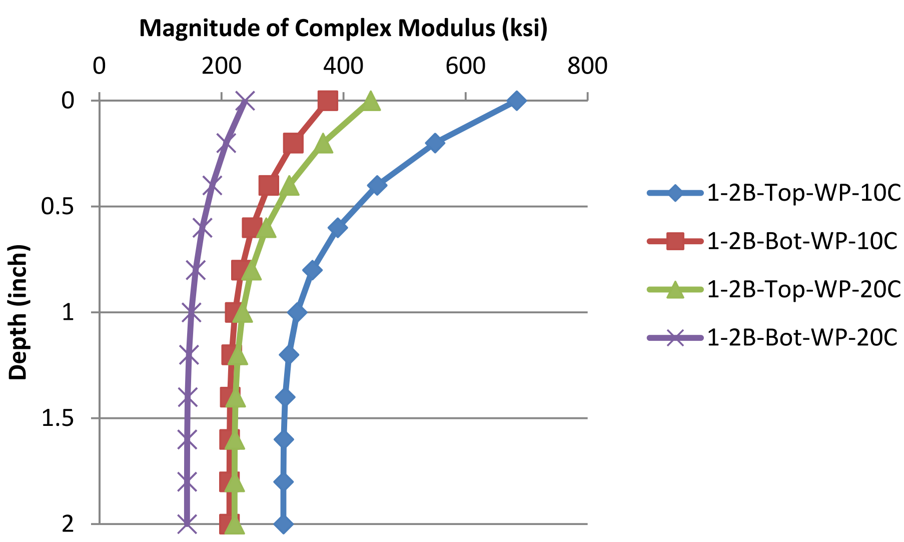


Figure 1. Complex moduli of wheel-path core in AWMA section at different temperature.

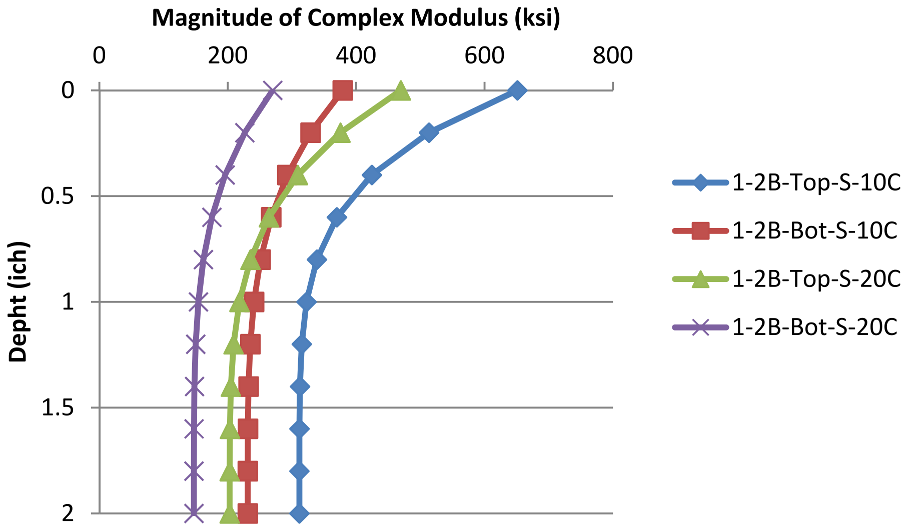


Figure 2. Complex moduli of shoulder core in AWMA section at different temperature.

Work Element E1a: Analytical and Micro-mechanics Models for Mechanical Behavior of Mixtures
Subtask E1a: Characterize Moisture Susceptibility of FAM

Status and Work Planned
Status: on schedule.

In this quarter, three tasks are completed:

1. Chapter 3: The Use of a DMA to Quantify Moisture Damage in Asphalt Mortars for the report of 'Moisture Damage of Asphalt Pavements: Mechanisms, Characterization, Prediction and Numerical Modeling' was drafted and submitted for review.

2. The Level 2 Report Y: 'Water Vapor Diffusion in Pavement and Its Effects on the Performance of Asphalt Mixtures' was drafted and submitted for review.

3. Part of the Chapter 5: Influence of State of Stress and Permanent Deformation Fracture and Healing in asphalt mixtures for the comprehensive fatigue report was also drafted and submitted for review.

REPORT B: CHARACTERIZATION OF FATIGUE DAMAGE AND RELEVANT PROPERTIES

The first draft of Report B is complete and is currently being reviewed by a professional editor before being advanced for submission and publication.

Other notes to be added if necessary depending on the format:

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 and has also been included in Chapter 7 of Report B on fatigue damage and other material properties. The work currently in progress expands and applies the reported findings to quantify the nonlinear response and damage in asphalt mortars.

Work Element F1d: Healing

Status and Work Planned: On schedule. We have completed the work associated with characterizing the intrinsic healing of asphalt binders as well as the overall healing in asphalt composites (mortars) using the viscoelastic continuum damage or work potential theory. The findings on these two aspects of healing are included in Report B. Protocols to quantify intrinsic as well as overall healing in AASHTO format have also been included in Report B. The work currently in progress is to further reinforce the efficacy of the proposed test methods.

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 previous quarters we have completed work on modeling the effect 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, 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.

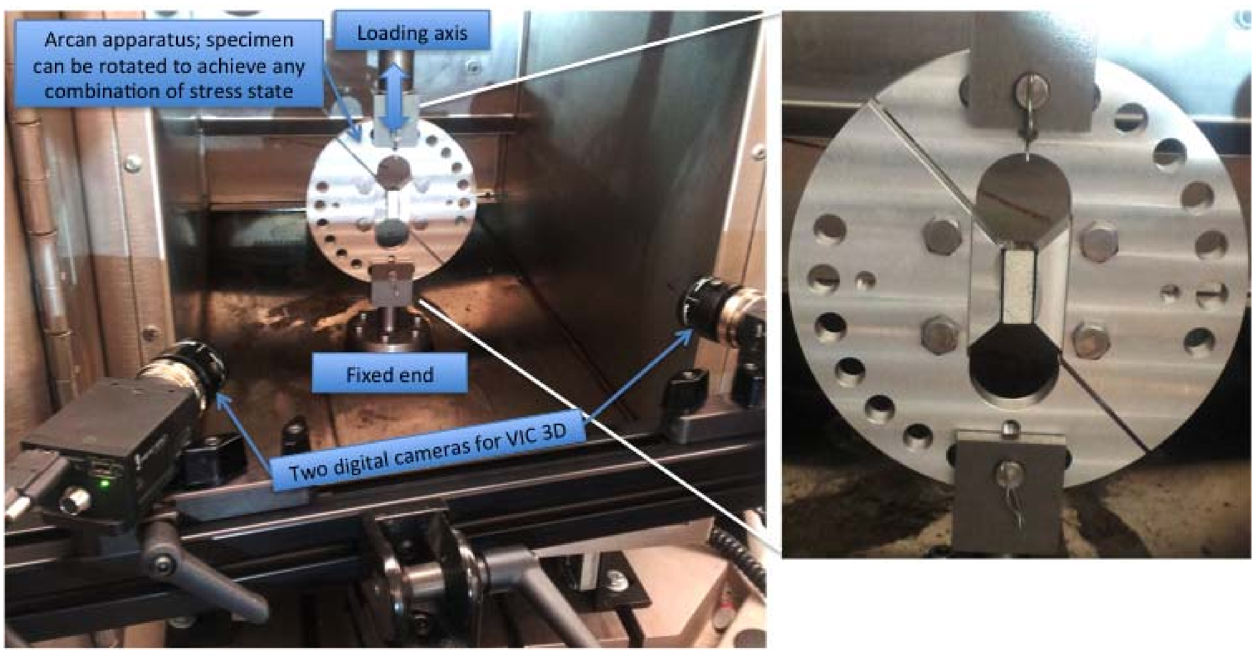


Figure F1b.1. Setup showing the VIC system to measure deformation in the test specimen in the Arcan apparatus.

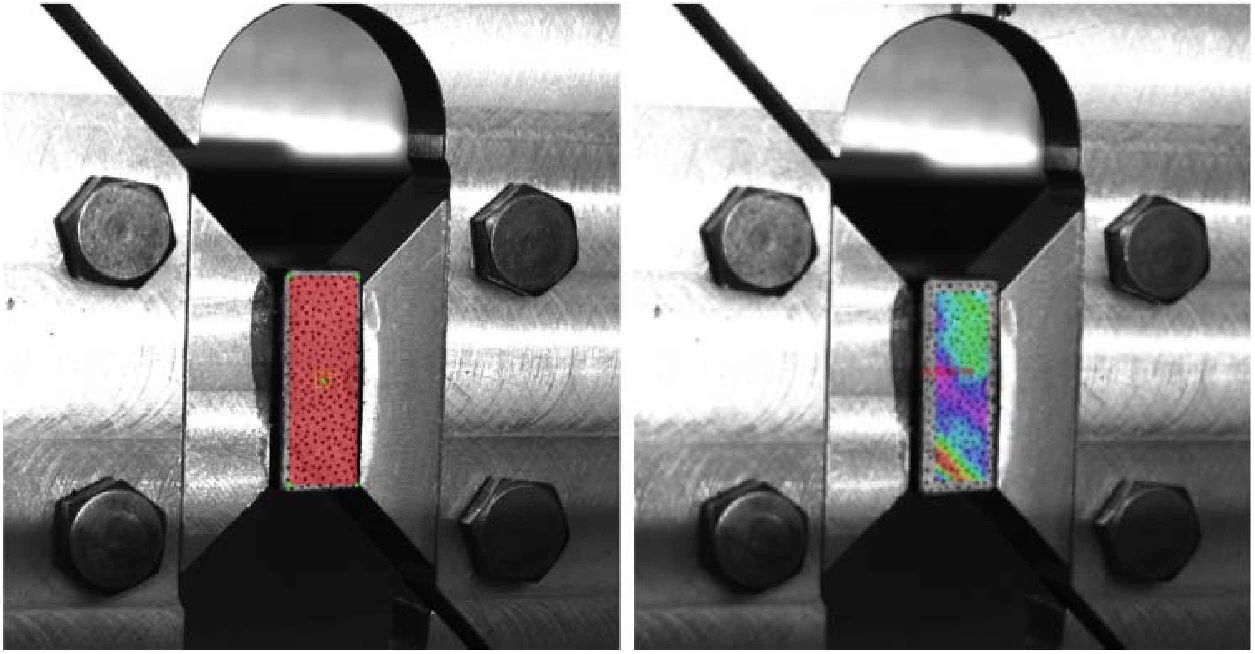


Figure F1b.2. VIC is used to measure the three dimensional strain field on an area of interest on the test specimen.

Work Element F1c: Material Properties: Aging

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

Status and Work Planned: Draft report submitted for editing. Final revision and editing is ongoing.

Analysis of WRI Yellowstone field cores will be conducted according to available resources as part of model validation

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°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.

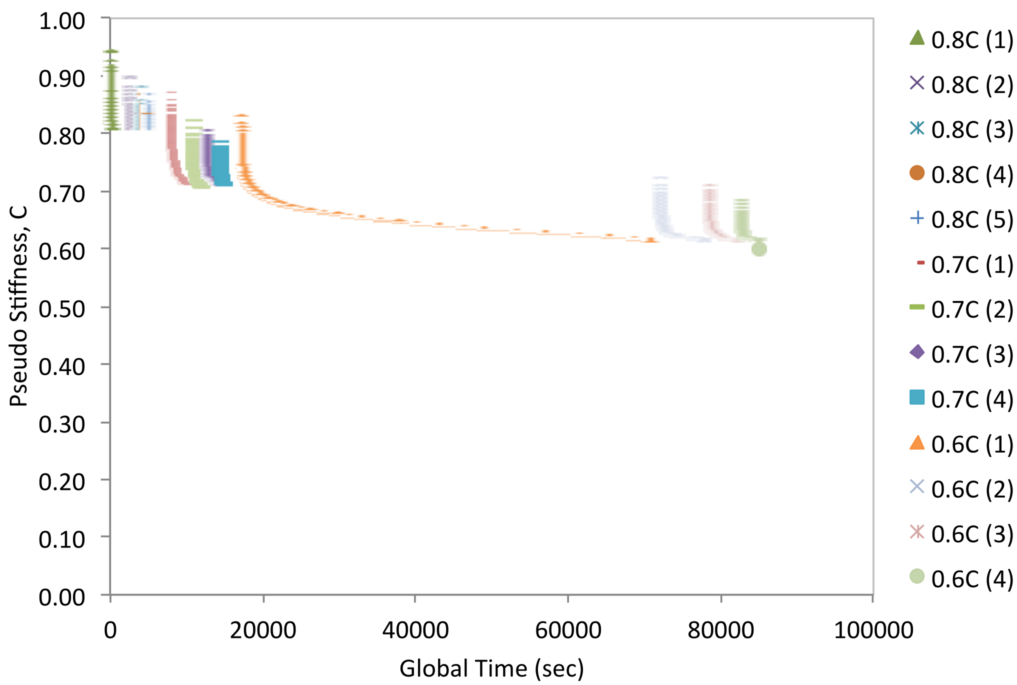


Figure F1d.1.a .Typical results multiple combinations of rest period duration and damage level. (Note: results shown are for qualitative reference only)

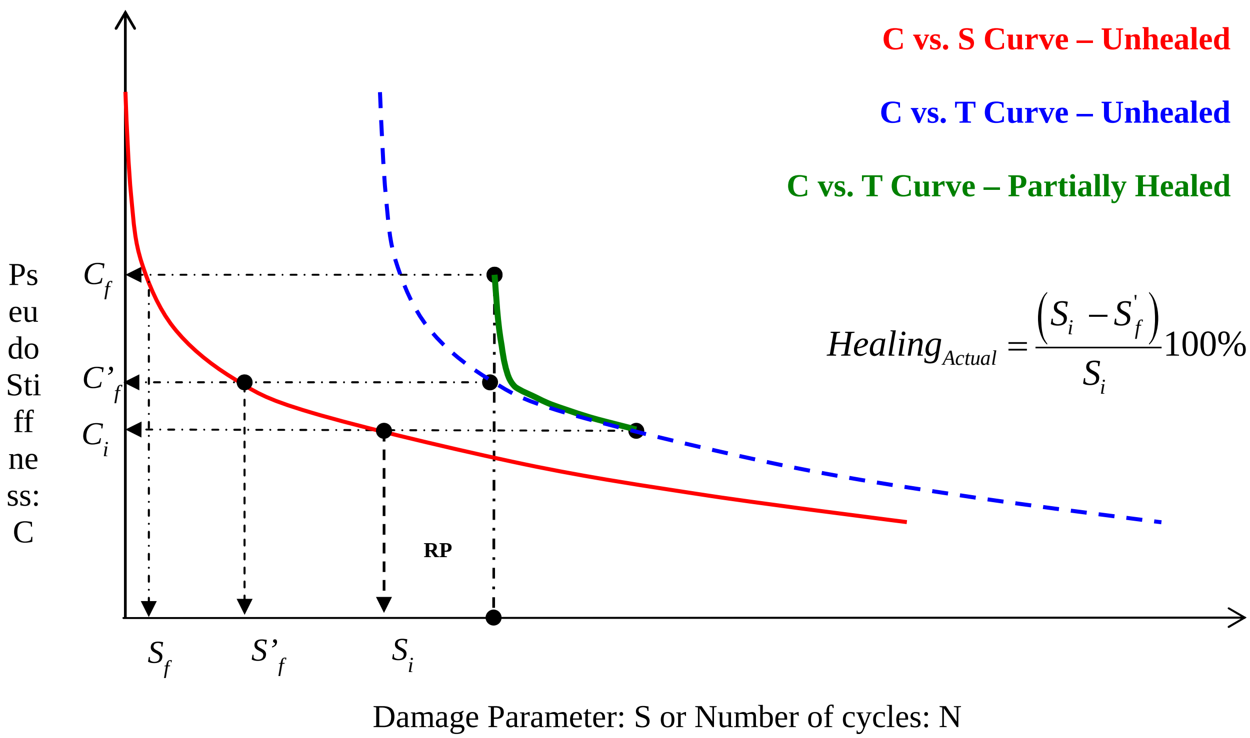


Figure F1d.1.b. Analytical method for determining the healing values from C vs. T and C vs. S curves.

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.

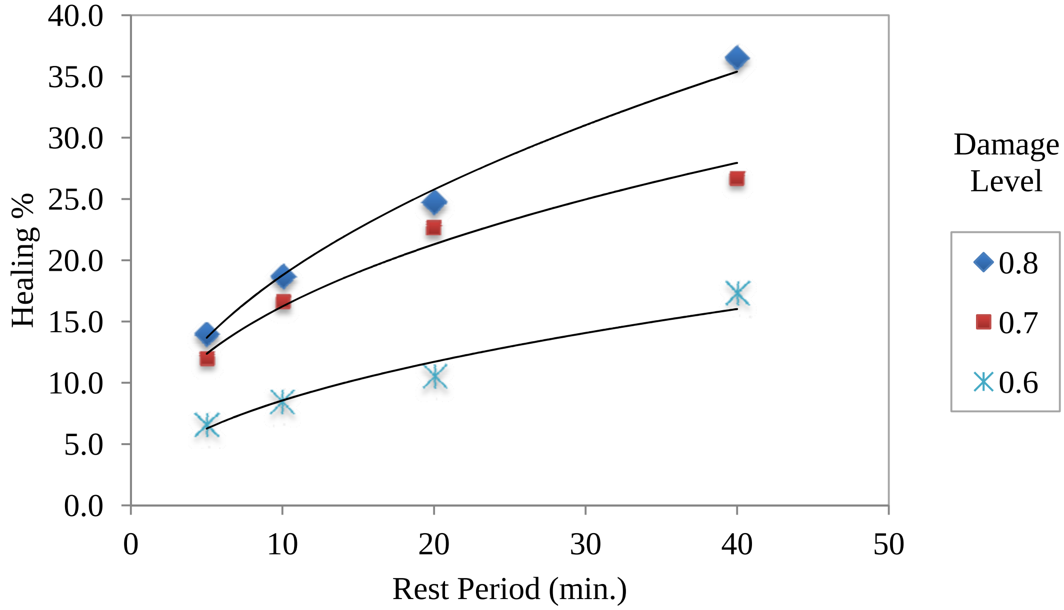


Figure F1d.2. Typical results from multiple combinations of rest period durations and damage levels (Materials: PG 67-22 binder and Limestone screenings < 1.19 mm; Geometry: 12.25mm diameter, 45 mm length; Loading: 250000 Pa, 10 Hz, 25^{o}C).

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.

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

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

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

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

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

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

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

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

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

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

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

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

<u>Status and Work Planned</u>: On Schedule. In this quarter, a technical presentation entitled "Mechanistic Modeling of Fracture in Asphalt Mixtures under Compressive Loading" was made in the 92nd Transportation Research Board (TRB) Annual Meeting in Washington, D.C., January 2013.

The draft of the ARC Report V was completed in this quarter, which summarized in detail the constitutive models, test protocols, and results obtained in the characterization of the asphalt mixtures in compression. Four appendixes were included in Report V to report: 1) the Test Method & Model of the "Continuum Damage Permanent Deformation Analysis for Asphalt Mixtures"; and 2) the Test Method Analysis Program of the "Nondestructive Characterization of Anisotropic Viscoelastic Properties of Undamaged Asphalt Mixtures under Compressive Loading". The Report V was also submitted to the ARC committee for review.

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

Included Work Elements/Subtasks

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

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

The focus of the current and future work is on implementing the procedures for identification of the model parameters in PANDA parameter identifier package. PANDA parameter identifier package includes series of Matlab codes that automatically read the raw data and return the model parameters. The focus is also on further calibration and validation of PANDA against ARC test results as well as the other available and collected experimental data (Waterways Experiment Station data and Ohio test sections). In addition, most of the current and future efforts are on finalizing the reports and organizing a workshop to illustrate PANDA capabilities that can be used by both practitioners and researchers. As documented in the list of deliverables, we are preparing a report that includes the theory of models included in PANDA, test methods and procedures to determine the models' parameters. The report on the test method for calibration of PANDA has been prepared and will be delivered to FHWA. The PANDA report will also be delivered by May 1st.

Work Element M4c: Unified Continuum Model

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

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. Results of the replicates have been received. These data have been analyzed to develop a simple and straightforward procedure that can be used systematically to identify the model parameters. The model will be validated against the cyclic strain controlled tests on moisture conditioned specimens. The focus of the next quarter is on further validation of moisture-induced damage model in PANDA against the ARC experimental data in both tension and compression.

Cited References

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

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

Status and Work Planned: The micro-damage healing model has been developed, implemented, and validated against experimental data including the ALF data in tension [see e.g. Abu Al-Rub et al. (2010), Abu Al-Rub and Darabi (2012), Darabi et al. (2012a, 2012b, 2012c, 2013)]. It is shown that the PANDA model is capable of predicting the fatigue damage response of asphalt concrete subjected to different loading conditions. The data and analysis demonstrate that micro-damage healing occurs not only during the rest period, but also during the cyclic strain controlled tests in the absence of the resting time. The ALF database includes the experimental data on four mixtures that differ in the binder type. Validation of the micro-damage model against the ALF mixes with modified binders has been started. The model will be further validated against the ALF data on the mixtures with modified binder as well as against the ARC data.

During this quarter, the procedure for identification of damage and micro-damage healing model has been implemented into PANDA parameter identifier package. PANDA parameter identifier automatically uses the raw data and returns the model parameters. The method for identification of damage and micro-damage healing model parameters is based on analyzing the uniaxial constant strain rate tests at three different strain rates. The focus during the coming quarter will be on refining the PANDA identifier package and to integrate it as part of the PANDA User Interface (PUI).

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

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

Cited References

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

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

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

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

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

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

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

Status and Work Planned: See M4c for details on the progress in the development of the continuum-based moisture-induced damage mode. Also see F1d-8 on the development of the continuum-based micro-damage healing model. We have completed the calibration and validation of the nonlinear viscoelastic, viscoplastic, and viscodamage constitutive models in PANDA using the ALF laboratory data based on compression and tension data at different temperatures. The laboratory tests needed to calibrate and validate PANDA for the first ARC

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

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

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

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

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

Cited References

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

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

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

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

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

Continuum-based Model for Aging

Status and Work Planned: In this quarter, the mechanistic-based phenomenological oxidative aging (or oxidative aging hardening) model has been developed and implemented into PANDA, Abu Al-Rub et al. (2012). An evolution function is proposed for the introduced oxidative aging internal state variable. The proposed aging model is formulated as a function of the diffused oxygen content and temperature evolution which ties the mechanical response of aged material to the underlying physics happening during the oxidative aging of asphalt concrete. Phenomenologically, the evolution of the aging internal state variable in asphalt concrete is related to the rate of carbonyl formation during the aging process of the asphalt binder. It is argued that oxidative aging mostly affects the viscous behavior of the aged material, such that the viscosity model parameters in the coupled nonlinear-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 effect of oxidative aging on nonlinear viscoelastic response of asphalt concrete has been investigated using dynamic modulus test data conducted on ARC mixture No. 1 for different air void percentages. It has been shown that the conventional shifting methods are not sufficient to capture nonlinear viscoelastic response of aged asphalt concrete materials. A mechanistic-based model has been proposed to couple the oxidative aging with the nonlinear viscoelastic model. Furthermore, a systematic and straightforward procedure has been developed to identify the model parameters associated with the oxidative aging model. Moreover, the constructed 2D microstructure of asphalt mixes has been simulated using PANDA to investigate the effect of oxidative aging on fatigue damage response of pavements. Computational methods have been developed to effectively obtain the oxygen diffusion coefficient of the mixture. Conducting laboratory tests to determine the oxygen diffusion coefficient of mixtures is a very time consuming and difficult task. During this quarter, the lab procedures have been combined with computational methods to propose a novel experimental-computational method to identify the oxygen diffusion coefficient.

We will continue to further calibrate and validate the aging model against more comprehensive data from TAMU and North Carolina State University. These data include tests 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, Vol. 41, pp. 439-454, 2013. http://dx.doi.org/10.1016/j.conbuildmat.2012.12.044

Work Element V3c: Validation of PANDA

Status and Work Planned: Please refer to the details presented in work elements M4c, F1d-8, and F3c. These work elements outline what has already been accomplished in validating the constitutive models that are implemented in PANDA as well as the validation work that will be carried out in the coming quarter. In this quarter, emphasis has been continued on the development of a systematic procedure for the identification of the nonlinear viscoelastic parameters of Schapery's nonlinear-viscoelastic model, Perzyna's viscoplastic model, and the damage model implemented in PANDA. Nonlinear viscoelastic and viscoplastic models are identified using a repeated creep-recovery test at various stress levels. It is concluded that the nonlinear viscoelastic material parameters are strongly dependent on the level of the confinement pressure such that these parameters should be made a function of the triaxial ratio (i.e. the ratio of the mean stress to the von Mises effective shear stress). The dynamic modulus tests as well as the repeated creep-recovery tests at various stress levels, conducted as part of the ARC testing plan, have already been used for calibrating the viscoelastic and viscoplastic models, respectively. The uniaxial constant strain rate tests in tension are also used to calibrate the damage component of PANDA model. The aging data based on the dynamic modulus test has also been used for calibration and validation of the oxidative aging model.

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

New experimental tests have been conducted by the Army Corps of Engineering at the Waterways Experiment Station, Vicksburg, Mississippi. Eight mixtures have been selected ranging from expected "poor" to "very good" rutting performance. The testing required for calibration of PANDA model have been conducted on these mixtures. Linear and nonlinear viscoelastic model parameters associated with these eight mixes are identified. Codes have been developed to automatically identify the model parameters using the experimental data. The focus will be placed on using these codes to completely calibrate PANDA against ARC mix No. 1. PANDA will be further validated against the repeated creep-recovery tests at different stress levels and temperatures. Four of the eight mixtures will be used as part of the full-scale accelerated pavement testing. Once calibrated, PANDA will be used to rank the rutting performance of full-scale accelerated pavement testing.

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

REPORT D: CHARACTERIZATION OF ASPHALT BINDERS USING ATOMIC FORCE MICROSCOPY

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

Status and Work Planned:
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.

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

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

REPORT E: MULTISCALE VIRTUAL FABRICATION AND LATTICE MODELING.

REPORT ON LATTICE MODEL AND CONTINUUM DAMAGE TO FRACTURE

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

Status and Work Planned: *Lattice Modeling*
This task is on schedule

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

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

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

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

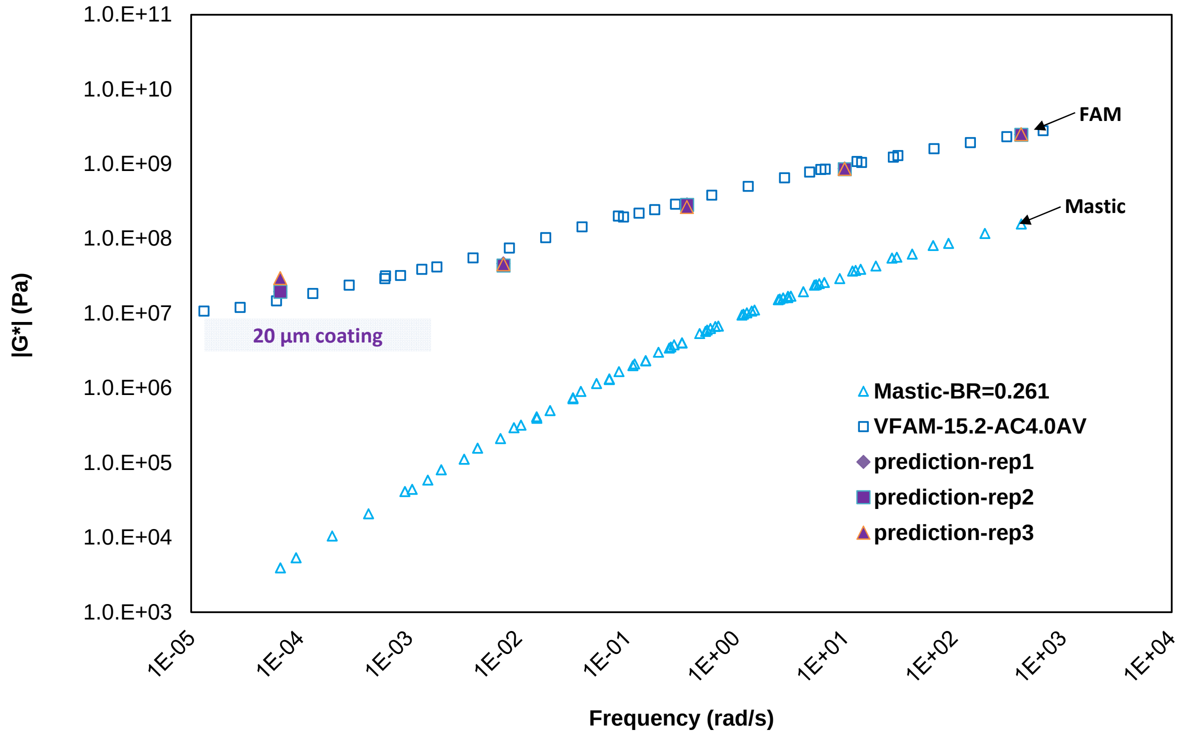


Figure 1. Dynamic modulus predictions for FAM from available mastic data.

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

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

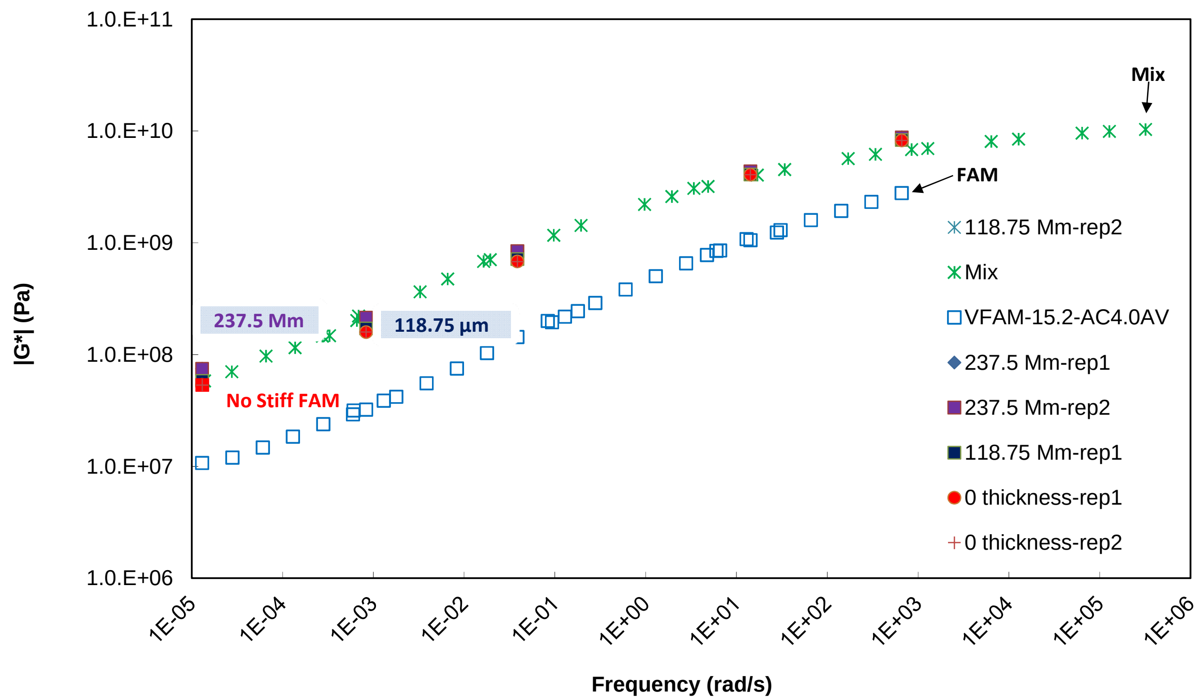


Figure 2. Dynamic modulus predictions for mix from available FAM data.

<u>Reference</u>

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

Continuum Damage to Fracture

This task is on schedule.

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

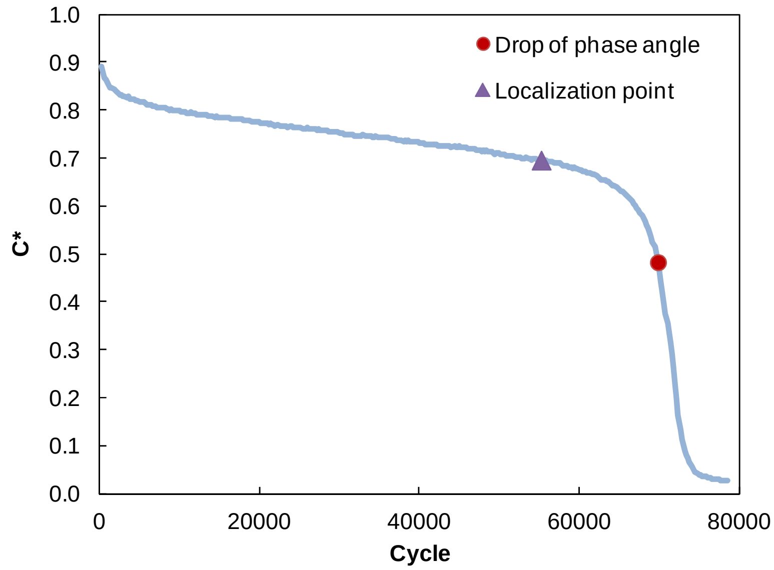


Figure 3. Schematic plot of failure point and localization point.

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

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

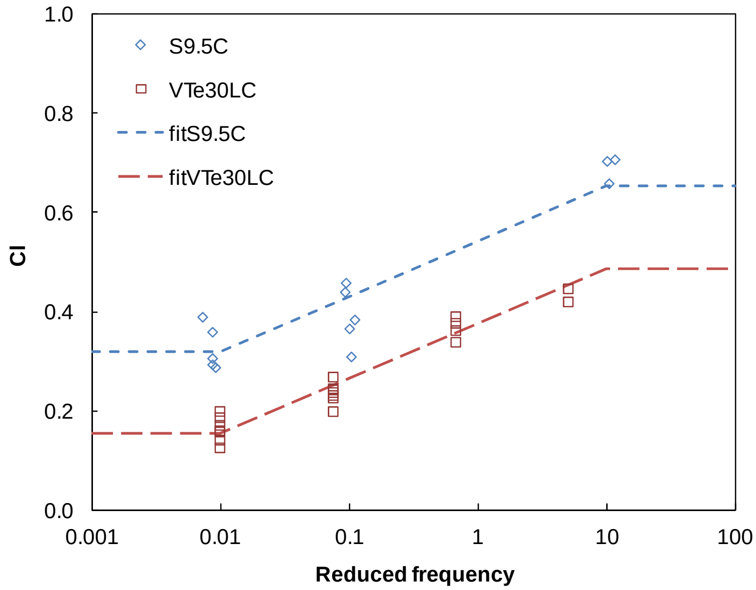


Figure 4. Development of localization envelope.

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

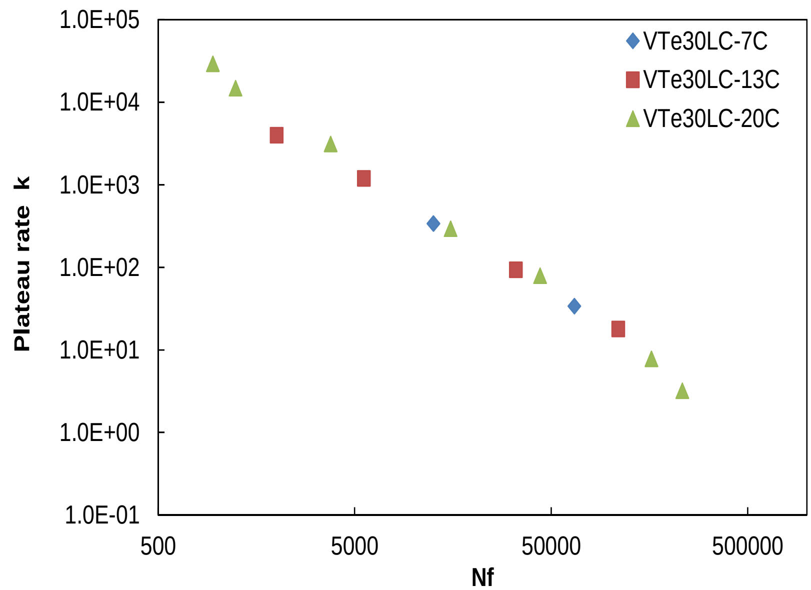


Figure 5. Relationship between plateau rate k and fatigue life N_f.

Reference

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

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

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

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

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

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

Status and Work Planned
On Schedule.

The following list describes the work items completed this quarter:

- Started the Phase I work plan for Dust Proportion (DP) study.
- Continued a literature review regarding fractionation procedures.
- Continued literature review regarding tension-compression uniaxial fatigue testing as an alternative fatigue test in case of the unavailability of the flexural bending beam fatigue test.
- Initiating a literature review regarding the major factors affecting fatigue endurance limit.
- Initiating literature review of continuum damage fatigue analysis.
- Determined the required retained percentage of RAP material on each sieve to obtain a precise estimation of the extracted RAP aggregate gradations.
- Completed the report summarizing the uniaxial thermal stress and strain test (UTSST) results for the of the high RAP content mixtures from University of New Hampshire.
- Assisted and sampled materials during the construction of the Arizona RAP field sections.

The following list the work planned for next quarter:

- Complete sieving the required amount of both RAP and original aggregates.
- Continue the fatigue endurance limit literature review including the major driving factors as well as obtaining and analyzing fatigue results generated from tension-compression uniaxial fatigue testing.
- Perform phase I of the DP work plan which include studying the rutting resistance of lab-produced RAP mixtures with several dust-to-binder proportions (1. 1.5, and 2%). Based on the anticipated results from phase I, potential factors will be included in phase II which will investigate the effect of dust-to-binder on fatigue life and endurance limit of RAP HMA mixtures.
- Sample field mixtures with several RAP contents

REPORT H: CRITICALLY DESIGNED HMA MIXTURES

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

Status and Work Planned
On Schedule.

The following list describes the work items completed this quarter:

- A dissertation summarizing the effort conducted under this work element was completed.
- Continued the work on Report H.
- Worked on the draft AASHTO procedure for evaluating the critical conditions of HMA mixtures.

The following list the work planned for next quarter:

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

REPORT I: THERMAL CRACKING RESISTANT MIXTURES

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

Status and Work Planned
On Schedule.

The following list describes the work items completed this quarter:

- The thermal stress and thermal strain measurements are currently being conducted on laboratory aged and field validation samples following the development of the draft AASHTO standard using uniaxial thermal stress and strain test (UTSST). Thus far, over 46% of the UTSST to be conducted on the mixtures has been completed.
- The aging and testing for the field validation sections are underway with nearly all of the binder aging and testing being complete.
- Evaluation of the Core materials has also begun. Over 98% of the binder aging has been completed thus far, with almost 50% of the accompanying testing being complete.
- Subsequent to some recent findings related to the systematic shifting of the activation energy of binders aged in mixtures and in laboratory pans, additional mixtures have been prepared and aged at 85°C. All of the samples have been aged and have been tested for dynamic modulus. Half have also been extracted and recovered for the binder testing portion which is also 50% complete.
- Conducting the direct tension test specimens for polymer-modified asphalt mixtures, about 40% of those samples having been tested.
- Completed the UTSST testing for the polymer-modified asphalt mixture to evaluate the proposed procedure for determining the mixture’s thermo-viscoelastic properties.
- Finalized the method for determining the relaxation modulus from thermal stress and strain measurements.
- Continued the work on the approach to relate the mechanical properties of asphalt mixtures to the chemical and rheological changes in asphalt binders due to oxidative aging.

The following list the work planned for next quarter:

- Complete the Core binder testing.
- Conduct mixture testing on two of the core materials.
- Continue the direct tensile strength test on polymer-modified asphalt mixtures.
- Continue working on the subroutines for thermal cracking analysis tool.
- Perform the UTSST and direct tension tests on field validation mixtures and various aged mixtures.

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

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

Status and Work Planned
Behind Schedule.

Several bugs were reported after the release of the 3D-Move Ver. 2 which largely delayed the work on the report. The focus of the UNR research team this quarter was to address and solve the various reported bugs in a timely and effective manner. Given no further significant bugs are reported, the work on the report will resume in the next quarter. The delivery date of the draft report has been revised

REPORT K: DEVELOPMENT OF MATERIALS DATABASE

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

Status and Work Planned
On Schedule.

It is currently planned to include as part of the report, a chapter on the compliance of the ARC Database with the Federal Data Quality Act. It is acknowledged that the report on the compliance with the Data Quality Act may have to be delivered as a separate document. The UNR team is working with AOTR Eric Weaver and possibly others at Turner-Fairbanks HRC to determine the most appropriate way to address this requirement.

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

- Testing and fixes to the file upload system (unplanned);
- Revised file upload reports;
- Measures test run report;
- Status of batch upload;
- Status of the public user interface; and
- General bug fixes.

The following list the work planned for next quarter:

- Complete batch file upload system;
- Add features to the test run import system that will allow users to replace or append existing measures;
- Complete measure reports to be used by consortium members and possible public users;
- Complete role documentation system;
- Continue work on the public user interface using independent study student resources;
- Revisit the FileLinker form as subsystem, as necessary.

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

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

Status and Work Planned
Behind Schedule (Final Report Submission)

Work Completed: Incorporation of review comments into existing draft final report was completed. The BBS procedure was implemented for work related to the NCHRP 9-50 project and other ARC activities. The NCHRP 9-50 work was related to evaluation of curing and residue properties of various emulsion setting times (fast to slow). Experience with a wide range of emulsion setting times revealed that in order to maintain a constant film thickness it is necessary to adjust the quantity used to prepare fresh emulsion BBS samples based on the asphalt content of the emulsion. It has been established that bond strength is related to the thickness of the film, this finding ensures the BBS test is applicable to comparing emulsions of different setting times. The effect of application temperature for hot applied binders was also evaluated in work related to the ARC. It was found that application temperature has a significant effect on bond strength, particularly in the wet condition. Based on this finding it is necessary to use the temperatures specified in the mix design for preparation of BBS samples. AASHTO TP-91 was revised to include these changes and will be included in the final report as and appendix.

Work Planned: Revise draft final report to incorporate new information related to the effects of application temperature and use of the BBS in testing of fresh emulsions. Complete internal review of final report, complete Section 508 formatting, and submit to FHWA.

Reasons for Delay: Additional time is required to incorporate new information related to both effects of application temperature and fresh emulsion sample preparation into the final report to serve as justification to proposed revisions to the AASHTO TP-91. No further testing is planned, final report in Section 508 format will be submitted early in 2013Q2.

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

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

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

Status and Work Planned
Behind Schedule (Final Report Submission)

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

Work Planned: Address comments from peer review feedback and prepare final report. Furthermore, content will be added with regards to the revised test procedure, and the fracture index. Additionally, the Asphalt Institute will be approached to discuss incorporating independent LAS measurements and correlations with mixture fatigue data produced by AI in the final report.

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

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

REPORT N: GUIDELINES FOR SELECTION OF MODIFICATION TECHNIQUES

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

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

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

Work Completed: Work on draft final guidelines for application of spreadsheet continued this quarter and is near completion. Extensive work on determination of the effects of extenders and alternative binders on performance were also completed this quarter, including the addition of 6 new extender types to the work plan, as further described in the “New Work Element” update document under “E3a”. The results of this work will be integrated into Report N.

Work Planned: Complete experimental plan for E3a. It is anticipated that all testing will be completed by 2013Q2. Results of Work Element E3a will be integrated into existing draft of E2a report during next quarter pending completion of the E3a work plan.

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

REPORT O: CHARACTERIZATION OF BINDER DAMAGE RESISTANCE TO RUTTING

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

Status and Work Planned
On Schedule

Work Completed: Recent work aimed at quantifying effect of binder elasticity and viscous response on mixture rutting mechanisms to determine optimum modified binder behavior that will minimize rutting potential of mixture was integrated into the draft final report. This work will contribute significantly to the analysis and discussion of Report O.

Work Planned: Complete draft final report and associated Section 508 formatting. Submit to FHWA.

Delivery Dates
Draft Report: 6/30/2013
Final Report: 12/31/2013

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
Behind Schedule

Work Completed: Significant progress was made in the development of guidelines for selecting mixing and compaction temperatures subtask that was added to this work element in the ARC Yr. 6 work plan. In regards to mixing temperatures development of a procedure to evaluate both the degree and quality of coating was completed. Results found that asphalt binder viscosity is strongly related to coating quality. The mechanisms of mixture compaction and how they change with compaction temperature were also clarified. Two main concepts are under further pursuit 1) Material lubricating the mix is mastic, not binder. 2) Compaction mechanisms are different based on the thickness of the film separating aggregate contacts. Development and preliminary concepts were pursued using mastic viscosity measured in the Bob and Cup Geometry and visualization of aggregate structure using the IPas technology, this work was summarized at the 2013 AAPT meeting. Both findings have the potential to significantly impact the conclusions and recommendations from previous work related to selection of mixing and compaction temperatures for WMA. The research team has also become involved in a task force related to the topic of mixing and compaction temperature selection recently and feels that there is an opportunity to integrate the findings of this group into the final report.

Work Planned: If the request for additional time is approved the research team will work on application of the coating test and extension of the mastic viscosity concepts to different mineral fillers and mixes. The anticipated outcome of this work is a test method for coating evaluation that includes a maximum limit on viscosity, and a test method for mastic viscosity that proposes limits for the optimum compaction temperature range. This work will be conducted in cooperation with the Mixing and Compaction Temperature Task Group (Binder ETG). Concurrently work on the report summarizing the impacts of WMA on mixture workability, asphalt/binder performance properties, and resistance to moisture damage.

Reasons for Delay: Recent findings suggest it is necessary to combine the MT/CT Guideline Task approved in the Yr. 6 work plan with the final report for WMA. Additional time is needed to complete the aforementioned tasks related to guidelines for mixing and compaction temperatures and to integrate these findings into the draft final report.

Delivery Dates
Draft Report: 9/30/2013 – extended from 3/31/2013
Final Report: 12/31/2013 – extended from 10/31/2013

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

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

Status and Work Planned
On Schedule

Work Completed: The coating analysis procedure that evaluates both the degree and quality of coating was finalized. A work plan aimed at determining the optimum fluids content for CMA was initiated and is 33% complete. Compaction and curing procedures were integrated into the study; as a result it was found that full curing is achieved after 72 hours at 60°C.

The fresh and residue properties of emulsions used for spray seals, chip seals, and micro-surfacing were completed and summarized. Results will be compared to mixture performance tests to set threshold values. Work was initiated with NCAT to identify field validation sections from various sections placed last summer.

Work continues by WRI on sampling emulsion residues from the field after 4 years in-service and characterizing their chemical properties and rheological properties using the 4mm Parallel Plate geometry in the DSR.

Work Planned: The experimental plan for selecting optimum fluids content will be completed. Based on recommendations various mix designs will be prepared at the optimum fluids content and various mixture performance tests will be performed. Candidate mixture performance tests include: Flow Number, Dynamic Modulus, and Moisture Resistance (TSR). Results will be compared to published values for HMA.

Testing of recovered and PAV aged residue properties of emulsions used in various applications, including both preservation and cold mix will continue. The field sampled emulsions from the NCAT test sections will be evaluated using the same testing procedures and results will be compared to field performance data. WRI will also continue field validation work using the 4 mm plate on material sampled from chip seals after 4 years in service.

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

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

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

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

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

Work Planned: Request NTIS formatting guidelines from FHWA and convert draft report to correct format. Resubmit NTIS report.

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

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

REPORT S: MOLECULAR DYNAMICS RESULTS FOR MULTIPLE ASPHALT CHEMISTRIES

This report can be delivered in non-508 format.

Included Work Elements/Subtasks

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

- Sub-subtask F3a-1.1. Specify desired asphalt compositions and chemistries for testing multiscale asphalt modeling effort (large cluster simulations) (URI, WRI)
- Sub-subtask F3a-1.2. Develop algorithms and methods for directly linking molecular simulation outputs and phase field inputs (URI, NIST)
- Sub-subtask F3a-1.3. Obtain temperature-dependent dynamics results for model asphalts that represent asphalts of different crude oil sources (URI)
- Sub-subtask F3a-1.4. Simulate changes in asphalt dynamics after inducing representations of chemical and/or physical changes to a model asphalt (URI)

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

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

Status and Work Planned

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

On Schedule.

Compositions were identified in previous quarters. A publication that disseminates new proposed compositions for AAA-1, AAK-1, and AAM-1 was submitted to the journal *Energy & Fuels* during January 2013. The *Energy & Fuels* associate editor declined to send the manuscript out for reviews as a consequence of a change in the journal's scope, in which roadway materials are now excluded. Subsequently the manuscript was submitted to *Fuel* in February 2013.

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

Slight delay during the past quarter.

Work continued on conducting molecular simulations of model asphalts and analyzing the results to obtain physical insights and free energy parameters. Results from the prior quarter for molecular simulation predictions of $|G^*|$ and phase angle δ, calculated from the spontaneous fluctuations in the stress tensor, were refined by identifying better methods for filtering the input data to obtain a better signal, i.e. more smooth and trustworthy G^* and δ results.

The efforts have focused on the new AAA-1 system, with results for prior model asphalt compositions set aside as the methods and understanding are refined. Interpretations using time-temperature superposition have also been started. A surprising finding has been that rises in storage and loss modulus with frequency do not show good superposition. Instead, a van Gurp-Palmen plot of G* vs δ over the different temperatures shoes similar shapes but poor overlap. The suggestion, as we currently infer it from the results, is that the model system is not thermorheologically simple over this temperature range. The interpretation is being continued to be tested as we write up the results.

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

Delay during the past quarter.

Work to simulate additional asphalt systems continues to proceed more slowly than expected. Simulations have been initiated for multiple additional model asphalts using new compositions, though simulations at additional temperatures are required prior to full data analysis. The delay is a result of two factors. The main factor is the ongoing new teaching load assigned to the PI, which has slowed research progress significantly. Getting existing computer hardware operational and new computer hardware in place has also been impacted by the very large teaching load.

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

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

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

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

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

MODEL: PHASE-FIELD MODEL OF ASPHALT BINDER FRACTURE AND COMSOL CODE FOR MODEL

Included work elements/subtasks
Work Element F4a: Phase-field modeling of crack interaction in asphalt binder
Subtask F4a-4.4: Crack interaction experiment of asphalt binder
Subtask F4a-4.5: Phase-field simulation of fracture failure of crack interaction in asphalt binder
Subtask F4a-4.6: Comparison between PFM and experiment and corresponding interpretation

Work Element F4b: A multi-scale approach of mode I crack based on Phase-field and Molecular Dynamic Simulation

Status and Work Planned
On Schedule

At this moment, this research progress is on time according to the plan. Subtasks F4a 4.4-4.6 have been finished. Work Element F4b the multi-scale simulation of Mode I cracking of asphalt binder will be conducted in the next quarter.

Since we have employed Phase-field model for in cracking analysis of asphalt binder, we are aware of the limitation. In order to simulate comprehensively, the multi-scale modeling approach is employed based on the continuum level tool Phase-field Model and the atomistic level tool Molecular Dynamic Simulation. The Phase-field Model is used to describe and predict the crack propagation using a phase-field variable which assumes one in the intact solid and negative one in the crack region. The fracture toughness is modeled as the surface energy stored in the diffuse interface between the intact solid and crack void. To account for the growth of cracks, a non-conserved Allen-Cahn equation is adopted to evolve the phase-field variable. The energy based formulation of the phase-field method handles the competition between the growth of surface energy and release of elastic energy in a natural way: the crack propagation is a result of the energy minimization in the direction of the steepest descent.

However, realize the fact that at the crack tip, the mechanical property including stress, strain distribution, etc. are complex due to its atomistic-structure-dependence and unable to be accurately solved by the phase-field system, the Molecular Dynamic Simulation is employed. The molecular structure of asphalt binder will be input into the simulation software Large-scale Atomic/Molecular Massively Parallel Simulator (LAMMPS). It is expected that the continuum Phase-field system will control the cracking process, and at the crack tip, MD simulation will dominate. The stress and strain from Phase-field will be used as the boundary condition in LAMMPS ($P \rightarrow M$) and then MD simulation returns the elastic energy into the two-way coupling system ($M \rightarrow P$). One thing should be noted is that at molecular level, the material elastic modulus will be dependent on the molecular structure. For consistence, we use the value of elastic modulus calculated in MD Simulation in our continuum Phase-field Model. Figure 1 shows the flowchart of our multi-scale modeling scheme.

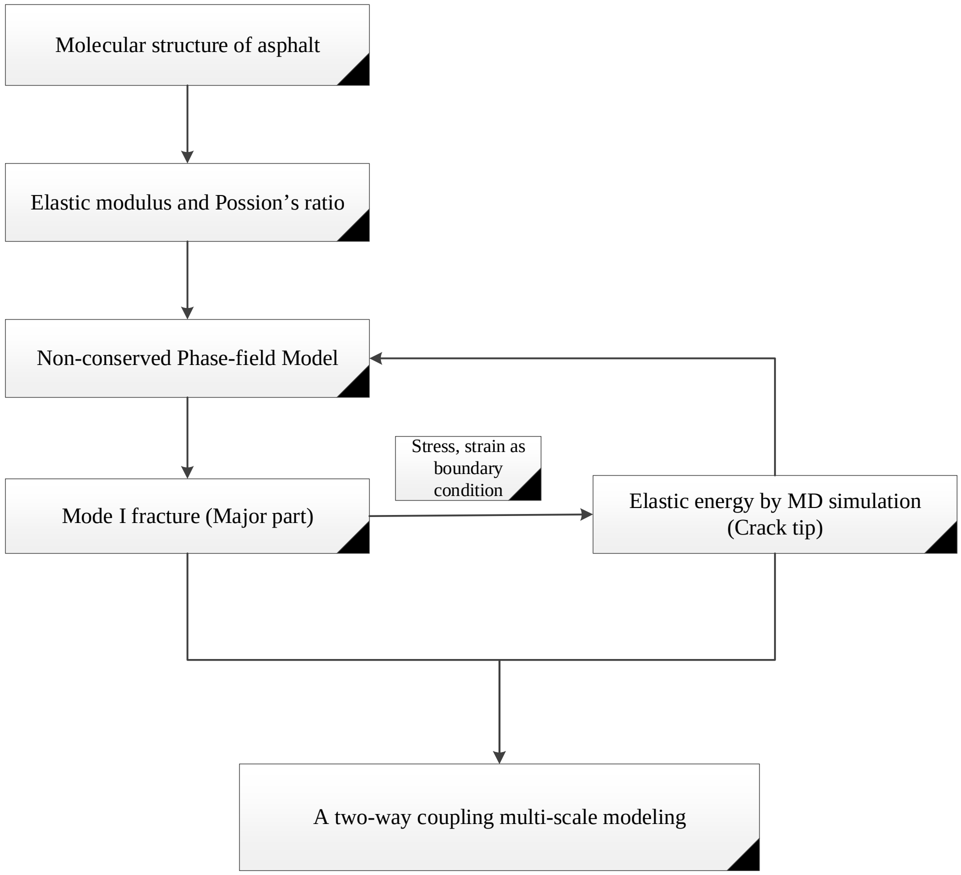


Figure 1. Flowchart of multi-scale modeling scheme.

The total energy in LAMMPS is expressed as the summation of the potential energy and the kinectic energy as

$$E_{Total} = E_{potential} + E_{kinect} \tag{1}$$

If we consider from the structure aspect, the total energy during the fracture process could also be divided to two kinds: the plastic work $W_{plastic}$ and elastic energy $E_{elastic}$, where the plastic work can be calculated as variation of potential energy at 0K as

$$W_{plastic} = \Delta E_{potential}(0\mathrm{K}) \tag{2}$$

The minimum value of the potential energy at the given time *t* is

$$E_{potential}^{min}(t) = \min_{\boldsymbol{R}=(r_1,\ldots,r_N)} E_{potential}\,(\boldsymbol{R}(t)) \tag{3}$$

where $\boldsymbol{R} = (r_1, \ldots, r_N)$ represents the atom coordinates.

And correspondingly, the plastic work at time *t* is calculated as

$$W_{plastic}(t) = E_{potential}^{min}(t) - E_{potential}^{min}(0) \tag{4}$$

Combine equation (1), (2), (3) and (4) and we can obtain the elastic energy shown in figure 1.

REPORT U: DESIGN GUIDANCE FOR FATIGUE AND RUT RESISTANCE MIXTURES

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

Status and Work Planned
Behind Schedule

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

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

REPORT V: CONTINUUM DAMAGE PERMANENT DEFORMATION ANALYSIS FOR ASPHALT MIXTURES

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

Status and Work Planned
Status: on schedule.

In this quarter, a technical presentation entitled “Mechanistic Modeling of Fracture in Asphalt Mixtures under Compressive Loading” was made in the 92nd Transportation Research Board (TRB) Annual Meeting in Washington, D.C., January 2013.

The draft of the ARC Report V was completed in this quarter, which summarized in detail the constitutive models, test protocols, and results obtained in the characterization of the asphalt mixtures in compression. Four appendixes were included in Report V to report: 1) the Test Method & Model of the “Continuum Damage Permanent Deformation Analysis for Asphalt Mixtures”; and 2) the Test Method Analysis Program of the “Nondestructive Characterization of Anisotropic Viscoelastic Properties of Undamaged Asphalt Mixtures under Compressive Loading”. The Report V was also submitted to the ARC committee for review.

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

Included Work Elements/Subtasks

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

Status and Work Planned

Status: on schedule.

The work under this work element is on schedule. The final report, entitled "Characterization of Fatigue and Healing Properties of Asphalt Mixtures" (Report W), has been prepared in this quarter and is ready for submission. All of the development work documented in previous quarterly report has been included in Report W to achieve the following objectives:

- Choose a test method suitable for characterizing fatigue cracking in an asphalt mixture with the presence of permanent deformation;
- Develop a pure mechanistic approach to separate fatigue cracking from permanent deformation using one asphalt mixture specimen and model the evolution of fatigue cracking;
- Develop a test method that can facilitate mechanistic analysis of healing; and
- Develop a pure mechanistic approach to model the healing process and to determine the healing rate.

Seven sections are contained in Report W, specifically:

- Section 1: Introduction
- Section 2: Characterization of asphalt mixtures using controlled-strain repeated direct tension test
    - Test configuration and materials
    - Simulation of stress curve and strain curve
    - Undamaged and damaged material properties
- Section 3: Characterization of fatigue damage in asphalt mixtures using pseudo strain energy
    - Material properties of asphalt mixtures under different stress levels
    - Endurance limit of asphalt mixtures
    - Calculation of pseudo strain
    - calculation of pseudo strain energy
    - Balance of pseudo strain energy
- Section 4: Model fatigue crack growth in asphalt mixtures using pseudo strain energy balance
    - Simulation of true stress, true strain, and true pseudo strain
    - Determination of damage density and average crack size

- Determination of average crack size and number of cracks
    - Determination of fracture parameters

- Section 5: Characterization of recovery properties of asphalt mixtures
    - Internal stresses
    - Principle of measurement of internal stresses
    - Experiment design to measure internal stresses
    - Determination of recovery properties

- Section 6: Characterization of healing of asphalt mixtures
    - Healing and recovery of asphalt mixtures
    - Balance equations for healing
    - Determination of healing curves
    - Evaluation of healing ability of different asphalt mixtures
    - Prediction of crack closure curves with undamaged properties

- Section 7: Summary

In addition to Report W, the last development work on healing of asphalt mixtures was finished in this quarter as the conclusion of this research work. As discussed in the last quarterly report, healing of asphalt mixtures is described by three healing parameters: $\dot{h}_1$ (short-term healing rate); $\dot{h}_2$ (long-term healing rate); and h_β (healing rate scale). In order to predict these healing rates based on fundamental material properties, they are formulated using the following equations:

$$\dot{h}_1 = a_1\left(\frac{1}{\Delta G^{LW} E_1}\right)^{b_1\kappa} \tag{1}$$

$$-\log\left(\dot{h}_2\right) = a_2\left[-\log\left(\frac{\Delta G^{AB}}{E_1}\right)\right]^{b_2\kappa} \tag{2}$$

$$h_\beta = a_\beta\left(\frac{\Delta G^{AB}}{\Delta G^{LW} E_1^{\,2}}\right)^{(1-h_0)b_\beta\kappa} \tag{3}$$

where ΔG^{LW} is non-polar surface bond energy; ΔG^{AB} is polar surface bond energy; E_1 and κ are fitting parameters for the relaxation modulus of undamaged asphalt mixtures; h_0 is the initial damage density; a_1 and b_1 are fitting parameters for $\dot{h}_1$; a_2 and b_2 are fitting parameters for $\dot{h}_2$; a_β and b_β are fitting parameters for h_β. For example, the data of a_1 versus $b_1\kappa$ of unaged asphalt mixtures (0 month) is fitted using a linear regression function; the data of a_1 versus $b_1\kappa$ of aged asphalt mixtures for 3 months and 6 months is fitted by other two linear regression functions, respectively. The R-squared statistics shows the goodness of fitting by the linear regression function.

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.

As mentioned in the previous quarter, the developed viscoelastic characterization (VEC) test protocol can be applied to characterize stiffness variations in field cores by the stiffness gradient profile. In this quarter, the VEC test was conducted on 8 field specimens from Yellowstone National Park (YNP), which have been aged for four years. The field cores are collected from both shoulder and wheel-path of the two sections of YNP, which are the Advera warm mix asphalt (AWMA) section labeled as 1-2, and the Sasobit warm mix asphalt (SWMA) section labeled as 1-3. Each field core contains both top and bottom layers, which were separated before testing. The field cores were cut into two rectangular specimens and then were used for the Direct Tension Test at 10°C and 20°C, respectively.

Table 1 summarizes the results of the stiffness gradient calculation for YNP field specimens. According to the results in table 1, the stiffness gradient profiles for each specimen are generated as shown in figures 1 to 4. The results of the stiffness gradient profiles can be used to characterize field cores as functionally graded material (FGM) in finite element models.

Table 1. Stiffness gradient profile for YNP field specimens.

Specimen ID	Temperature (°C)	n	k	Bottom Modulus (ksi)	Surface Modulus (ksi)
1-2B-Top-WP	10	4.08	2.27	301	684
1-2B-Bot-WP	10	4.11	1.76	213	374
1-2B-Top-S	10	4.94	2.09	311	651
1-2B-Bot-S	10	3.92	1.64	231	379
1-3B-Top-WP	10	4.28	1.70	321	546
1-3B-Bot-WP	10	4.90	1.35	271	364
1-3B-Top-S	10	4.90	1.89	251	476
1-3B-Bot-S	10	4.93	1.65	195	322
1-2B-Top-WP	20	4.09	2.01	221	444
1-2B-Bot-WP	20	3.74	1.66	144	239
1-2B-Top-S	20	4.13	2.31	203	469
1-2B-Bot-S	20	4.15	1.83	147	270
1-3B-Top-WP	20	4.10	2.05	200	410
1-3B-Bot-WP	20	3.80	1.64	150	245
1-3B-Top-S	20	4.21	2.34	148	346
1-3B-Bot-S	20	4.34	1.52	139	211

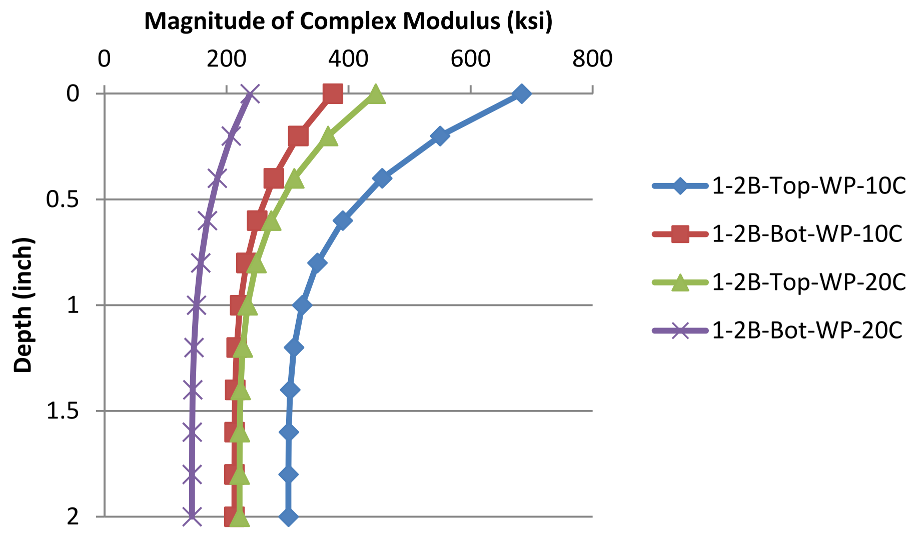


Figure 1. Complex moduli of wheel-path core in AWMA section at different temperature.

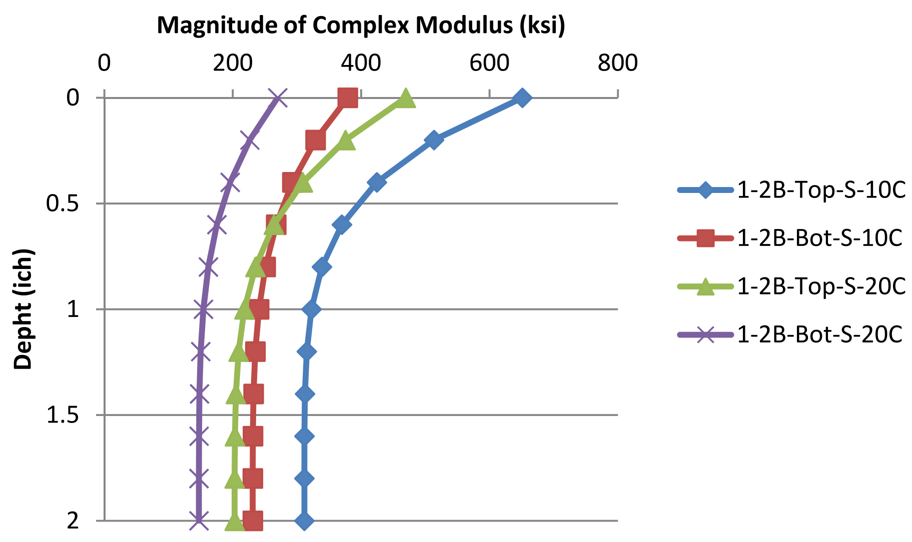


Figure 2. Complex moduli of shoulder core in AWMA section at different temperature.

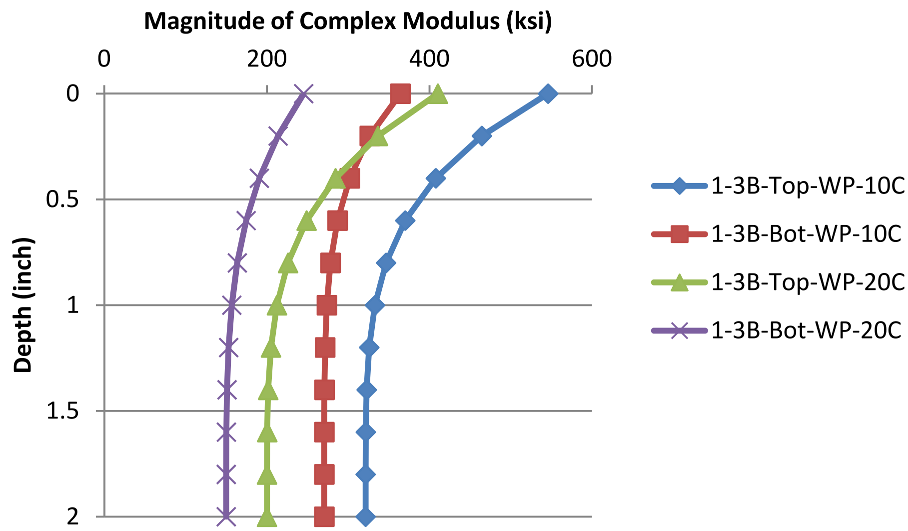


Figure 3. Complex moduli of wheel-path core in SWMA section at different temperature.

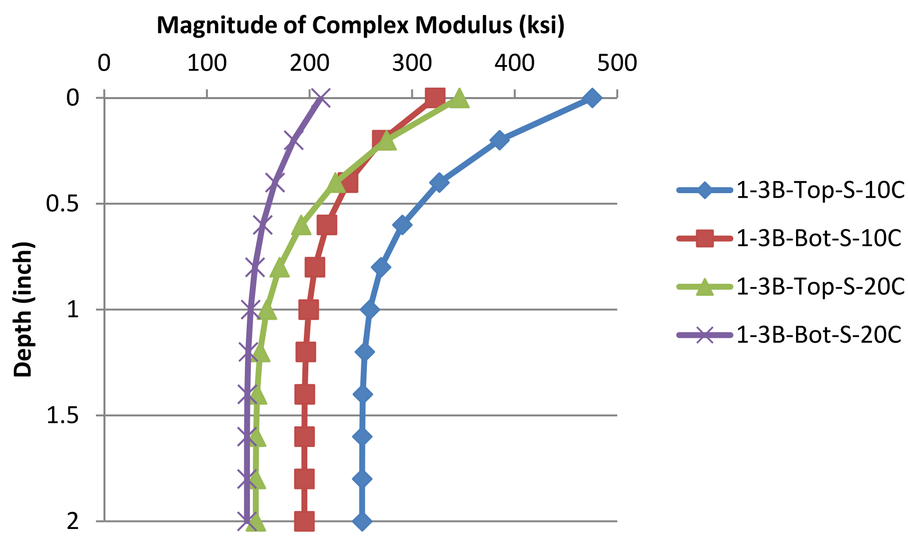


Figure 4. Complex moduli of shoulder core in SWMA section at different temperature.

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, three tasks are completed:

4. Chapter 3: The Use of a DMA to Quantify Moisture Damage in Asphalt Mortars for the report of 'Moisture Damage of Asphalt Pavements: Mechanisms, Characterization, Prediction and Numerical Modeling' was drafted and submitted for review.

5. The Level 2 Report Y: 'Water Vapor Diffusion in Pavement and Its Effects on the Performance of Asphalt Mixtures' was drafted and submitted for review.

6. Part of the Chapter 5: Influence of State of Stress and Permanent Deformation Fracture and Healing in asphalt mixtures for the comprehensive fatigue report was also drafted and submitted for review.

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

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

Status and Work Planned
Completed.

Submitted the Report Z in NTIS format to FHWA for review.

TEST METHODS

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

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

Status and Work Planned
Behind schedule

Work is progressing according to the year six work plan. The geometric stress progression test without rest periods has worked well in characterizing damage to localization in eight different mixtures in Work Element E2e. An automated Excel spreadsheet that uses the Solver function to perform the reduced cycles analysis was completed this quarter and applied to eight different mixtures. Data from the Fénix fracture energy was analyzed and compared to C-critical, the point in the reduced cycles analysis where localization occurs. No meaningful correlations were identified. This could be because of the difficulty of accurately identifying C-critical, but could also indicate that crack initiation, as characterized by uniaxial fatigue test, is generally not closely related to crack propagation for asphalt mixes. As noted in previous studies in these data there appears to be a good relationship between modulus and C-critical that applies for essentially all HMA mixes, whereas energy to failure varies widely among the eight mixtures. It appears that crack initiation is largely a function of mixture modulus, while crack propagation depends both on modulus and properties of the aggregate and/or asphalt-aggregate interface.

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

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

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

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

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

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

Status and Work Planned

References published:

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

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

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

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

Test method document:

The test method document has been completed and referenced in Report V "Continuum Damage Permanent Deformation Analysis for Asphalt Mixtures" as an appendix.

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

Included Work Elements/Subtasks

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

Status and Work Planned

References published:

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

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

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

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

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

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

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

Test method document:

The test method document has been completed and referenced in Report W "Characterization of Fatigue and Healing Properties of Asphalt Mixtures" as an appendix.

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

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

Status and Work Planned

References published:

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

Test method document:

The test method document has been completed and referenced in Report W "Characterization of Fatigue and Healing Properties of Asphalt Mixtures" as an appendix.

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

Included Work Elements/Subtasks

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

Status and Work Planned

References published:

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

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

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

Test method document:

The test method document has been completed and referenced in Report X “Characterization of Field Cores of Asphalt Pavements” as an appendix.

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

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

Status and Work Planned

References Published:

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

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

Test method document:

The test method document has been completed and referenced in Report V "Continuum Damage Permanent Deformation Analysis for Asphalt Mixtures" as an appendix.

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
Behind Schedule.

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

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

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

Status and Work Planned
On Schedule

Work Completed: Work began on the experimental plan design last quarter and is approximately 33% complete. The initial phase of the work is focused on evaluating different methods to determine optimum fluids (emulsion + water) content. Once the optimum fluids content is determined a second study will be designed to evaluate performance properties using test methods commonly used for conventional HMA. The relationship between performance and curing time will also be investigated.

Work Planned: Complete optimum fluids content experiment and begin work on investigation of the development of strength (curing) and fully cured CMA performance properties.

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

DRAFT AASHTO PRACTICE: EVALUATION OF RAP AGGREGATES

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

Status and Work Planned
On Schedule.

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

Completed Report Z, "Effect of Extraction Methods on the Properties of Aggregates in Reclaimed Asphalt Pavement," in NTIS format and submitted to FHWA for review and input.

DRAFT AASHTO PRACTICE: IDENTIFICATION OF CRITICAL CONDITIONS FOR HMA MIXTURES

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

Status and Work Planned
On schedule.

The following list describes the work items completed this quarter:

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

The following list the work planned for next quarter:

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

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

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

Status and Work Planned
On Schedule

The following list describes the work items completed this quarter:

- Prepared a Matlab code to calculate the relaxation modulus from the thermal stress and strain as measured using the Uniaxial Stress and Strain Test (UTSST).
- Revised the UTSST draft AASHTO procedure.

The following list the work planned for next quarter:

- Testing control specimens to validate the approach presented to determine thermo-viscoelastic properties of asphalt mixtures using ATCA device.
- Revise and refine the UTSST AASHTO draft as need it.

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

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

Status and Work Planned
Completed

Work Completed: Additional revisions were made to the draft standard including conversion of all units to SI, requiring that the application temperature used in sample preparation matches the intended production temperatures, and adjusting the sample size consideration for emulsion testing. The standard now determines the quantity of fresh emulsion required for the test based on the asphalt content of the emulsion. Both changes are important as research indicates that application temperature has a significant effect on wet bond strength. Furthermore, previous work established that film thickness influences bond strength, therefore it is necessary to maintain a constant film thickness for all emulsion products.

Work Planned: Submit revised standard and justification for proposed changes to AASHTO Technical Section 2a and the Emulsion Task Force. Work with these groups to finalize the standard.

Reasons for Delay: Additional time was needed to generate supporting data for proposed specification modifications and to revise standard accordingly. Standard is now complete and will be distributed for review early in 2013Q2, a total of six months extension is requested to account for submission of the standard and external peer review.

Delivery Dates
Final Version of AASHTO TP-91: 9/30/2013 - extended from 6/30/2013

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

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

Status and Work Planned
Completed

Work Completed: Test procedure was updated and combined with the BYET procedure in AASHTO format. The AASHTO standard in addition to the BYET procedure is intended to provide reliable alternatives for the standard elastic recovery and ductility tests using a DSR. The AASHTO draft document was submitted to the Binder ETG with a request for time on the agenda to present in the May 2013 meeting.

Work Scheduled: Present AASHTO draft procedure to Binder ETG meeting in May and implement any feedback or suggestions received. A finalized test procedure will be prepared for AASHTO standardization if so decided by the Binder ETG.

Reasons for Delay: Internal review of standard delayed submittal to early 2013. Draft has now been completed and submitted.

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

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

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

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

Work Completed: The revised test procedure, ruggedness testing plan, and samples were distributed to the 6 participating laboratories. Two additional laboratories, Asphalt Institute and FHWA Turner-Fairbank, were added to the previous laboratories participating which included MTE Services, North Carolina State University, University of Wisconsin-Madison, and Utah DOT. Results from 3 of the participating labs have been received and analyzed, with results from the other labs pending.

Work Planned: Ruggedness results and analysis will be presented as an update to the FHWA Binder ETG in May 2013. AASHTO Procedure will be updated to include findings from ruggedness results.

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

AASHTO TEST METHOD: BINDER YIELD ENERGY TEST (BYET)

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

Status and Work Planned
Completed.

Work Completed: Previously submitted draft standard was revised and combined with the DSR-Elastic Recovery AASHTO standard, thus both deliverables will be fulfilled in a single AASHTO standard procedure document. The draft AASHTO BYET and ER-DSR procedure was completed and submitted for presentation to the Binder ETG in May 2013.

Work Planned: Present AASHTO draft procedure to Binder ETG meeting in May and implement any feedback or suggestions received. A finalized test procedure will be prepared for AASHTO standardization if so decided by the Binder ETG.

Delivery Dates
Completed, combined with ER-DSR test for one AASHTO procedure. Dates are listed under the ER-DSR deliverable.

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
Completed

Work Completed: Draft AASHTO procedure that includes input from the manufacturer was completed and sent to the FHWA Mixture ETG for consideration.

Work Planned: Present procedure to Mixture ETG or other groups as requested and address any comments that arise during the review process.

Revised Delivery Dates
Draft AASHTO Method: Complete (1/31/2013).
Final AASHTO Method: 6/30/2013 (5 months after submission of draft). Will consult with FHWA on timing and review group.

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

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
Behind Schedule

Work Completed: Work on draft AASHTO standard was started.

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

Reasons for Delay: Completion of other standards due 3/31/2013 required more effort than expected, as a result the lubricity standard was delayed.

Delivery Dates
Draft AASHTO Method: 6/30/2013 - from 3/31/2013
Final AASHTO Method: 12/31/2013 - from 9/30/2013 (6 months after date of initial submission)

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

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

Status and Work Planned
Behind Schedule

Work Completed: Development of draft AASHTO standard was completed.

Work Planned: Complete internal review and **s**ubmit draft AASHTO standard to Mixture ETG for consideration. Revise as needed after review.

Reason for Delay: Additional time was needed for internal review of the procedure prior to submission. Review is complete and draft standard will be submitted to FHWA by 4/30/2013.

Delivery Dates
Draft AASHTO Method: 4/30/2013 – extended from 3/31/2013 and 12/31/2012
Final AASHTO Standard: 9/30/2013

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: Curing molds were used to prepare samples in mixture design experiment. Based on initial results the molds were successful in maintaining the geometry of the sample during curing. Initial data also indicates that full curing is achieved using oven curing at 60°C for 72 hours. This time period was established based on monitoring of moisture loss in the sample at 24 hour increments. After 72 hours, no moisture loss was observed.

Work Planned: Continue use of curing molds in work related to development of CMA mix design procedure and develop an experimental plan to quantify strength gain with time for CMA.

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

DRAFT AASHTO TEST METHOD: RAP BINDER PG TRUE GRADE DETERMINATION

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

Status and Work Planned
Completed.

Work Completed: Work related to the importance of time and temperature on blending efficiency between virgin and recycled binders was completed. The results of this work indicate that both parameters significantly influence blending efficiency, thus have an effect on the properties measured by the mortar testing method. These results also provide technical justification for using the mortar grading procedure as it is the only available method that is capable of incorporating blending efficiency (through adjusting mixing time and temperature) into evaluation of the effects of recycled binders on performance properties.

Work Planned: Revise standard to reflect importance of mixing time and temperature on blending efficiency. Present justification for changes, new analysis template, and other items to Mix ETG at May meeting. Coordinate external review efforts or revise procedure based on outcomes of May 2013 ETG meeting. Submit final version of standard to FHWA.

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

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

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

Status and Work Planned
Completed.

Work Completed: In this quarter the team employed experimental and numerical modeling approaches (FEM) to assess energy dissipation through viscous dissipation and crack formation in asphalt binders using the SENB at low temperatures to assess range of applicability of Linear Elastic Fracture Mechanics (LEFM) to asphalt binders at low temperatures.

Work Planned: With a draft AASHTO standard document under consideration by the FHWA Binder Expert Task Group, efforts are aimed toward developing practical specification criteria to enable use of the BBR-SENB as a project specific binder selection and grading procedure.
A follow-up presentation may be given at the May 2013 Binder ETG meeting if requested.

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

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

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

Status and Work Planned
Completed

Work Completed: Completed draft AASHTO Standard. Document was submitted to FHWA for presentation to FHWA Binder ETG.

Work Planned: Presentation at May 2013 Binder ETG Meeting and revision of draft standard if necessary.

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

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

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

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

Status and Work Planned
Behind Schedule

Work Completed: Combined test procedures developed by UW Madison and University of Nevada Reno to allow for evaluation of thermo-volumetric and fracture properties in the same test method. Comparison tests on identical sets of material are being carried out by both UWM and UNR labs for comparison of test procedures in terms of equivalency.

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

Reason for Delay: Additional time was needed to coordinate combination of the test procedures. The standard is complete and is an agenda item for the May 2013 Mix ETG.

Revised Delivery Dates
Draft AASHTO Test Method: 4/30/2013 (extended from 3/31/2013 and 12/31/2012)
Presentation to Mix ETG (if necessary): 5/2/2013.
Final AASHTO Test Method: 6/30/2013

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

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

Status and Work Planned
Behind Schedule

Work Completed: Completed draft AASHTO standard inclusive of newly developed aggregate structure indices.

Work Planned: Internal review and submittal of draft AASHTO standard to the FHWA Mixture ETG to be considered for inclusion on the agenda for the fall 2013 ETG meeting.

Reasons for Delay: Minor delays were encountered due to internal review of the procedure. Review is complete and draft standard will be submitted by 4/30/2013.

Delivery Dates
Draft AASHTO Method: 4/30/2013 (extended from 3/31/2013)
Final AASHTO Standard: 9/30/2013

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
SubtaskE1c-1: Warm Mix Asphalt
Subtask E1c-2: Improvement of Emulsions' Characterization and Mixture Design for Cold Bitumen Applications

Status and Work Planned
Completed

Work Completed: Materials for development of the precision and bias statement were received and proportioned. Labs for participation were identified.

Work Planned: Develop work plan and complete precision and bias testing. Revise ASTM standard to include precision and bias statement and make any other revisions as needed.

Reasons for Delay: Delays encountered in developing work plan to address all aspects of precision and bias statement (i.e. single operator, multi-operator, multi-laboratory). Work plan will be developed and executed early in 2013Q2.

Delivery Dates
Draft ASTM Standard: Complete
Finalize ASTM Standard to include Precision and Bias Statement: 9/30/2013 (extended from 3/31/2013)

TEST METHOD AND ANALYSIS PROGRAM: SELF-CONSISTENT MICROMECHANICS MODELS 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, R., and Lytton, R. L. (2013). "Selective Absorption of Asphalt Binder by Limestone Aggregates in Asphalt Mixtures." *Journal of Materials in Civil Engineering*, Vol. 25, No. 2, American Society of Civil Engineers (ASCE), pp. 219-226.

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

Test method document:

The test method document has been completed and referenced in Report W "Characterization of Fatigue and Healing Properties of Asphalt Mixtures" as an appendix.

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

Status and Work Planned
On Schedule.

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

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

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

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

Proposed Grouping of Deliverables

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

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

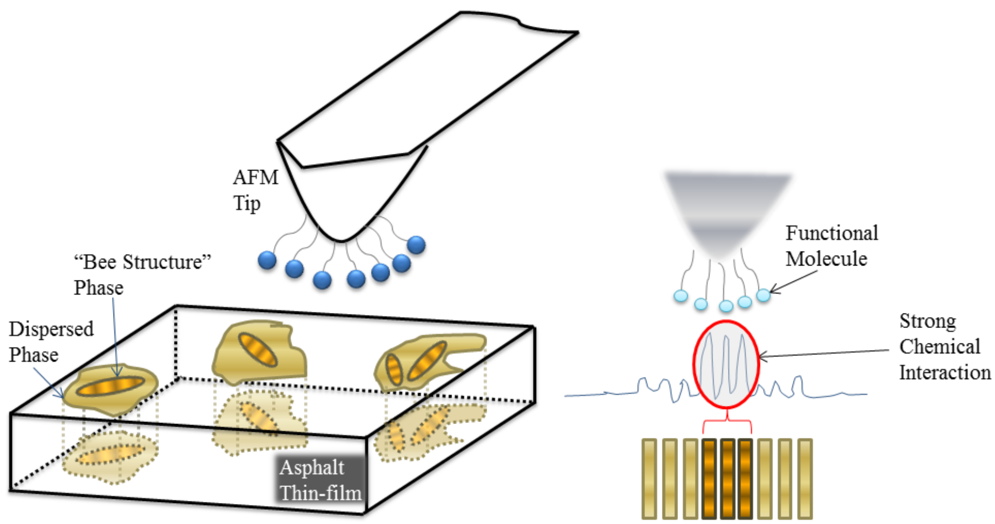


Figure F2d1. AFM mapping of surfaces with chemical contrast. By using the appropriate tip functionality, a specific surface image depicting chemical groups can be achieved based on the tip-surface interaction. (Adapted from Nanocraft).

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

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

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

Due to equipment problems with one of our AFM systems no work was conducted on this subtask this past quarter. We have some time allotted next quarter for work on this method, but we are currently sharing one instrument among three subtasks so progress is limited.

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
Delivery of a draft AASHTO ductile-brittle method has been delayed in order to incorporate a stress rate as well as a temperature parameter in the determination. The need to share equipment is also delaying progress on this subtask. To accommodate equipment sharing and add stress rate to the method we anticipate a six month delay for this deliverable.

Development of this test method will continue in the next quarter. An AFM-based direct tension test is being employed to assess ductile-brittle properties of asphalt binders. Results indicate that the transition is sensitive to stress rate as well as temperature. Current work is directed toward adding a variable stress rate term to the method.

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

A draft has been completed for an AASHTO AFM-based micro/nano-scale direct tension test. Results of this study show that rate-sensitive dissipated energy can be a significant component of the overall energy associated with asphalt fracture. Additional testing to validate and quantify this important concept continues.

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

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: None this quarter, review of standard was put on hold by the Mix ETG. FHWA made the decision to delay pursuit of AASHTO approval at this time.

Work Planned: Revise the standard as necessary or include it as an appendix in Report R.

Delivery Dates
Draft AASHTO Method: Complete (9/30/2012)
Final AASHTO Standard: Complete (3/31/2013) No further action required based on FHWA instruction.

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:

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

The following list the work planned for next quarter:

- Validate the developed software subroutine to predict temperature profile in asphalt layer using LTPP data.
- Evaluate the software subroutine to predict the carbonyl area growth as a function of time by comparing the prediction with the laboratory measured values.
- Assess the subroutine software to calculate thermal build-up stress in pavement.

SOFTWARE: DYNAMIC MODEL FOR FLEXIBLE PAVEMENTS 3D-MOVE

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

Status and Work Planned
On schedule.

Most of the work done in this quarter focused on the following: (1) debugging technical errors of the new version (Ver 2) and also the previous version (Ver 1.2); and (2) developing new platform for next 3D-Move version (Ver. 3); and (3) maintained the 3D-Move Forum.

Debugging Technical Errors

- The last beta-version of the 3D-Move Analysis (ver. 2.0) was released on February, 2013. After releasing, there have been some problems and questions related to pavement responses and performance models. Few users reported display of error messages when using the performance calculation option with SI units. This was traced to the wrong use of the performance models, many of which are unit sensitive. Many of the performance models were developed in US units and when the program is run in SI units, the entire inputs to the performance equations have to be changes to US units before use. This problem has been fixed.
- Another problem reported by some users revealed an incorrect use of dynamic modulus master curve developed in SI units with the performance models. This problem again was similar to issues pointed out in the preceding paragraph. This resulted in the wrong use of the modulus in the performance equation that predicts tensile fatigue cracking of the HMA. This problem has also been fixed.
- Additionally, another error which was reported relates to the installation of the software on 64 bit windows operation system. This problem was due to an inconsistency between 32 and 64 bit .net platforms. This problem has been fixed.
- Another problem encountered by some users was the slight differences in responses calculated by 3D-Move version (Ver 1.2) and current version (Ver 2.0) for dynamic load analysis cases. The DOS core of software was rechecked to find out the reasons of this issue. After rechecking, it was clear that the problem was due to some modifications done on DOS core of the software to reduce time of analysis. The Ver. 2.0 uses a higher time step in the calculation of dynamic response history. Therefore, when response values from the two versions of the program are compared side by side they will not match. However, when comparison is made after the time histories are plotted there are only minimal differences. 3D-Move assumes the pavement structure to be made of finite number of layers. When a semi-infinite case for the bottom layer (say subgrade) is to be considered, a sufficiently large thickness should be assumed for the subgrade when using 3D-Move. In Ver. 2.0, the case of semi-infinite bottom layer is modeled by assigning a thickness 240 times the combined thickness of layers above

- Finally, in version 1.2 there was a bug in the software when the database of non-uniform tire interaction pressures (Option C) is used with SI units. This problem has also been fixed.

New Platform for Next Version (Ver. 3)

The other work done in this quarter includes developing a new platform for next version of 3D-Move. The main features of this platform are:

- Capability of running two or more projects simultaneously by using parallel processing technology;
- Incorporation of additional empirical procedures that are available to calculate asphalt dynamic modulus;
- Interchangeability between SI and US unit systems, in the middle of a 3D-Move run;
- Use of Artificial Neural Network in the interpolation of non-uniform tire contact pressure distribution from the database;
- Inclusion of additional options for output in PDF and Crystal Report formats. Currently, the output is displayed in Text and Excel formats only.

The following list the work planned for next quarter:

- Assist users with issues ranging from usage questions, concepts clarifications, and bugs.
- Work on the new platform for next version of 3D-Move (Ver. 3).
- Keep maintaining the 3D-move forum.

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

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

Status and Work Planned
Technical work - On Schedule. Decision about integrating reports – final decision delayed.

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

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

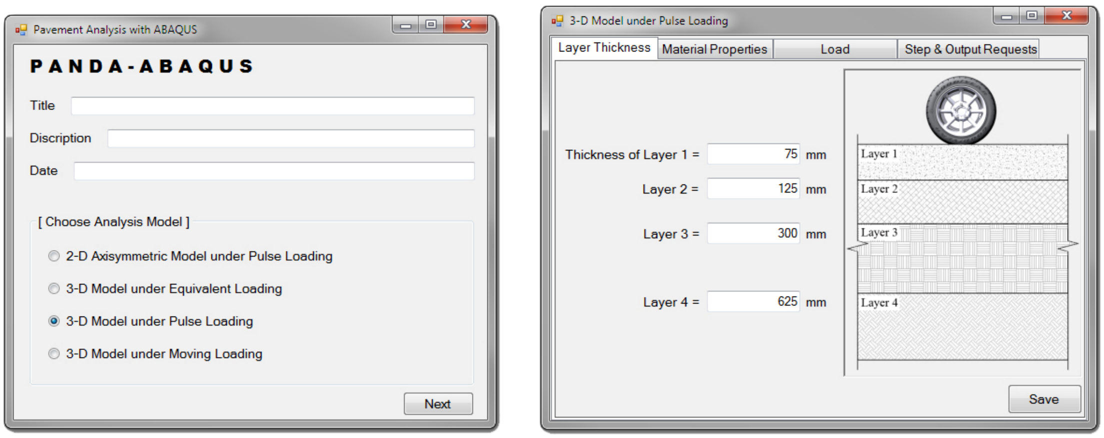
SOFTWARE: PANDA: PAVEMENT ANALYSIS USING A NONLINEAR DAMAGE APPROACH

Included Work Elements/Subtasks

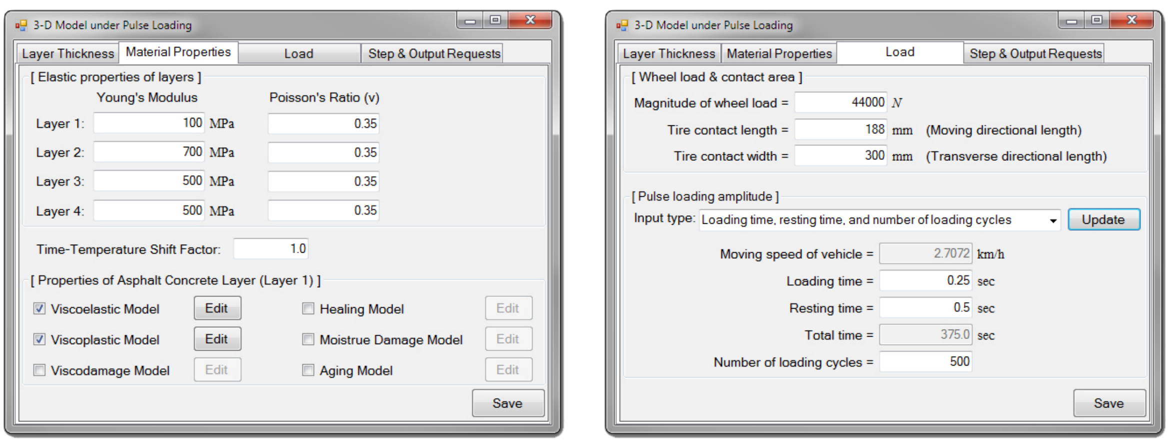
Status and Work Planned:

The PANDA User Interface (PUI) has been created to facilitate the use of the PANDA model in Abaqus software. In order to allow users to utilize versatile features of Abaqus without having in-depth knowledge in Abaqus pre-processing functions, the PUI was developed at Texas A&M University by a team of researchers who are familiar with Abaqus and have expertise in the development of user friendly interfaces. PUI is customized for pavement applications such that users can conduct performance simulations of pavements without having the in-depth knowledge of using Abaqus. In the PUI, users are required to specify the thickness of each layer, the properties of each layer, the wheel load magnitude, and the mode of analysis (e.g. 2D plane strain, 2D axisymmetric or 3D). The PUI translates these inputs into Abaqus language and creates the input file that can be used directly by Abaqus to perform the simulations. Therefore, users will benefit from all pre-processing and post-processing capabilities of Abaqus through the PUI.

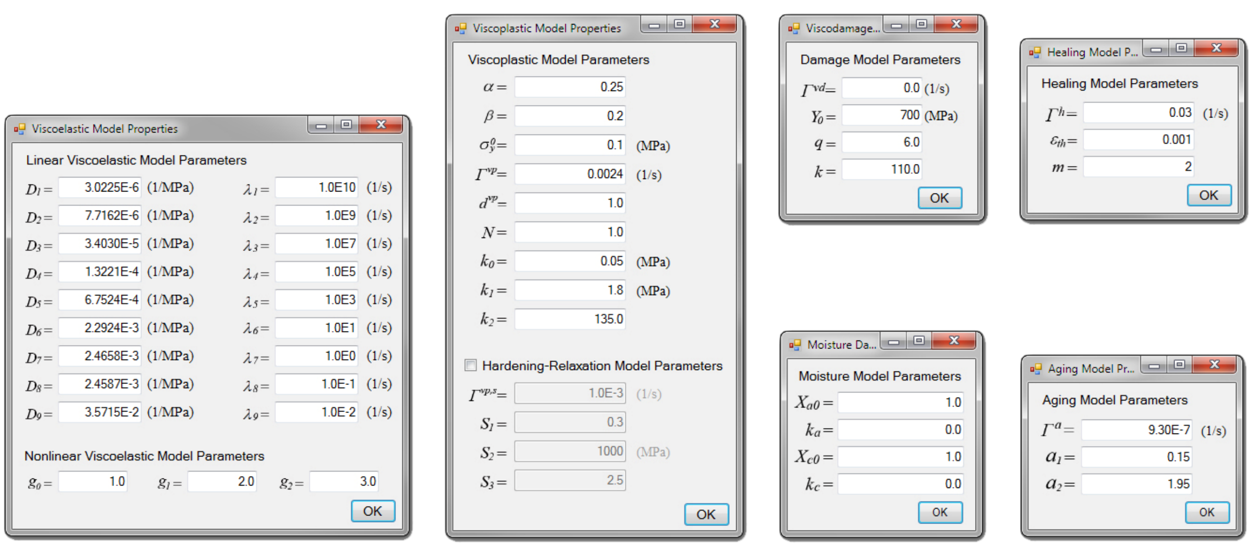
Figure 1 schematically shows different modules developed as part of PUI. A shown in figure 1, PUI interface enables the pavement engineers to simulate and analyze the pavement responses subjected to traffic loading without the need to create the model directly in Abaqus software. As the same time, researchers will have access to Abaqus and materials subroutines if they choose to further develop the models.



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



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



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

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

This interface has the following capabilities:

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

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

The focus of the current and future work is on refining the PUI and integrating PANDA parameter identifier package with PUI. The focus will also be on organizing a workshop during June 2013 to illustrate the effectiveness of using PANDA models with PUI. This workshop will present and provide training on Pavement Analysis using Non-Linear Damage Approach (PANDA) that is developed by the ARC researchers at Texas A&M University. The workshop will be offered over a span of two days. The first day will cover the theory of models used in PANDA, calibration of the PANDA constitutive models using experimental data, and laboratory experiments and analytical techniques that are used to determine model parameters. The second day will be devoted mostly to demonstrating the PANDA User Interface (PUI) that allows the user to access the capabilities of the model implemented in Abaqus finite element software without requiring in-depth experience in Abaqus pre-processing functions. This will be followed by conducting sensitivity analyses of PANDA response using different material properties and pavement structures.

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

Subtask E2b-2: Compatibility of RAP and Virgin Binders

Status and Work Done This Quarter

The Pal-Rhodes model that was developed from Einstein's colloidal theory to account for the flow properties of more concentrated suspensions was employed to characterize the flow properties of extracted recycled asphalt pavement (RAP) binder blends with virgin asphalt. The Pal-Rhodes model used for studing the RAP/virgin blend binders is formulated as follows:

$$\eta_{blend} = (\eta_0)\left(1 - K_{blend}(x_a)\right)^{-2.5} \tag{1}$$

Where

η_{blend} = viscosity of blend binder
η_0 = viscosity of maltene fraction
x_a = asphaltene content
K= solvation factor

The viscous property of the continuous maltene (solvent) phase of the blend is defined as

$$(\eta_0) = x_{RAP}(\eta_0)_{RAP} + x_{neat}(\eta_0)_{virgin} \tag{2}$$

while the asphaltene (suspended) phase is defined as

$$(x_a) = x_{RAP}(x_a)_{RAP} + x_{virgin}(x_a)_{virgin} \tag{3}$$

Given the mass fractions of RAP x_{RAP} and virgin x_{virgin} asphalt to be blended, the respective asphaltene contents will be $(x_a)_{RAP}$ and $(x_a)_{neat}$ and maltene viscosities will be $(\eta_0)_{RAP}$ and $(\eta_0)_{virgin}$, respectively.

Equation 1 indicates that the viscosity of the blended binder can be expressed as a function of the viscosity of the maltene fraction of the blend and the asphaltene content of the blend. The viscosity of the maltene fraction of the blend can be expressed as a linear function of the virgin binder and RAP binder, as shown in equation 2. The asphaltene content of the blended binder can also be expressed by linear relationship of the virgin binder asphaltene content and the RAP binder asphaltene content, as shown in equation 3.

The results from our data at 20°C and 0.005 rad/sec show that different extracted RAP binders influence virgin binders differently in terms of their rheological behavior. For example, the extracted Manitoba RAP binder has a greater effect on RTFO-aged asphalt AAA-1 than on RTFO-aged asphalt AAC-1. On the other hand, the South Carolina extracted RAP binder has a greater effect on RTFO-aged asphalt AAC-1 than on RTFO-aged asphalt AAA-1.

Work Planned Next Quarter

Solubility parameters based on the measurements from Automated Flocculation Titrimetry (AFT) for RTFO-aged asphalts and the blends with extracted RAP binders will be conducted. Rheological properties will be correlated to solubility parameters to investigate how compatibility properties relate to rheological properties with respect to different RAP binder contents.

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

Work Done This Quarter

Extensive work on Work Element E3a: Effects of Extenders and Alternative Binders on Performance was completed this quarter, including the addition of 6 new extender types to the work plan. High, intermediate and low temperature binder testing has been carried out on the extended binders and blending relationships have been developed for use of this material. Chemical and structural analysis is also underway parallel to these activities to determine nature and mechanisms of extender effect on binders. The results of this work will be integrated into Report N.

Work Planned Next Quarter

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

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

Significant Problems, Issues and Potential Impact on Progress

None.

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

Work Done This Quarter

Development continued for the fresh emulsion characterization framework, specifically as it relates to application of the BBS test to estimate curing of emulsions. All procedures were finalized and implemented on additional materials. A total of six emulsions have been tested including those applied to chip seals, spray seals, and micro-surfacing. The performance properties of the recovered and PAV aged residues for these materials were also evaluated using the performance tests selected based on intended field application.

A new opportunity for validation was discovered through collaboration with NCAT. Field sampled materials were received and residues recovered. Field monitoring of performance by NCAT is now underway. WRI also continues validation efforts to sample emulsions, extract particulate matter, and measure performance properties (using 4 mm parallel plate) on four chip seal sections constructed nearly four years ago as part of the federal lands project.

The decision was made to suspend any investigation into different residue recovery methods until a standard procedure for the alternative vacuum recovery method becomes available.

Work Planned Next Quarter

Apply fresh emulsion and emulsion residue testing frameworks to additional emulsions intended for use in all three major applications. Test procedures will be evaluated and revised as necessary.

Residue properties of materials from NCAT sections will be tested and compared to early performance data measurements. WRI will continue work on validation work related to FLH sections. UW-MARC will pursue potential validation sites in Wisconsin.

Proposed Research Product and Timeline

Results will be summarized as part of Report Q: Improvement of Emulsion Characterization and Mixture Design for Cold Bitumen Applications

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

Work Element E3c: Laboratory Assessment of Mixture Long Term Aging

Work Done This Quarter

Experimental and theoretical work continued this quarter to define the critical properties of mineral aggregates that affect aging, through evaluation of asphalt mastics. Two additional filler types were added to the matrix and laboratory aging and extraction tests were conducted on a large number of mastics formulations consisting of two base binders with very different asphaltene content and a number of fully characterized mineral aggregate fillers at different volume fractions. Aging evaluation was carried out both by looking at the aging ratio as defined by the ratio of complex shear modulus before and after aging as an indicator of effect on mechanical properties, and change of average coefficient of contraction and glass transition temperature through dilatometric Tg measurements as a measure of structural and chemical composition changes through aging. These studies have provided an indication of the effect of aggregate mineralogy and properties in terms of affecting binder compositional changes during aging.

Work Planned Next Quarter

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

Proposed Research Product and Timeline

Results will be summarized in a final report titled: “Laboratory Assessment of Long Term Aging of Asphalt Mixtures” it is proposed this deliverable be labeled as “Report Z.”
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

No WMA monitoring was planned in this quarter.

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

WRI

Sampling of construction materials and construction monitoring of a new Arizona RAP project on SR 74 was conducted in February and March 2013 by both WRI and NCAT personnel. The project used two different crude source asphalts with three levels of RAP, 0, 20, and 30 percent. The two asphalt sources were from Valero and Paramount. There were two different grades of each asphalt used, PG 76-16 for the 0 and 20 percent RAP mixes and PG 70-22 for the 30 percent RAP mixes. Arizona DOT policy PPD 20 required the binder grade change at the 30 percent RAP level. The same aggregate source and RAP source was used for all sections and the same gradation was used for comparable sections, i.e. the gradation for the 0 percent RAP Paramount and Valero sections was the same, etc.

The project consisted of milling 3 inches of the existing pavement and replacing with 3 inches of new mix. The existing pavement removed during milling was not used as the RAP source for the project. The contractor had prepared coarse and fine RAP stockpiles prior to the start of the project. Approximately 7000 feet of each mix was placed, all in the westbound lane on SR 74 approximately between milepost 10 and milepost 2. A ¾ inch surface course using terminal blend crumb rubber (AR-ACFC) was placed over all of the sections in April 2013. However, the width of the milling was approximately 1 foot wider than the surface course which will allow an ability to obtain core samples in the future to assess the aging of the 6 mixes.

Sampling of all construction materials was performed during construction with a total of 478 five-gallon samples obtained. Most of the sampled material will be shipped to the FHWA-MRL in Sparks, Nevada. Core samples were obtained of each placed mix.

After placement of the AR-ACFC surface course in April, 12 500-foot performance monitoring sections were identified and marked, 2 monitoring sections per material.

NCAT
The project team documented mix production and field construction in four field projects last year. Each project included two test sections as follows:

1. The first project was constructed on I-84 in Connecticut. The same mix design with approximately 20 percent RAP was produced hot with and without a foaming WMA technology for the two test sections.
2. The second project was built on US 287 in Texas. The same mix design with 20% RAP and 5% RAS was used in this project. The mix was produced hot for the control section and produced warm with the Cecabase additive for the test section.
3. The third field project was built on US 69 in Mississippi. Two different mix designs were used in this project. The mix paved in the control section used 15% RAP and that in the test section used 25% RAP. Both the mixes were produced warm with a foaming WMA technology.
4. The fourth project was constructed on County Road 159 as part of the pavement preservation study at NCAT. Three 4.75 mm mixes—virgin mix, 45% RAP mix, and 5% RAS mix—were produced for thin lift overlays in this project.

Laboratory testing of the materials sampled from the four field projects last year is underway at NCAT.

<u>Work Planned</u>

The project team will continue testing the materials sampled from the four field projects last year. In addition, the team is preparing for field projects that are planned for this year as follows:

1. Four test sections will be built in early May on I-70 between Eagle and Wolcott, Colorado. The four sections will include 20% RAP HMA (control), 20% RAP WMA, 30% RAP HMA and 30% RAP WMA. Except for the control mix, 2500 tons will be produced and paved for the three test mixes.
2. The project team is still working with a contractor to build six test sections in Indiana. Data from these test sites will be shared between this task and NCHRP 9-52.