Western Research INSTITUTE

Asphalt Research Consortium

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INTRODUCTION

This document is the Quarterly Report for the period of April 1 to June 30, 2012 for the Federal Highway Administration (FHWA) Contract DTFH61-07-H-00009, the Asphalt Research Consortium (ARC). The Consortium is coordinated by Western Research Institute with partners Texas A&M University, the University of Wisconsin-Madison, the University of Nevada Reno, Advanced Asphalt Technologies, and the National Center for Asphalt Technology.

This Quarterly Report is presented in an entirely new format based upon discussions 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 four areas, Reports, Test Methods and Practices, Models and Software, and Other Research Activities. 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 April 1 to June 30, 2012 is first quarter of the Year 6 contract year. Reviewers may want to reference the previous Annual Work Plans and many other documents that are posted on the ARC website, www.ARC.unr.edu. The more detailed information about the research such as approaches to test method development, data collection, and analyses will be reported in research publications as part of the deliverables.

SUPPORT OF FHWA AND DOT STRATEGIC GOALS

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

TABLE OF ASPHALT RESEARCH CONSORTIUM DELIVERABLES

(Note: Highlighted areas show changes)

Deliverable	Description	ARC Member	Draft Submittal Date	Final Submittal Date
Report A	Summary report on Moisture Damage	TAMU	12/30/2011	10/30/2013
Report B	Characterization of Fatigue Damage and Relevant Properties	TAMU	3/30/2012	10/30/2013
Report C	**PANDA:** Pavement Analysis using a Nonlinear Damage Approach	TAMU	3/30/2013	10/30/2013
Report D	Characterization of Asphalt Binders using Atomic Force Microscopy	TAMU	3/30/2013	10/30/2013
Report E	Lattice Model and Continuum Damage to Fracture	NCSU	12/30/2011	8/30/2012
Report F	Microstructure Cohesive Zone Modeling for Moisture Damage and Fatigue Cracking	UNL	12/30/2011	8/30/2012
Report G	Design System for HMA Containing a High Percentage of RAP Material	UNR	12/31/2013	3/31/2014
Report H	Critically Designed HMA Mixtures	UNR	5/31/2013	11/30/2013
Report I	Thermal Cracking Resistant Mixes	UNR	8/31/2013	12/31/2013
Report J	Pavement Response Model to Dynamic Loads 3D Move	UNR	3/31/2013	9/30/2013
Report K	Development of Materials Database	UNR	6/30/2013	12/31/2013
Report L	Development and Validation of the Bitumen Bond Strength Test (BBS)	UWM	Completed 10/31/11	9/30/2012
Report M	Development of Test Procedures for Characterization of Asphalt Binder Fatigue and Healing	UWM	Completed 10/31/11	9/30/2012
Report N	Guideline for Selection of Modification Techniques	UWM	9/30/2013	6/30/2014
Report O	Characterization of Binder Damage Resistance to Rutting	UWM	12/31/2012	8/31/2013
Report P	Quantifying the Impacts of Warm Mix Asphalt on Constructability and Performance	UWM	3/31/2013	10/31/2013
Report Q	Improvement of Emulsion Characterization and Mixture Design for Cold Bitumen Applications	UWM	9/30/2013	6/30/2014
Report R	Studies on Tire-Pavement Noise and Skid Response	UWM	Completed 12/31/11	9/30/2012
Report S	Molecular dynamics results for multiple asphalt chemistries	URI	5/31/2013	12/31/2013
Report T	Progress Toward a Multi-scale Model of Asphalt Pavement- Including Test Methods for Model Input Parameters	WRI	5/31/2013	12/31/2013
Report U	Design Guidance for Fatigue and Rut Resistance Mixtures	AAT	12/31/2012	6/30/2013
AASHTO Method	Simplified Continuum Damage Fatigue Analysis for the Asphalt Mixture Performance Tester	AAT	12/31/2012	6/30/2013
AASHTO Method	Wilhelmy Plate Test	TAMU	Completed	9/30/2012
AASHTO Method	Universal Sorption Device	TAMU	Completed	9/30/2012
AASHTO Method	Dynamic Mechanical Analysis	TAMU	Completed	9/30/2012
ASTM Method	Automated Flocculation Titrimetric Analysis	WRI	Completed	
AASHTO Method	Determination of Polymer in Asphalt	WRI	Completed	
AASHTO Method	A Method for the Preparation of Specimens of Fine Aggregate Matrix of Asphalt Mixtures	TAMU	12/31/2010	7/31/2012
AASHTO Method	Measuring intrinsic healing characteristics of asphalt binders	TAMU/UT	12/31/2010	9/30/2012

Deliverable	Description	ARC Member	Draft Submittal Date	Final Submittal Date
AASHTO Method	Test Methods for Determining the Parameters of Material Models in PANDA (Pavement Analysis Using Nonlinear Damage Approach)	TAMU	12/31/2010	3/31/2013
Test Method & Model	Continuum Damage Permanent Deformation Analysis for Asphalt Mixtures	TAMU	11/30/2013	5/31/2014
Test Method & Model	Characterization of Fatigue and Healing Properties of Asphalt Mixtures	TAMU	10/31/2013	4/30/2014
Test Method Analysis Program	Nondestructive Characterization of Tensile Viscoelastic Properties of Undamaged Asphalt Mixtures	TAMU	Completed	
Test Method & Model	Characterization of Field Cores of Asphalt Pavements	TAMU	9/30/2013	3/31/2014
Test Method Analysis Program	Nondestructive Characterization of Anisotropic Viscoelastic Properties of Undamaged Asphalt Mixtures under Compressive Loading	TAMU	Completed	
AASHTO Practice	Mix Design for Cold-In-Place Recycling (CIR)	UNR	12/31/2013	
AASHTO Practice	Mix Design for Cold Mix Asphalt	UWM	9/30/2013	
AASHTO Practice	Evaluation of RAP Aggregates	UNR	12/31/2012	
AASHTO Practice	Identification of Critical Conditions for HMA mixtures	UNR	12/31/2012	
AASHTO Method	Thermal Stress Restrained Specimen Test (TSRST)	UNR	5/31/2012	
AASHTO Method	Determining Asphalt Binder Bond Strength by Means of the Bitumen Bond Strength Test (BBS)	UWM	Completed	
AASHTO Method	Measurement of Asphalt Binder Elastic Recovery in the Dynamic Shear Rheometer (DSR)	UWM	12/31/2012	
AASHTO Method	Estimating Fatigue Resistance of Asphalt Binders Using the Linear Amplitude Sweep	UWM	Completed	
AASHTO Method	Binder Yield Energy Test (BYET)	UWM	Completed	
AASHTO Method	Measurement of Rigden Voids for fillers	UWM	9/30/2012	
AASHTO Method	Measurement of Asphalt Binder Lubricity Using the Dynamic Shear Rheometer (DSR)	UWM	3/31/2013	
AASHTO Method	Procedure for Evaluation of Coating for Cold Mix Asphalt	UWM	12/31/2012	
AASHTO Method	Cold Mix Laboratory Specimen Preparation Using Modified SGC Molds	UWM	5/31/2013	
AASHTO Method Software	RAP Binder PG True Grade Determination	UWM	12/31/2012	
AASHTO Method	Measurement of Asphalt Binder Fracture Properties Using the Single Edge Notch Bending Test	UWM	9/30/2012	
AASHTO Method	Test Method for Measurement of the Glass Transition Temperature of Asphalt Binders	UWM	12/31/2012	
AASHTO Method	Test Method for Measurement of the Glass Transition Temperature of Asphalt Mixtures	UWM	12/31/2012	
AASHTO Method Software	Analysis of Asphalt Mixture Aggregate Structure through Use of Planar Imaging and Image Processing & Analysis System (IPAS)	UWM	3/31/2013	

Deliverable	Description	ARC Member	Draft Submittal Date	Final Submittal Date
AASHTO Method	Determining the Resistive Effort of Asphalt Mixtures during Compaction in a Gyrator Compactor using an Internal Device	UWM	Completed	3/31/2013
AASHTO Method	Micromechanical Properties of Various Structural Components in Asphalt using Atomic Force Microscopy (AFM)	TAMU	3/1/2011	10/30/2013
AASHTO Method	Test Method for Fatigue of Binder and Mastics: A cyclic direct tension test that can provide direct evaluation of fatigue for binder and mastic. It can also provide model validation and model parameter inputs.	VT	4/30/2013	
AASHTO Method	Evaluate Healing using Continuum Damage Approach	TAMU/UT	12/30/2012	10/30/2013
Test Method & Analysis Program	Self-Consistent Micromechanics Models of Asphalt Mixtures	TAMU	Completed	
Test Method & Analysis Program	Rutting Prediction of Asphalt Binder Considering Stress-Dependence of Creep Behavior	TAMU	12/31/2012	
AASHTO Method	Method to determine surface roughness of aggregate and fines based on AFM	WRI	1/30/2013	
AASHTO Method	A method to determine ductile-brittle properties via AFM measurements	WRI	4/30/2013	
AASHTO Method	AFM-based micro/nano-scale cyclic direct tension test	WRI	3/31/2013	
Model	HMA Thermal Stresses in Pavement	UNR	3/31/2014	
Software	Dynamic Model for Flexible Pavements 3D-Move	UNR	9/30/2013	
Model	Improved Oxygen and Thermal Transport Model of Binder Oxidation in Pavements	TAMU	10/31/2012	3/31/2013
Model	Pavement Air Voids Size Distribution Model for use in an Oxygen and Thermal Transport Model of Binder Oxidation in Pavements	TAMU	10/31/2012	3/31/2013
Model	Approaches to interpret MD simulation results and experimental data to quantify the composition and temperature dependence of free energy.	URI	12/31/2012	
Model and Software	Phase-Field Model of Asphalt Binder Fracture and COMSOL Code for Model	VT	1/31/2013	
Software	PANDA Software (Pavement Analysis using a Nonlinear Damage Approach)	TAMU	10/1/2013	

REPORTS

REPORT A: SUMMARY REPORT ON MOISTURE DAMAGE

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: In this quarter, the coefficient of water vapor diffusion was modeled using Equation 1 for both Nustar and Valero binder. In order to measure this water vapor diffusion coefficient, the fine asphalt mixture (FAM) specimens were exposed to a relative humidity of 100% at a constant room temperature of 23°C for a period of 4 months. During the experiment, the overall mass increase of the specimens is measured with a micro balance scale with accuracy of 0.001 gram. The model used to measure the water vapor diffusion coefficient can be expressed as:

$$M_{abs}(t) = M_{\max}(1 - e^{-\alpha t}) \tag{1}$$

where M_{abs} = the mass increase of specimens with the increase of time; $M_{\max}$ = the maximum mass that the specimen can gain; and α = the exponential rate of water diffusion. This model can be modified to satisfy the typical diffusion equation, and an approximation is given in Equation 2.

$$M_{abs}(t) = M_{\max}\left(1 - e^{-\frac{3Dt}{\left(d/2\right)^2}}\right) \tag{2}$$

where D= the diffusivity of fine aggregate mix (m^2/s); and d = the diameter of the specimen (m).

From the measured data, the water diffusivity in FAM specimen with Valero binder ranges from $2.12E^{-11}$ m^2/s to $3.04E^{-11}$ m^2/s and the water diffusivity in FAM specimen with Nustar binder ranges from $2.29E^{-11}$ m^2/s to $2.85E^{-11}$ m^2/s, both of which are within reasonable ranges compared to the literature data.

Another task that was accomplished in this quarter is that the both of the dry and wet FAM specimens fabricated with the Valero and Nustar binders are tested using the Dynamic Mechanical Analyzer (DMA) to obtain their fatigue properties.

REPORT B: CHARACTERIZATION OF FATIGUE DAMAGE AND RELEVANT PROPERTIES

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

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

Work Element F1d: Healing.

Status and Work Planned: Work is on schedule. We have completed the work associated with characterizing the intrinsic healing of asphalt binders as well as the overall healing in asphalt composites (mortars) using the viscoelastic continuum damage or work potential theory. The protocol is currently being revised and applied to different modes of loading and other core ARC materials as discussed in the on-going technical research.

Work Element F1b: Viscoelastic Properties.

Subtask F1b-1: Viscoelastic properties under cyclic loading.

Status and Work Planned: During the previous quarters we have reported a constitutive model and a methodology to measure the nonlinear viscoelastic properties of asphalt binders as well as the effect of the multi-axial stress state on these properties. The model was calibrated and validated using the Dynamic Shear Rheometer (DSR). The findings from this work have been published (or are in publication queue) in the form of journal articles in the Journal of the Mechanics of Time Dependent Materials. In addition, the time dependent nature of the bulk modulus and Poisson's ratio for asphalt binders was also determined. These measurements are very important to clarify some of the assumptions that are typically made during computational modeling of asphalt materials. The findings from this part of the study are currently being documented in the form of two journal articles.

Following the work on the asphalt binders and based on the inputs received from the members of the models ETG, the affect of multi-axial stress state and nonlinearity on viscoelastic and damage properties of asphalt composites (mortars) is currently being measured. Although the constitutive modeling is the same as before, the experimental method was changed to use the Arcan apparatus instead of the DSR.

During this and the previous quarter we had conducted some preliminary tests to measure the linear viscoelastic properties as well as damage evolution in FAM specimens subjected to a multi-axial stress state. Computational modeling of FAM specimens with different geometries in an Arcan apparatus was carried out. This was done to optimize the dimensions of the FAM specimen that would yield a uniform stress-state across the cross-section and subsequently facilitate the analysis of the test results.

In the next quarter we plan to continue testing with the Arcan apparatus to quantify the influence of multi-axial stress state on the linear viscoelastic properties of the core ARC materials.

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 quarters, we reported a test and analytical procedure to measure the overall healing in asphalt composites (fine aggregate matrix) using a dynamic shear rheometer (DSR). The characteristic overall healing curve for the material was shown to be independent of the mode of loading used to obtain the curve. This approach is largely based on the Viscoelastic Continuum Damage theory (VECD) that is currently used for the analysis of fatigue cracking resistance of asphalt mixtures using the asphalt materials performance tester (AMPT).

Two variations of this approach are currently being carried out. The first variation is to improve the test protocol by applying several combinations of damage and rest period to the same test specimen, thereby reducing the number of test specimens required. Tests along this line are currently in progress and data are being analyzed and compared to the previous protocol to validate this approach.

Work Element F1c: Material Properties: Aging.

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

Status and Work Planned: 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.

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.

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

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

Status and Work Planned: The work on this report is on schedule. All the constitutive equations that are necessary for predicting the thermo-hygro-chemo-mechanical properties of asphalt mixtures and the performance of asphalt pavements have already been incorporated into PANDA. Therefore, the mechanistic-based approach for integrating rutting, fatigue damage, micro-damage healing, moisture-induced damage, and oxidative aging has already been incorporated in the PANDA model. The focus of the current and future work is on further calibration and validation of the PANDA model against available and collected experimental data.

Work Element M4c: Unified Continuum Model.

Status and Work Planned: The moisture-induced damage model as part of PANDA has been fully developed and numerically implemented. Emphasis is placed on the consideration of the pore-water pressure that accelerates crack evolution and propagation due to presence of moisture and washing away of the mastic due to flow of moisture through the asphalt cracks and void both as a result of fast traffic loading.

Moreover, 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 completely show the crack propagation and damage concentration after moisture conditioning the specimens. These simulations can be used to conduct virtual moisture-damage simulation experiments.

Since the ARC experimental data from North Carolina State University are available now, the focus of the next quarter is on analyzing the data in order to fully calibrate and validate the moisture-induced damage model in PANDA.

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

Status and Work Planned: In this quarter, the continuum micro-damage healing model, which has been developed by Abu Al-Rub and co-workers [see e.g. Abu Al-Rub et al. (2010), Abu Al-Rub and Darabi (2012), Darabi et al. (2012a, 2012b)], is validated against extensive experimental data that are done in tension and are part of the ALF data. These tests include constant strain rate, cyclic displacement controlled, and cyclic stress controlled tests over a range of temperatures, strain rates, loading frequencies, and stress/strain levels/amplitudes. The results from this validation have been reported in Darabi et al. (2012c). Furthermore, the model predictions show that the coupled viscoelastic-viscoplastic-viscodamage-healing (VE-VP-VD-H) 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 significant results from the developed continuum damage-healing frameworks have been detailed in Darabi et al. (2012c).

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

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

Status and Work Planned: See M4c for details on the progress in the development of the continuum-based moisture-induced damage mode. Also see F1d-8 on the development of the continuum-based micro-damage healing model. We have completed the calibration and validation of the nonlinear viscoelastic and viscoplastic constitutive models in PANDA using the ALF laboratory data based on compression and tension data under different temperatures. Moreover, a key-element in the constitutive modeling of the viscoplastic deformation of asphalt concrete has been developed and fully validated. This key-element is a newly proposed viscoplastic deformation mechanism called "*viscoplastic hardening-relaxation*". The viscoplastic hardening-relaxation refers to the partial recovery in the hardening ability of the asphalt concrete during the rest period (or unloading time). Therefore, the asphalt concrete can accumulate more permanent deformation during the next loading cycle. In fact, it is shown in Darabi et al. (2012a, 2012b) that none of the available viscoplasticity theories are capable of predicting the accumulation of permanent deformation in asphalt mixtures under cyclic loading conditions, specifically at high temperatures. Therefore, the physically-based viscoplastic hardening-relaxation mechanism should be incorporated for effective modeling of the permanent deformation of asphalt concrete and in turn modeling the rutting performance of asphalt pavements.

A cyclic hardening-relaxation model is proposed that significantly enhances the prediction of the viscoplastic strain of asphalt concrete under cyclic compressive-loading conditions at high temperatures. The hardening-relaxation mechanism is physically tied to the changes in the material's microstructure during the rest period. A memory surface that memorizes the viscoplastic deformation history is defined in the viscoplastic strain space as the general initiation and evolution criteria for the hardening-relaxation mechanism. The proposed model is implemented in PANDA-Abaqus and in the PANDA standalone finite element software. Model predictions show that the proposed model predicts well both axial and radial viscoplastic responses of asphalt concrete subjected to the cyclic creep tests at different loading times, unloading times, confinement levels, and loading scenarios.

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

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

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

Continuum-based Model for Aging

<u>Status and Work Planned</u>: In this quarter, the mechanistic-based phenomenological oxidative aging (or oxidative aging hardening) model has been fully developed and implemented into PANDA. The details of this oxidative aging model have been presented in Abu Al-Rub et al. (2012). The model is based on introducing a physically-based oxidative aging internal state variable which captures the effect of aging on the viscoelastic, viscoplastic, and viscodamage responses of bituminous materials. 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 that include single creep, creep-recovery, repeated creep-recovery, monotonic tension and compression, uniaxial tensile and compressive loading-unloading, and relaxation tests as well as against the rutting performance simulations of an asphalt layer. It is shown that the proposed aging model predicts proper trends for the effect of oxidative hardening on the various mechanical properties of the asphalt concrete, such as the increase in the stiffness and strength, the decrease in ductility, and early initiation and rapid evolution of damage with aging.

The oxidative aging model as part of PANDA will be validated against the available experimental data from the ARC testing. The data from North Carolina State University are available and will be used for further calibration and validation of oxidative aging model.

<u>Work Element V3c</u>: Validation of PANDA.

<u>Status and Work Planned:</u> 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. This identification procedure is based on a repeated creep-recovery test at various stress levels. It is concluded that the nonlinear viscoelastic material parameters are strongly dependent on the level of the confinement pressure such that these parameters should be made a function of the triaxial ratio (i.e. the ratio of the mean stress to the von Mises effective shear stress). The dynamic modulus tests as well as the repeated creep-recovery test at various stress levels, conducted as part of the ARC testing plan, have already been used for calibrating the viscoelastic and viscoplastic models, respectively. The aging data based on the dynamic modulus test are available and currently used for calibration and validation of the oxidation aging model.

Also, we have continued to carry out the ARC testing plan on the first asphalt mixture in compression. The data in tension are now available as provided by North Carolina State University. The list of planned tests has been presented in the 6th year work plan. Almost 80% of the planned testing on the first asphalt mixture is finished.

Focus will be placed on validation of PANDA using the ARC testing plan. The compression testing is currently conducted at Texas A&M University whereas the tensile testing is conducted at North Carolina State University.

REPORT D: CHARACTERIZATION OF ASPHALT BINDERS USING ATOMIC FORCE MICROSCOPY

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.

REPORT E: MULTISCALE VIRTUAL FABRICATION AND LATTICE MODELING REPORT ON LATTICE MODEL AND CONTINUUM DAMAGE TO FRACTURE

Work Element M4a: Lattice Micromechanics Model and Model to Bridge Continuum Damage and Fracture.

Lattice Modeling

Status and Work Planned: This task is on schedule.

In the previous quarter, a trend of under-prediction was observed for the master curve of each scale of the material, with the most significant under-prediction found in the fine aggregate matrix (FAM) scale. The other predictions seem to be reasonably close to the experimental observations.

The significant error found in the predictions is believed to be caused by the inability to capture the load paths that run through the aggregate-to-aggregate particle contacts inside the material. The current algorithm creates particles in a dilute form, and it specifically prohibits aggregate particles from touching each other. Although a simple solution could be to remove this condition that prohibits aggregate contact, such an approach creates visually unrealistic microstructures.

Preliminary implementation of this concept shows improvement in upscaling the master curve of the mastic to that of the FAM. Further work is underway, and the results will be presented in the next quarterly report.

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.

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.

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.

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

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:

- Completed the report entitled: "Effect of Extraction Methods on the Properties of Aggregates in Reclaimed Asphalt Pavement." This report will be incorporated in the comprehensive Report G. Furthermore, the findings of this study were considered by NCAT in the NCHRP 9-46 project for high RAP mix design.
- UW has completed the continuous grade evaluation procedure; a master's thesis is available and the procedure will be summarized in the final report.

The following list the work planned for next quarter:

- Conduct a literature review pertinent to the specification of Dust Proportion (DP) for HMA mixtures and evaluate its applicability to RAP mixtures.
- Review actual RAP mixtures from various sources to establish representative ranges of DP in actual RAP mixtures being produced and constructed around the country. In addition, review any available field performances of the identified RAP mixtures.
- Evaluate the recommendations of NCHRP 9-45 regarding the impact of fillers on the constructability and performance of HMA mixtures and their applicability to RAP mixtures.
- Submit AASHTO Draft Procedure for continuous grading to FHWA Asphalt Mixture and Construction Expert Task Group for review and consideration.
- Ruggedness and expanding database for continuous grade procedure, inclusive of different RAP and RAS sources.

REPORT H: CRITICALLY DESIGNED HMA MIXTURES

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

Status and Work Planned
Accelerated Schedule.

The following list describes the work items completed this quarter:

- UNR completed all the testing for the mixtures listed in the experimental matrix of the FN study.
- A report entitled: “Flow Number Experiment: Asphalt Mixtures Critical Temperatures for Rutting Evaluation,” summarizing the findings and the recommended procedure for rutting evaluation of HMA mixtures was submitted to FHWA Asphalt Mixture and Construction Expert Task Group for review and input.

The following list the work planned for next quarter:

- Validate the findings of the FN study using two mixtures from WesTrack and two mixtures from local projects in Reno, Nevada.
- Assess the use of AMPT to determine the critical conditions of an asphalt mixture.
- Submit a draft version of Report H to FHWA for review and feedback.

REPORT I: THERMAL CRACKING RESISTANT MIXTURES

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

Status and Work Planned
On Schedule.

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

- Completed all of the original binder kinetics and mixture aging for the thermal cracking analysis.
- Except for the TSRST and Direct Tension, all the mixture testing has been completed. Testing is currently being conducted on laboratory aged and field validation samples.
- 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. Almost 65% of the binder aging and 25% of the binder testing have been completed thus far.
- Subsequent to some recent findings related to the systematic shifting of the activation energy of binders aged in mixtures and in laboratory pans, additional mixtures are being prepared and aged at 85°C. These mixtures will then be tested in the same manner as the previous mixtures aged at 60°C.
- Completed the enhancements to the TSRST in the areas of specimen shape, gluing process, and thermal strain modular setup. A mathematical solution was developed to provide the following low temperature properties for asphalt mixtures:
    - Transition temperature and modulus
    - Slope of thermal relaxation modulus at transition
    - Micro-cracking initiation temperature and modulus
    - Micro-cracking initiation stress
    - Fracture temperature and modulus
- Continued the modeling effort for the temperature profile and carbonyl area predictions.
- UW has completed chapters for SENB testing and TG and CTE characterization, measurement and sensitivity analysis.

The following list the work planned for next quarter:

- Continue mixture aging and testing of laboratory aged and field validation samples.
- Conduct mix designs for selected core materials.
- Assess the effect of cooling rate and initial starting temperature on the low temperature properties of asphalt mixtures.
- Assess and correlate the linear viscoelastic properties of asphalt mixtures with the aging level of asphalt binders through the measured carbonyl area values.
- Continue working on the thermal cracking analysis tool

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

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

Status and Work Planned
On Schedule.

Completed the writing for several chapters of the report. Work will continue on the report.

REPORT K: DEVELOPMENT OF MATERIALS DATABASE

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

Status and Work Planned
On Schedule.

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

- Improvements and bug fixes were made to the File Upload system.
- Significant portions of the batch subsystem were completed.
    - Created forms and tables to define status information.
    - Modified the report selection subsystem to select reports based on batch information.
    - Created a drill down form to view batch information.
    - Created a similar drill-down form to approve batch information.
- Multi-factor properties:
    - Completing property decoupling.
    - Multi-factor creation system complete.
    - Working on multi-factor editing.
- Move Files form completed.
- Introduction of a status indicator on all form to display relevant information.
- Miscellaneous bug fixes.
- Populate data to the database.

The following list the work planned for next quarter:

- The batch subsystem used to categorize and approve reports is complete. Extending test runs to batches will be completed.
- Complete bug fixes and final changes to the multi-factor properties.
- Given the number and complexity for the various roles, a table will be crated and integrated with the system so that users are clear on the actions that can be performed by a given role.
- Revise the prototype for the public user interface.
- Several quarters ago, a prototype was created to 'link' report files. To date, this subsystem was not ever used. Users devised a use for this form. The development team will revisit this topic.
- It has been decided that a feedback system, similar to a blog, is needed for both public and internal users. This system will be developed.
- ARC users will continue to populate data to the database.
- Develop and submit QC/QA plans and protocols.

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

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

Status and Work Planned
Behind Schedule

Work Completed: Comments from reviewers have been addressed and incorporated into the final version of the report.

Work Planned: Revise report to include recommended modifications to the current BBS test procedure and test results related to application of the BBS to mastics and measurement of the contact angle between the aggregate and asphalt binder. Final delivery date was extended three months to meet achieve these objectives.

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

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

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

Status and Work Planned
Behind Schedule

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

Work Planned: Address comments from peer review and submit final report. The final end date of the project is contingent on receipt of peer review comments, tentatively a three month extension to 9/30/2012 is proposed.

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

REPORT N: GUIDELINES FOR SELECTION OF MODIFICATION TECHNIQUES

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

Status and Work Planned
On Schedule

Work Completed: Analysis tool has been developed for PG assessment based on modification type and concentration. The first two chapters of the final report have been drafted.

Work Planned: The final report includes task E3a (Effect of Extenders and Oil modification). This task began in Year 6 and will continue until the end of the project.

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

REPORT O: CHARACTERIZATION OF BINDER DAMAGE RESISTANCE TO RUTTING

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

Status and Work Planned
On Schedule

Work Completed: Experiments and reporting for subtask E1b-2 is complete and ready for integration into the final report. A series of white papers on proposed modification of the MSCR protocols detailed in AASHTO MP-19 and AASHTO TP-70 have been submitted to the Asphalt Institute for review and possible collaboration on additional research. These white papers will be summarized to provide additional chapters for the report. A M.S. thesis that describes the development of iPAS and the importance of aggregate structure in rutting resistance is also available and will be included in the final report.

Work Planned: Finalize proposed modification to MSCR procedure based on feedback provided by the Asphalt Institute. Synthesize existing documents into one coherent final report. Continue modeling efforts to define the role of binder elasticity in mixture rutting performance.

Delivery Dates
Draft Deadline: 12/31/2012
Final Report Deadline: 8/31/2013

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

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

Status and Work Planned
On Schedule

Work Completed: Two separate documents were completed to support development of the draft report. At UW-Madison, a Ph. D. dissertation titled "Quantifying the Impacts of Warm Mix Asphalt on Constructability and Performance" was completed at UW Madison. The document focuses on laboratory evaluation of workability, moisture damage, and binder performance. The University of Nevada-Reno completed the testing for WMA mixes sampled from the Manitoba field project. Results were summarized in a thesis entitled: "Mechanistic Properties of Field and Laboratory-Produced Warm Asphalt Mixtures from Manitoba, Canada" was published.

Work Planned: Synthesize and combine documents produced by UW Madison and University of Nevada Reno for preparation of the draft final report. Develop experimental plans to complete remaining subtasks and address new tasks specified in the Year 6 work plan. After plans are developed begin testing.

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

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

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

Status and Work Planned
On Schedule

Work Completed: For CMA a literature review is 50% complete pending completion of a study designed to evaluate the compaction and curing of cold mix asphalt, study completion is expected in September 2012. In related efforts the University of Nevada Reno completed testing and analysis for CIR. Results are summarized in a thesis entitled "Designing Cold Mix Asphalt (CMA) and Cold-In-Place Recycling (CIR) Using the Superpave Gyratory Compactor. A second publication titled "Mix Design of Cold-In-Place Recycling was submitted and accepted to the ISAP 2nd International Symposium on Asphalt Pavements & Environment.

Work Planned: Based on results of literature review, curing and compaction study, and on preliminary findings by UNR select appropriate compaction and curing conditions, performance tests, and materials (emulsions and gradations) for CMA. UNR will continue to validate the proposed mix design approach for CIR mixes.

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

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

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

Status and Work Planned
On Schedule

Work Completed: Draft final report in Section 508 Format was submitted for review.

Work Planned: Address review comments and finalize report.

Delivery Dates
Draft Deadline: 12/31/2011 (Submitted)
Final Report Deadline: 9/30/2012

REPORT S: MOLECULAR DYNAMICS RESULTS FOR MULTIPLE ASPHALT CHEMISTRIES

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 is nearing completion.

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

On Schedule.

Work is progressing on conducting molecular simulations of model asphalts and analyzing the results to obtain physical insights and free energy parameters. Work during the quarter continued a focus on developing a method to convert calculations of spontaneous stress fluctuations into predictions of frequency-dependent complex modulus $|G^*|$ and phase angle δ. Preliminary results have been obtained so far for one model asphalt system (new model of SHRP AAA-1). The results will be interpreted during the next quarter, and the method will also be applied to model asphalt systems that have been simulated previously in order to enable comparisons of chemical effects. A manuscript that describes the dynamics results for the new AAA-1 system will be completed and submitted for publication.

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

On Schedule.

Work to simulate additional asphalt systems is proceeding more slowly than expected but remains on schedule. Simulations have been initiated for multiple additional model asphalts using new compositions, though simulations at additional temperatures are required prior to full data analysis. The slowdown was caused by a decision to have a new graduate student on the project initially focus their time on the complex modulus tool rather than on new simulations. This delay will be remedied in the next quarter through devoting additional PI and graduate student time to the simulations. New computer hardware will also speed the calculations.

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

On Schedule.

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

It is anticipated that the model for free energy will be a sequence of molecular simulations, interpretations, correlations, interpolations, and extrapolations that provide the free energy as a cumulative output. This involves much more complexity than is typically found in the representation of an asphalt model via an equation, a spreadsheet, or a simple computer program. Thus in the next quarter an idea will be considered to incorporate the Model Deliverable into the contents of Report S.

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

Included work elements/subtasks
Work Element F3a: Phase-field modeling of crack propagation in asphalt binder
Subtask F3a-2.1: Formulation of the non-conserved phase-field model for crack propagation
Subtask F3a-2.2: Implementation of the numerical model on the COMSOL software platform
Subtask F3a-2.3: Simulations of mode I cracking and comparisons with experiments and classical theory of fracture mechanics
Subtask F3a-2.4: Determination of the asphalt fracture toughness at low temperature by standard experimental procedures
Subtask F3a-2.5: Simulations of crack propagation under mode II loading and mixed-mode loading
Subtask F3a-8. ab initio Calculations of Asphalt Molecular Structures and Correlation to Experimental Physico-Chemical Properties of SHRP Asphalts (WRI-TUDelft, URI, VT)

Status and Work Planned
On Schedule

Finite-element based simulations of asphalt binder damage-self healing phenomena are in progress. Asphalt binder physico-chemical properties, determined experimentally and inferred from semi-empirical modeling efforts presently provide input data for these simulations.

Currently all research elements are on schedule according to the revised plan. The subtasks F3a-2.1-4 listed above have been finished. The subtask Subtask F3a-2.5 will be completed in next quarter.

1. Review of asphalt cracking behavior at low temperature
2. Analysis of asphalt mode I cracking by classic Griffith theory
3. Analysis of asphalt mode I cracking failure by Phase field method
4. Experiment verification of the phase field method

Cracking failure of asphalt binder, being one of the most serious problems in pavements, has attracted many researchers' interests. During the last quarter, the cracking failure behavior, especially the Mode I cracking failure of asphalt binder at low temperature has been experimentally assesses. The ASTM Method E 399-90 is followed for determining the facture toughness. The fracture energy can then be derived based on the test data.

The ASTM Method is established based on the Classical Fracture Mechanics (CFM). The Griffith's fracture criterion is adopted to predict whether the crack propagates. In this criterion, the crack propagates only if the released elastic energy overcomes the fracture energy, which is a material property associated with the creation of crack surface.

Similar to Griffith's theory, the Phase-Field Method (PFM) also treats the cracking problem from an energy perspective. A phase-field variable is used to identify the crack: -1 in the crack void, +1 in the intact solid, and in between on the crack surface. The fracture toughness is then replaced by surface energy, akin to the surface tension between two fluids. Because the crack void may increase during the crack propagation, a non-conserved Allen-Cahn equation is use to evolve the phase-field variable. Figure 1 gives the magnified view of a mode I crack propagation at different instants.

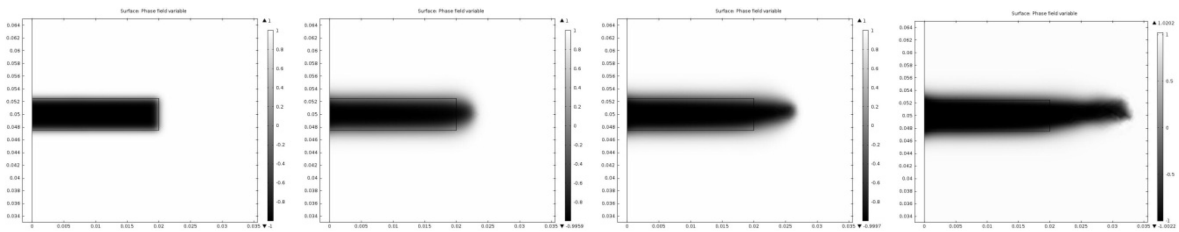

Figure 1. Crack propagation at different instants.

By running simulations with different loading conditions, we can determine the critical load under which the crack starts to propagate. For mode I cracks, results by PFM agree very well with those by CFM and experiments, as shown in Table 1. Here, the experiments are carried out in the Asphalt Lab at VTTI. A tensile stress is applied to the specimen, which is increased until the specimen breaks. The simulations follow the same procedure as the experiments.

Table 1. Comparison of the critical stresses from different approaches for mode I cracks.

Crack length (mm)	Experiment (MPa)	CFM(MPa)	PFM(MPa)
5	0.201	0.228	0.25
8	0.1544	0.146	0.16
9	0.1	0.123	0.145

REPORT U: DESIGN GUIDANCE FOR FATIGUE AND RUT RESISTANCE MIXTURES

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

Status and Work Planned
On Schedule

Work is progressing according to the year six work plan. Laboratory testing for the Hirsch model refinements and the resistivity model refinements has been completed. Also permeability data has been obtained from various publications for the permeability model refinements. Analysis of the data for these three models is underway. For the fatigue model refinements, programming of the geometric stress progression test with and without rest periods has been completed and all of the testing without rest periods has also been completed. Finally, fixtures for the Fenix fracture energy test have been ordered and all of the Fénix test specimens have been prepared.

Next quarter, the remaining laboratory tests will be completed. This includes the geometric stress progression tests with rest periods, and the Fénix fracture energy tests. Data analysis for refinement of all four models will continue.

TEST METHODS

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

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

Status and Work Planned
On Schedule

Work is progressing according to the year six work plan. The geometric stress progression test without rest periods has worked well in characterizing damage to localization in eight different mixtures in Work Element E2e. Work is underway to develop an automated spreadsheet, much like Mastersolver, that can be used to reduce and analyze geometric stress progression test data collected with the Asphalt Mixture Performance Tester using reduced cycles analysis.

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

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

Work Element/Subtask F1a: Cohesive and Adhesive Properties.
Work Element/Subtask F1d: Healing

Status and Work Planned: The protocols for the Wilhelmy Plate test, the Universal Sorption Device, Dynamic Mechanical Analysis, Method for Preparation of Specimens of Fine Aggregate Matrix of Asphalt Mixtures, and measuring intrinsic healing characteristics of asphalt binders have been developed and are now being finalized in AASHTO format. The protocol for evaluation of healing using continuum damage approach is being finalized and will be completed in the next four or five months.

ASTM METHOD: AUTOMATED FLOCCULATION TITRIMETRIC ANALYSIS

Included Work Element/Subtasks

None.

Status and Work Planned

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

DRAFT AASHTO METHOD: DETERMINATION OF POLYMER IN ASPHALT

Included Work Elements/Subtasks

None.

Status and Work Planned

Completed and submitted for AASHTO review.

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

Work Element V3c: Validation of PANDA.

Status and Work Planned: The work on this AASHTO method is on schedule. All the testing protocols necessary for the full calibration of validation of the PANDA model has been developed and verified. The focus of future work will be on writing these testing protocols in an AASHTO format.

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
On schedule.

The mechanistic models characterizing the viscoplastic and viscofractural properties of the asphalt concrete in compression were developed and had been summarized in previous quarterly reports of work elements F2c and E1a. In this quarter, the mechanistic models and the associated laboratory mixture testing protocols were verified by performing the laboratory tests and data analyses on the ARC materials. A variety of laboratory tests for the characterization of the anisotropy, viscoelasticity, viscoplasticity and viscofracture of the asphalt concrete were finished on two ARC asphalt mixtures: 1) NHL (Nustar binder and Hanson limestone) and 2) VHL (Valero binder and Hanson limestone). Data analyses and model verifications were intensively processed and partial testing results and material properties were obtained by applying the data processing program to the testing data. Details of the achievements made in this quarter are summarized as follows:

1) Laboratory Tests on ARC Asphalt Mixtures
To obtain the material properties and model parameters in the mechanistic models for the viscoelastic, viscoplastic and viscofractural characterization of the asphalt concrete in compression, laboratory tests based on previously proposed testing protocol were performed on the lab-mixed-lab-compacted (LMLC) ARC asphalt concrete specimens that were fabricated with two types of ARC asphalt binder, two air void contents and three aging periods. Two replicate specimens were fabricated for each combination of the asphalt binder, air void content and aging condition.

2) Determination of Viscoplastic Material Properties of ARC Mixtures
The viscoplastic model's parameters determined for the ARC mixtures included the slope and the intercept of the viscoplastic yield surface (α and κ_0), the strain hardening parameters (κ_1 and κ_2), the slope of the viscoplastic potential function (β) and the yield strength ratio of extension to compression (d). These parameters were used in the constitutive models for the viscoplastic characterization of the asphalt concrete, which also can be used as the input parameters of the PANDA program. In addition, some of the model parameters were theoretically related to the engineered material properties such as cohesion (C) and internal friction angle (φ) as well as the modified vector magnitude (Δ') that characterize the inherent anisotropy of the asphalt mixture due to aggregates' preferential orientations.
Since one aggregate gradation was used for all of the mixture, the measured internal friction angles (ϕ) in Table 2 remain close for all of the ARC mixtures tested. The yield strength ratio of extension to compression (d)depends solely on ϕ (i.e., $d = \frac{3-\sin\phi}{3+\sin\phi}$), thus d also stays close for

the mixtures tested. A stiffer asphalt concrete (e.g., due to low air voids or longer aging period) tends to have a greater C, κ_0, and κ_1, all of which quantify the bonding properties of the asphalt concrete. In addition, the measured slope (α) and intercept (κ_0) of the yield surface in Table 2 can also be accurately predicted by using C and ϕ (i.e., $\alpha = \frac{2\sin\phi}{\sqrt{3}(3-\sin\phi)}$ and $\kappa_0 = \frac{6C\cos\phi}{\sqrt{3}(3-\sin\phi)}$).

In the next quarter, the testing data will be completely analyzed and more material properties for the ARC mixtures will be determined that includes the viscoelastic parameters ($E(t)$ and α_T), viscoplastic parameters (Γ and n) and viscofractural parameters (ξ_{ij}, A_i and n_i). In addition, the summary of the proposed mechanistic model for anisotropic compressive characterization of asphalt concrete, testing protocol, testing results of ARC mixtures and data analysis program will also be drafted in a written document as one of the ARC products.

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

Status: on schedule.

The energy-based mechanistic approach has begun to be used on various asphalt mixture since last quarter. The last quarterly report introduced the materials (includes twenty different types of asphalt mixtures), experiments, and the analysis results on the variation of material properties and the average air void size. The testing and data analysis continues in this quarter regarding the fatigue resistance of different asphalt mixtures.

One of the essential outputs produced by the energy-based mechanistic approach is the damage density. The damage density is fomuated in the form of Paris' law, which contains two coefficents: A' and n'. Based on basic mechanical principles and mathematical manipulations, A' and n' can be expressed as a funtion of measured material properties, respectively. The value of n' represents the fatigue resistance of the asphalt mixture, a smaller n' representing greater fatigue resistance. To verify the rational and accuracy of using A' and n' as indicators of fatigue resistance, they are used to evaluate the effect of asphalt binder, effect of air void content, and the effect of aging on twenty different types of asphalt mixtures. The testing and analysis of the results include:

- Comparisons are conducted on the AAD and AAM mixtures, which have the same Texas limestone aggregate, and NuStar and Valero mixtures, which have the same Hanson limestone aggregate. The results indicate that the AAD mixtures have better resistance to fatigue cracking than the AAM mixtures and that the Valero mixtures have much better resistance to fatigue cracking than the NuStar mixtures in all the unaged and aged conditions.
- Comparisons are performed on the asphalt mixtures with 4% air void content an 7% air void content. It shows that the asphalt mixtures with 7% air void content are always more susceptible to cracking than those with 4% air void content under repeated loading.
- Comparisons are conducted on unaged and aged specimens for all AAD, AAM, NuStar, and Valero mixtures. The results indicate the aged asphalt mixtures are more susceptible to fatigue cracking than unaged mixtures. The fatigue resistance of asphalt mixtures decreases with an increase of the aging period.

The data analysis of the fatigue and healing tests on the twenty differnet types of asphalt mixtures will continue in the next quarter. It is intended to privode a comprehensive information in terms of the ability of the energy-based mechanistic approach to predict fatigue and healing in asphalt mixtures. Supplementary results will contain: 1) the characteristics of the recovery modulus; 2) the healing ability of twenty types of asphalt mixtures; 3) relating the healing rates to fundamental material properties, etc.

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
Completed and published.

Reference: 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.

FHWA delivery to be determined.

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

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

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

<u>Status and Work Planned</u>
Status: on schedule.

In this quarter, the methodology to find the undamaged, fracture and healing properties of field-aged specimens has been completed and verified with actual field cores from Arizona. An extensive sensitivity analysis was performed using the Functionally Graded Material (FGM) user defined subroutine to ABAQUS to evaluate the response of the field-aged specimens in the Overlay Tester (OT) test. The field specimens from Arizona were tested and analyzed using the test protocol of field cores. The test and analytical-numerical model results include the stiffness gradient, fracture and healing properties of the field cores. The work completed in this quarter is summarized as follows.

3) Sensitivity analysis of the field-aged specimen in OT test
A sensitivity analysis was conducted for a specific crack length in a field specimen to study the effect of the stiffness gradient function shape on different variables in the test. For this purpose, the model was run for a specimen with a crack length of 22.225 mm (0.875 inches) for different gradient curves by changing the n value but using a constant k value. The J-integral, stiffness profile, horizontal strain profile and the maximum principal stress contours are some of the outputs that were compared in this study.

The results of the simulations indicate that, as the n value increases, the larger part of the specimen is under compression. A zero n value represents the uniform stiffness profile (laboratory condition), and the higher n values are for a greater stiffness gradient near the surface. The authors' experience with field specimens shows that the n value usually increases with age. The simulation confirms that a larger portion of the specimen will be under compression in highly aged specimens; therefore, even with very small openings during the OT test, the number of load cycles is not a reliable criterion to compare two specimens.

As previously discussed, the results of the stiffness gradient model are inputted into the FGM numerical model to determine the strain profiles above the crack for various crack lengths in the aged field specimen. After that a replicate specimen is tested with the OT and the data are analyzed using the fracture and healing module along with the outputs from the FE program.

4) Results of the analysis of the fracture and healing properties of Arizona specimens

The OT test was conducted in two steps (nondestructive and destructive) to find the undamaged and damaged properties of the field specimens. Table 1 shows the undamaged and damaged properties of eight field specimens. The results for one specimen did not converge during the analysis. All the results were calculated at 20ºC because the OT test is conducted in 20ºC. A and n are the modified Paris' law fracture parameters and B and m are the modified Paris' law healing parameters. Equations 1 and 2 show the modified Paris's law for the fracture and the healing.

$$\frac{dC(N)}{d(N)} = A\left[\frac{W_{Rt}(N)}{c.s.a}\right]^n \tag{1}$$

$$\frac{dC(N)}{d(N)} = B\left[\frac{W_{Rc}(N)}{c.s.a}\right]^m \tag{2}$$

where $c.s.a = 2bC(N)$, $W_{Rt}(N)$ and $W_{Rc}(N)$ are functions of the tensile and compressive Pseudo strain work as they vary with load repetitions, respectively. A larger value of B indicates the large amount of healing that occurs in each closing load cycle. The results of A and B values show that the mixtures with binders 1 and 3 have relatively the same crack susceptibility but the mixture type 1 has a better healing performance. Therefore, the crack growth rate in mixtures with binder type 1 is lower than with other mixtures. The mixture with binder types 3 and 4 are very brittle and the crack grows very fast in these two mixtures because these mixtures have poor healing performance.

Table 1. The viscoelastic properties of the field-aged asphalt mixtures.

Sample ID	**Lift**	**E1 (MPa)**	**A**	**n**	**B**	**m**	**Crack Growth Function**
AZ1-1	Top	825	0.025	2.32	0.92	6.64	$C = 11.92N^{0.1698}$
AZ1-1	Bottom	987	0.035	1.55	0.19	4.6	$C = 9.0297N^{0.2909}$
AZ1-2	Top	687	0.008	2.54	0.0057	9.29	$C = 19.2963N^{0.1736}$
AZ1-2	Bottom	778	0.016	2.46	0.0045	8.6	$C = 24.4297N^{0.183}$
AZ1-3	Top	911	0.026	1.87	0.08	3.44	$C = 9.3218N^{0.2536}$
AZ1-3	Bottom	671	0.027	1.89	0.048	4.19	$C = 15.5067N^{0.2037}$
AZ1-4	Top	776	N/A	N/A	N/A	N/A	$C = 39.2988N^{0.0609}$
AZ1-4	Bottom	418	N/A	N/A	N/A	N/A	$C = 39.7281N^{0.0706}$

The crack growth versus the displacement repetitions in the OT test of a field-aged specimen is similar to the crack growth curves for the laboratory compacted specimen but unlike the laboratory compacted specimen, there is a significant crack growth in the first few load cycles because the asphalt concrete near the surface is highly stiff and brittle.

The work planned in next quarter includes the testing and analysis of the field cores from Yellowstone National Park. In addition, the mixture stiffness gradient results will be compared to the binder extraction test results, to find the possible correlations.

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

Included Work Elements/Subtasks

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

Status and Work Planned
Completed and published.

References:

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., 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.

FHWA delivery to be determined.

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

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

Status and Work Planned
On Schedule.

UNR completed the testing for CMA and CIR and the thesis entitled: "Designing Cold Mix Asphalt (CMA) and Cold-In-Place Recycling (CIR) Using Superpave Gyratory Compactor" was published. Furthermore a paper entitled: "Mix Design of Cold-in-Place Recycling" was submitted and accepted to the ISAP: "2nd International Symposium on Asphalt Pavements & Environment," that is scheduled for October 1-3, 2012 in Fortaleza, Brazil.

Work will continue to validate the proposed mix design approach for CIR mixes.

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

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

Status and Work Planned
On Schedule

Work Completed: Literature review on existing mix design and compaction methods. Experimental plan was executed to develop laboratory methods to estimate coating of CMA and identify the factors affecting aggregate coating for several aggregate-emulsion systems.

Work Planned: Define the relationship between coating and performance. Identify optimum compaction and curing conditions for mix design and performance testing.

Delivery Dates
Estimated Completion Date: 9/30/2013

DRAFT AASHTO PRACTICE: EVALUATION OF RAP AGGREGATES

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

Status and Work Planned
On Schedule.

The relevant report entitled: "Effect of Extraction Methods on the Properties of Aggregates in Reclaimed Asphalt Pavement," was completed. The findings of this report will be incorporated into the AASHTO practice. In the next quarter, work will begin on writing the draft AASHTO practice.

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.

In the next quarter, work will begin on writing the draft AASHTO practice after the submittal of the draft version of Report H to FHWA.

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

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

Status and Work Planned
On Schedule

The following list describes the work items completed this quarter:

- Completed the enhancements to the TSRST in the areas of specimen shape, gluing process, and thermal strain modular setup.
- Developed a mathematical solution to calculate the following low temperature properties for an asphalt mixture using the TSRST data for restrained and unrestrained specimens:
    - Transition temperature and modulus
    - Slope of thermal relaxation modulus at transition
    - Micro-cracking initiation temperature and modulus
    - Micro-cracking initiation stress
    - Fracture temperature and modulus

The following list the work planned for next quarter:

- Submit AASHTO Draft Procedure for TSRST to FHWA Asphalt Mixture and Construction Expert Task Group for review and consideration.

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: Standard has been approved by AASHTO (TP-91). A video demonstrating the testing procedure has been produced and will be submitted for posting on the ARC website.

Work Planned: Final report for related work element (Report L) is under review. Revised version of the report will include suggested revisions to the AASHTO test procedure and discuss application of the BBS test to evaluation of mastics.

Delivery Dates
Revised Standard: 9/30/2012.

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

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

Status and Work Planned
On Schedule

Work Completed: Test development and initial results summarized in ARC Report “M”. Work began in writing the test procedure in AASHTO format.

Work Scheduled: Finalize draft testing procedure and submit to the Binder Expert Task Group in AASHTO format.

Delivery Dates
Completion of Draft Standard: 12/31/2012

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

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

Status and Work Planned
Completed

Work Completed: AASHTO Test Procedure was recently approved. As a follow up to the procedure, internal ruggedness testing was completed and samples for inter-laboratory ruggedness testing were prepared.

Work Planned: Develop work plan for inter-laboratory testing and submit to participating laboratories. Begin study and report on progress next quarter. The results of the study will be used to assess the need for revisions to the current procedure.

Delivery Dates
Completion of inter-laboratory ruggedness testing and final test procedure: 12/31/2012

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: A test method in AASHTO format was completed. After review, the FHWA Binder ETG decided not to support submission of the test to AASHTO for approval.

Work Planned: The test method will be re-introduced to the ETG for consideration or submission to ASTM will be considered.

Delivery Dates
Final Decision on Test Method: 12/31/2012.

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

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

Status and Work Planned
Behind Schedule

Work Completed: Draft test procedure in AASHTO format was prepared and submitted to the domestic manufacturer of the device for review. Feedback from the manufacturer has been received and will be included in the final procedure.

Work Planned: Finalize AASHTO procedure based on feedback from manufacturer and distribute to the appropriate Expert Task Group for review.

Reasons for Delay: Review of procedure by the manufacturer was delayed as comments were received after the original target completion date (7/1/12). Now that comments are available, this task can proceed as planned.

Revised Delivery Dates
Completion of AASHTO Standard: 9/30/2012.

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

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

Status and Work Planned
On Schedule

Work Completed: Established the relationship between asphalt binder lubricity and mixture workability. Based on the results, the limitations of the current test procedure were identified.

Work Planned: Address limitation of testing procedure by defining the effects of surface type, surface texture, and use of mastics on the asphalt binder coefficient of friction. Also investigate use of oscillatory mode of loading to improve test repeatability.

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

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

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

Status and Work Planned
On Schedule

Work Completed: Development of procedure for evaluation of CMA coating is complete and was detailed in a publication in the AAPT 2012 meeting.

Work Planned: Testing of additional emulsion/aggregate systems is underway to identify significant factors and assess need for refinement of the procedure.

Delivery Dates
Completion Date: 12/31/2012

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

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

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

Work Completed: Initial results indicate that the perforated molds provided by the equipment manufacturer produces samples that demonstrate volumetrics consistent with expectations based on the literature and experience with other mixture types.

Work Planned: Use available equipment to prepare samples with varying emulsion/aggregate combinations and establish the required curing conditions for CMA.

<u>Delivery Dates</u>
Completion Date: 5/31/2013

DRAFT AASHTO TEST METHOD: RAP BINDER PG TRUE GRADE DETERMINATION

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

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

Work Completed: Development of continuous grading procedure completed and verified. Test procedure was put in AASHTO format and submitted to RAP TWG for consideration.

Work Planned: Ruggedness testing at intermediate and high temperatures. Testing will continue to expand the sample database to include additional sources of RAP and RAS.

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

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

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

Status and Work Planned
On Schedule

Work Completed: Validation of SENB evaluation parameters with mixture testing and field performance was completed. Development of draft standard in AASHTO format is in progress.

Work Planned: Establish proper testing conditions (temperature and loading rate) according to pavement temperatures and cooling rates in the field. Quantify the amount of viscous energy dissipated during the test to determine if fracture energy principles are applicable. Apply concepts of time-temperature superposition to fracture parameters.

Delivery Dates
Completion Date: 9/30/2012

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

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

Status and Work Planned
On Schedule

Work Completed: Development of draft standard procedure in AASHTO format is in progress.

Work Planned: Complete standard procedure and submit to Asphalt Binder ETG for review.

Delivery Dates
Completion Date: 12/31/2012

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

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

Status and Work Planned
On Schedule

Work Completed: Development of draft standard procedure in AASHTO format is in progress.

Work Planned: Complete research to finalize test conditions and establish relationship with asphalt binder glass transition temperature. Finalize draft standard procedure and submit to Asphalt Mixture ETG for review.

Delivery Dates
Completion Date: 12/31/2012

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

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

Status and Work Planned
On Schedule

Work Completed: Development of draft standard in progress and research continues focused on demonstrating the value of planar imaging in defining the quality of asphalt mixtures.

Work Planned: Conduct comparison between 3-D and planar imaging. Define evolution of aggregate structure with compactive effort and relate aggregate structure with performance.

Delivery Dates
Completion Date: 3/31/2013

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

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

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

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

Work Planned: Completion of precision and bias testing, analysis of data, and inclusion of precision and bias statement in standard. The next ASTM meeting is December 2012.

<u>Delivery Dates</u>
Completion Date: 3/31/2013

TEST METHOD: TEST METHOD FOR FATIGUE OF BINDER AND MASTICS: A CYCLIC DIRECT TENSION TEST THAT CAN PROVIDE DIRECT EVALUATION OF FATIGUE FOR BINDER AND MASTIC

<u>On-Going Technical Research</u>
Sub-subtask F3a-1.2. Develop algorithms and methods for directly linking molecular simulation outputs and phase field inputs (URI, VT)
Subtask F3a-2.5: Simulations of crack propagation under mode II loading and mixed-mode loading
Subtask F3a-4. Overall integration for multiscale modeling (VT, URI, and WRI)
Subtask F3a-5. Experimental verification and validation (VT, URI, and WRI)

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

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
Completed and published.

Reference: 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.

FHWA delivery to be determined.

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

Status and Work Planned: Many researchers have shown that the Superpave tests and the RCRT poorly predict the rutting resistance of asphalt binders whose creep-recovery response are stress-dependent (see D'Angelo et al. (2007); Masad et al. (2009); Anderson et al. (2010)) It is necessary for a new protocol in order to compare the rutting resistance of asphalt binders and to take into account the stress-dependence of the creep behavior. One such method involves the use of a nonlinear viscoelastic model. In this method, an appropriate nonlinear viscoelastic model was chosen and asphalt binders were tested using standard experiments. The data from the experiments were used to estimate the model parameters for each asphalt binders. The binders were ranked by comparing model parameters. This method for assessing the rutting potential of asphalt binders is being developed.

The model selected for this protocol had to be able to describe the nonlinear viscoelastic behavior of most asphalt binders reasonably well. Such a model was developed by the research team, using the Gibbs-potential based thermodynamic framework developed by Rajagopal and Srinivasa (2011). The model is a modification of the Oldroyd-B model and is as shown below.

$$\mathbf{T} = -p\mathbf{1} + \bar{\eta}\mathbf{D} + \mathbf{T}_{\mathrm{E}}^{\mathrm{V}},$$

$$\eta\mathbf{D} = \left\{1 + \frac{\alpha}{\eta^{2n}}\left(\mathbf{T}_{\mathrm{E}}^{\mathrm{V}} \cdot \mathbf{T}_{\mathrm{E}}^{\mathrm{V}}\right)^{n}\right\}\mathbf{T}_{\mathrm{E}}^{\mathrm{V}} + \lambda\overset{\nabla}{\mathbf{T}_{\mathrm{E}}^{\mathrm{V}}},$$

$$\mathrm{tr}(\mathbf{D}) = 0,$$

where $\mathbf{T}$ is the Cauchy stress, $\mathbf{D}$ is the symmetric part of the velocity gradient, and η, $\bar{\eta}$, λ, α and n are model parameters.

We have shown that the model described the primary nonlinear response of asphalt binders including nonlinear creep and stress-relaxation behavior, thinning behavior and the appearance of normal force perpendicular to the plane of shear in shear tests.

Experiments were conducted on five asphalt binders that were tested in the FHWA's Accelerated Load Facility in order to validate the model and to quantify the rutting potential. The experiments were conducted using a Dynamic Shear Rheometer, Physica MCR 300, with 25 mm diameter parallel-plate geometry and 1 mm separation of plates. The experiments include creep-recovery tests at five different stress levels and steady-shear experiments at five different strain-rates. These experiments were conducted at three different temperatures - 60, 70 and 80^0 C. In the creep-recovery experiments, creep loading was applied for one-second and the recovery of strain after unloading was observed for about 300 seconds or more.

In the next quarter, the model validation will be completed and a method for quantification of rutting potential will be proposed. For model validation, the model predictions will first be fit to steady-shear experiment results for each asphalt binder at each temperature. The model parameters obtained through fitting will be used to determine the predictions of the model for the creep and recovery experiments. The model predictions would then be compared with the experimental results to validate the model. In order to quantify the rutting potential of the asphalt binders, the model parameters will be compared with the rutting data recorded in the Accelerated Load Facility.

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

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

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

Preliminary development of this test method has been completed. Additional develop of this method will continue in the next quarter

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

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

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

Development of this test method will continue in the next quarter.

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

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

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

This test method is near completion. Aspects of this method will be utilized to complete test method “A Method to Determine Ductile-Brittle Properties via AFM.”

<u>On-going Technical Research</u>
M1b-2: Work of Adhesion at Nano-Scale using AFM
M2a-2: Work of Cohesion at Nano-Scale using AFM

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:

- Developed the software subroutine to predict temperature profile in asphalt layer.
- Continued working on the software subroutine to predict the carbonyl area growth as a function of time.

The following list the work planned for next quarter:

- Validate the developed software subroutine to predict temperature profile in asphalt layer using LTPP data.
- Complete and validate the software subroutine to predict the carbonyl area growth as a function of time.
- Work on the uniaxial continuum model software to calculate thermal stress in pavement.
- Arrange for an extended meeting between UNR team and UWM team to discuss the various components of the thermal stress analysis tool.
- Assess the use and possible modification of the ILL-TC software developed by Illinois.

SOFTWARE: DYNAMIC MODEL FOR FLEXIBLE PAVEMENTS 3D-MOVE

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

Status and Work Planned
On schedule.

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

- Debugging technical errors of the new version (2.0) and also the previous version (1.2).
    - Version 2.0 was beta-tested under a variety of conditions to find compilation and other errors. Almost all of them have been fixed. For example, in asphalt material property section, program was not able to calculate phase angles because of a mathematical constrain under some specific conditions.
- Developing post-processing component for Pavement Performance Models (PPM).
    - The post-processing involves user-friendly documentation of the results and portability of the results to other platforms. For performance models (NCHRP 1-37A and VESYS), documentation of performance equations, limits of performance indicator, reliability etc. are being provided in Microsoft excel format.
- Development of 3D surface graph to show non-uniform contact stress distributions.
    - As mentioned in previous reports, Options C of axle configuration is non-uniform contact stress distribution over non-uniform tire imprint. The contact stress distributions and tire imprint data are selected from the database generated by Vehicle-Road Surface Pressure Transducer Array (VRSPTA) and Kistler MODULAS devices. For intermediate conditions (e.g., tire load or pressure) interpolation is used. Since tire imprint and corresponding contact stress distribution are major factors in the selection of the response points for performance analysis, a graphical display of such data is important. So by using this graphical display, user can visualize 3D contact stress plot and counter map of contact stress for the selected tire in default loads and any other intermediate load.

The following list the work planned for next quarter:

- Complete debugging technical errors of the new version (2.0) and previous version (1.2).
- Complete the post-processing component for PPM and incorporate into version 2.0.
- Update the help files and examples in the software.
- Maintain 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

Subtask F3a-1: *ab initio* Theories, Molecular Mechanics/Dynamics and Density Functional Theory Simulations of Asphalt Molecular Structure Interactions
Sub-subtask F3a-1.2. Develop algorithms and methods for directly linking molecular simulation outputs and phase field inputs (URI, NIST)
Subtask F3a-4. Overall integration for multiscale modeling (VT, URI, and WRI)
Subtask F3a-5. Experimental verification and validation (VT, URI, and WRI)

Status and Work Planned

On Schedule

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

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

We use a Phase field model to simulate the cracking process. The total free energy includes three parts: the gradient energy, the local energy and the elastic energy

$$F = \int_{\Omega} (f_{gr} + f_{loc} + f_{el}) dV, \tag{1}$$

where we use double-well potential for local energy and the elastic energy can be calculated from the structural analysis module of COMSOL. To simulate the expansion of crack void, we adopt the non-conserved Allen-Cahn equation

$$\frac{\partial \phi}{\partial t} = -M \frac{\delta F}{\delta \phi}, \tag{2}$$

where M is the mobility parameter which controls the cracking speed and the energy dissipation. In order to facilitate the finite-element calculations, the following weak form of Eq. (2) is input to COMSOL:

$$\int_{\Omega} \frac{\partial \phi}{\partial t} \tilde{\phi} d\Omega = \int_{\Omega} -\frac{M\lambda}{\epsilon^2} \left(\left(\epsilon^2 \nabla \phi \cdot \widetilde{\nabla \phi} \right) + (\phi^2 - 1)\phi\tilde{\phi} + \frac{\epsilon^2}{\lambda} \frac{\partial f_{el}}{\partial \phi} \right) d\Omega \tag{3}$$

where ϕ is the phase field variable, $\tilde{\phi}$ is the test function, ϵ is the capillary width that controls the interfacial thickness, and λ is the mixing energy density which is related to surface tension γ by $\lambda = \frac{3\gamma\epsilon}{\sqrt{8}}$. This equation is solved together with the structural analysis module in COMSOL.

SOFTWARE: PANDA: PAVEMENT ANALYSIS USING A NONLINEAR DAMAGE APPROACH

<u>Work Element M4c</u>: 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.

<u>Status and Work Planned</u>: There are two main products of the PANDA model; the PANDA-Abaqus subroutine and the PANDA standalone finite element software. The PANDA-Abaqus subroutine is complete and is currently under testing for removing any errors and bugs and for increasing its computational efficiency. Also, at this point, an alpha version of the PANDA standalone finite element software is available. The focus of the current and future work is on the development of the graphical user-friendly interface (GUI) of PANDA. Also, moisture-induced damage and oxidative aging models that are part of the PANDA model will be integrated into the PANDA standalone finite element software.

PANDA Software

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

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

OTHER RESEARCH ACTIVITIES

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

Work Done This Quarter

A number of aromatic and paraffinic oils were selected and a study of blending mechanisms and the performance implications of oils modification has begun. This study includes the development of the ideal blending procedure for oil modifiers.

Work Planned Next Quarter

Efforts will continue to identify pertinent blending mechanisms and finalize a blending procedure. A range of asphalt binder performance tests will be selected and conducted to assess the implications of oil modification on performance properties. A limited mixture study will also be designed to assess the effects of oil modification on mixture coating and compactability.

Proposed Research Product and Timeline

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

Significant Problems, Issues and Potential Impact on Progress

None.

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

Work Done This Quarter

A study to evaluate the sensitivity of the evaporative thin film residue recovery method specified in ASTM D7497 Method B was designed and testing has begun. The study aims to evaluate the sensitivity of recovery in thin films to substrate type, emulsion chemistry, and emulsion viscosity. Evaluation parameters include the moisture loss vs. time relationship and high and intermediate performance properties measured in the DSR. A three step shear method has been identified to evaluate emulsion viscosity using the Brookfield Rotational Viscometer and is under development. The test method was designed to simulate storage, pumping, spraying, and placement on the roadway surface. In regards to long term chip seal performance a long term aging study was designed to evaluate the evolution of emulsion residue properties with aging time and to investigate impacts on chip seal durability.

Work Planned Next Quarter

Analyze results of residue recovery sensitivity study and based on findings define next steps regarding suggested modifications to the current standard and assess the need to modify the approach used for performance grading of emulsions. Complete development of the emulsion viscosity and begin drafting procedure in AASHTO format. Apply results of emulsion long term aging and chip seal durability study to identify binder and associated mixture tests to support development of an emulsion grading specification capable of evaluating performance throughout the treatment design life.

Proposed Research Product and Timeline

Emulsion grading protocols will be summarized in specification tables.
Specification tables and results will be added as a chapter to 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

Timeline provided in ARC Yr 6 work plan was modified to align the end date of this work element with the timeline for ARC Report Q. The result was an extension in the deadline for the project from 3/31/2013 to 9/30/2013.

Work Element E3c: Laboratory Assessment of Mixture Long Term Aging

Work Done This Quarter

A study of mastic laboratory aging using various film thicknesses in the PAV has begun. Use of mastics was selected to assess the influence of aggregate mineralogy and physical properties on development of performance properties. The mineral fillers used to create the mastics were selected to represent a range of physical and chemical properties. To evaluate the relationship between aging and performance rheological tests using standard methods in the DSR and bond strength tests using the bitumen bond strength (BBS) device were selected.

Work Planned Next Quarter

Continue experimental plan to assess the role of aggregate in aging through the study of the shear (DSR) and tensile properties (BBS) of mastics. Apply results of initial screening experiment to long term mixture aging and field performance data collected by University of Nevada Reno to validate conclusions and define the mechanisms of long term mixture aging.

Proposed Research Product and Timeline

Results will be summarized in a final report titled: “Laboratory Assessment of Long Term Aging of Asphalt Mixtures”
Due Date for Draft Report Submittal: 9/30/2013
Due Date for Final Report Submittal: 6/30/2014

Significant Problems, Issues and Potential Impact on Progress

None.

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

Work Done This Quarter

No WMA monitoring was planned for this quarter.

Work Planned Next Quarter

Monitoring of the Manitoba WMA and the Yellowstone sections are planned for the next quarter.

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

Work Done This Quarter

The ARC, Ohio DOT, and Ohio University are collaborating on placing new experiments on LTPP SPS-1, SPS-2, SPS-8, and SPS-9 sections that are being reconstructed or rehabilitated on U.S. 23 in Delaware County. Some of the sections are being reconstructed as perpetual pavement sections with significant instrumentation and material sampling for calibration of PANDA. The SPS-9 sections are being rehabilitated and two different binder sources (from different crudes/blends) will be used in the mill and fill construction. The Ohio DOT will require that foaming technology be used in production but the mix will be produced and compacted at hot-mix temperatures. Sampling of construction materials will be conducted at this location also.

The Kansas comparative performance site was monitored in May 2012.

Work Planned Next Quarter

A meeting with Ohio DOT and the contractor on the Del 23 project is scheduled for August 1. Paving of the sections is also scheduled to occur during the next quarter.

A high RAP and HMA comparison project is in the planning stages with Michigan DOT and Rieth-Reilly Construction. A planning meeting may be held in early August.

It is planned to monitor the Manitoba RAP sections during the next quarter.