Western Research
INSTITUTE

Asphalt Research Consortium

Work Plan for 21 Month Extension
April 1, 2012 – December 31, 2013

September 2011

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

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

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

TABLE OF CONTENTS

RESEARCH PLAN FOR 21-MONTH EXTENSION OF FEDERAL HIGHWAY ADMINISTRATION CONTRACT DTFH61-07-H-00009 “ASPHALT RESEARCH CONSORTIUM”

INTRODUCTION

This document is the proposed Research Plan for a 21 month extension period of the Federal Highway Administration (FHWA) Contract DTFH61-07-H-00009, the Asphalt Research Consortium (ARC). The 21 month extension period is for April 1, 2012 to December 31, 2013. In some cases, the work is referred to as “Year 6”. The main focus of the extension is directed toward successful completion of the primary focus areas defined by FHWA and preparation and review of project reports in Section 508 format. The focus areas are divided into four categories: (1) Integrated Aging, Moisture Damage, Rutting, and Fatigue 3D, Finite Element Method (FEM) primary response and performance prediction model (PANDA); (2) ARC database; (3) Engineered Materials; and (4) Performance Monitoring Sections. The Consortium is coordinated by Western Research Institute with partners Texas A&M University, the University of Wisconsin-Madison, the University of Nevada Reno, and Advanced Asphalt Technologies.

The 21 Month Extension Work Plans seek to complete the research that was extensively detailed in the Years 2 - 5 Work Plans which were grouped into seven areas, Moisture Damage, Fatigue, Engineered Paving Materials, Vehicle-Pavement Interaction, Validation, Technology Development, and Technology Transfer. It is noteworthy to state that many of the Work Elements and Subtasks that were in the early work plans have now coalesced into the planned Deliverables and Research Products. Only the work planned in the extension period is shown in the plan. Therefore, the numbering scheme is not intuitively obvious. An additional section is added at the end of the work plans that provides detailed outlines for the expected research reports.

A considerable amount of the background information for the 21 Month Extension Work Plan is contained in the Work Plans from Years 2, 3, 4, 5 and Quarterly Reports, and associated documents on the website, www.ARC.unr.edu.

PROGRAM AREA: MOISTURE DAMAGE

CATEGORY M1 AND M2: ADHESION AND COHESION

Work Element M1b: Work of Adhesion

Subtask M1b-2: Work of Adhesion at Nano-Scale using AFM (WRI)
This subtask has been combined with Subtask M2a-2: Work of Cohesion at Nano-Scale using AFM (WRI)

Major Findings & Status

In the absence of moisture, fracture tends to occur within the asphalt (cohesive) in a plane approximately parallel to the substrate surface, leaving a thin film of asphalt on the surface, even at extremely low (liquid nitrogen) temperatures.

After several hours of exposure to moisture, either as liquid or saturated vapor, fracture of an asphalt glass interface occurs at the interface (adhesive), leaving an essentially clean glass surface, even at fairly warm (25 C) temperatures. The strength of the bond between asphalt and a smooth glass surface is decreased greatly by exposure to moisture.

Crystallizable waxy materials are distributed throughout the thickness of the asphalt adhesive film, however, these waxy materials do not exhibit the familiar ‘bee structure’ appearance except at an air/asphalt interface. Crystallizable waxy materials appear to concentrate to some extent at the air/asphalt interface. The size and shape of crystalline structures is strongly dependent upon cooling rate. Slow cooling results in large crystalline structures.

Waxy materials can crystallize at a crack face, and may thus provide a mechanism for an initial “lacing together’ or healing action at that interface. A wax crystal matrix may provide a ‘scaffold’ upon which other asphalt constituents can assemble as the asphalt ‘heals’.

Pursuant to these two subtasks, procedures and equipment capabilities have been developed to measure work of adhesion/cohesion as functions of temperature and stress rate. The procedure also generates a profile of the ductile/brittle transition with respect to temperature and stress rate. In addition, a technique has been developed that will allow us to measure the rheological phase angle associated with various micro/nano-scale structural features.

Techniques have been developed/adapted that provide a quantitative measure of surface energy (work of adhesion/cohesion) through analysis of relatively simple force displacement curves. These techniques should also allow us to quantitatively separate surface energy and visco-plastic contributions from the overall work of adhesion/cohesion, and to determine how the relative magnitude of these fracture energy components changes with respect to temperature, stress/strain rate, oxidative aging, and the presence of moisture.

New AFM imaging techniques developed under these subtasks have provided a method to look at the internal structure of asphalt binders as well as the morphology of fracture surface.

Subtasks M1b-2 and M2a-2 measure adhesive and cohesive properties of asphalt binders at micro/nano-scale using an AFM instrument. When assessed in terms of the energy required to create and/or advance a crack face there is little or no practical distinction between adhesive and cohesive properties. However, when designing or modifying (as in the case of asphalt binders) an adhesive for a particular application, the distinction between adhesive and cohesive fracture becomes quite significant. A primary objective of both of these subtasks is to develop a practical method to accurately measure work of adhesion and/or cohesion to provide a needed input to advanced pavement performance models. Additionally, tools developed under these subtasks will allow for the direct measurement of the energy required to create new crack surface and should also allow us to conveniently break this energy into surface energy and visco-plastic dissipation terms.

The behavior of a binder, with respect to cracking susceptibility, is strongly related to the visco-plastic dissipation component of the overall fracture energy. A method to measure how this dissipative portion of the fracture energy changes with respect to temperature, stress/strain rate, and oxidative aging for a particular binder is critical for the successful application of advanced pavement performance models. AFM techniques developed at WRI under ARC subtasks M1b-2 and M2a-2 provide a relatively simple approach for obtaining these critical input data.

Both the surface energy and visco-plastic components of the overall fracture energy change with temperature, however, only the visco-plastic component is frequency dependant. This fact provides a convenient mechanism that we use to separate the contributions of these two components from the measured fracture energy. Pull-off-force at a fixed temperature is plotted as a function of pull-off rate and the result is extrapolated to the zero-rate condition. The rate-dependant visco-plastic dissipation term that is generated is an essential input for pavement performance models that aim to predict the cracking susceptibility of a particular mix.

The accessorized AFM metrology system assembled at WRI for use on these subtasks provides a reasonably simple tool with which to measure fracture energy with controlled temperature and stress rate, and as such can be used to distinguish surface energy and visco-plastic contributions to the overall fracture energy. The same measurements also provide a ductile/brittle profile that can be related to temperature, stress/strain rate, aging and material type. Also, the AFM provides the capability of imaging fracture faces. These images indicate whether a fracture was mainly cohesive or adhesive in nature, and also provide a classic indicator with respect to the ductile/brittle characteristic of the fractured material.

As work has progressed on these two subtasks, as we see what works and what doesn’t, some deviation from the course envisioned prior to the beginning of work has necessarily occurred. Both of these subtasks have been directed toward a better understanding of the mechanisms and energy release associated with asphalt fracture. Initial work has shown that adhesive failure is probably of little consequence except when environmental contaminants (i.e. moisture) enter the picture. Generally, the same type of testing has been used to measure both adhesion and cohesion. For the purpose of this study two additional variables (moisture exposure and substrate type) will be manipulated to push the system toward adhesive type failures. Imaging of fracture surfaces indicates the type of failure and may provide some insight into how water interacts at the asphalt/aggregate interface.

The work plan for subtask M1b-2 states: “The primary objective of this subtask is to determine the entropic contribution to the surface free energy of adhesion in support of other subtasks within the work element relating to surface energy.” The project is on track to meet this goal. An AFM technique that can be used to determine the entropic contribution to the measured fracture energy has been developed and demonstrated through some preliminary testing. Adhesion measurements for representative aggregate surfaces with various levels of moisture exposure using this technique constitute the majority of the experimental work remaining for this subtask. By the end of year five work we expect to have completed several representative examples of adhesive (and/or cohesive) fracture energy, in terms of both surface energy and visco-plastic dissipation, plotted as a function of moisture exposure for various asphalt/aggregate combinations.

The plan for work element M2a states: “The primary outcome of this task is to determine material properties (viscosity, plasticity) that influence the relationship between the theoretical work of cohesion and the practical work of cohesion.” An AFM technique that allows us to measure fracture energy and to separate it into its constituent surface energy and visco-plastic dissipative components has been developed under subtask M2a-2. This technique is being employed to map visco-plastic dissipation and surface energy changes as a function of temperature for several various asphalts. Experiments are also planned that will incorporate moisture as a test variable. This subtask is projected to be on track for completion as scheduled.

Issues Identified During the Previous Year and Their Implications on Deliverables

Subtasks M1b-2 and M2a-2 have proven to be strongly linked with work conducted on one subtask invariably being also applicable to the other. Experiments conducted to date strongly indicate that the interfacial components and the amount of moisture that reaches the asphalt/substrate interface are the main determinant as to whether fracture is predominately adhesive or cohesive. Work on these subtasks to date strongly indicates that adhesion hysteresis is linked to changes in the visco-plastic dissipation component of the fracture/healing energy as well as other factors, including roughness and/or chemistry of the substrate surface. Measurement of the surface roughness of common aggregate materials has been delayed while we have pursued methods to measure visco-plastic dissipation. We anticipate that the deliverable associated with surface roughness measurements will be delayed by three months.

21-Month Extension Work Plan

Techniques developed under ARC subtasks M1b-2 and M2a-2 provide a method capable of measuring fracture energy and breaking it down into its surface energy and visco-plastic dissipative constituents (Capella et al. 2005; Chizhik et al. 1998; Fischer-Cripps 2000; Clifford and Seah 2005; Moeller 2009). This capability has significant potential for generating accurate measured values for the fracture energy components (particularly with respect to visco-plastic dissipation) that are essential inputs for the advanced pavement performance model being developed under various other ARC subtasks. It is well known that asphalt tends to harden as it ages, and available techniques work reasonably well for relating increase in hardness to the degree of aging. The relationship between oxidative aging and cracking susceptibility is much more poorly understood. The AFM technique developed for use in subtasks M1b-2 and M2a-2 provides a valuable tool that can be used to study the effect of oxidative aging on the components of fracture energy and ductile/brittle characteristics.

For reasons as outlined in a preceding paragraph, we propose combining subtasks M1b-2 and M2a-2 into a single adhesion/cohesion subtask for year six work. The primary objective of this subtask will be to provide measured input values for fracture energy (in terms of both surface energy and visco-plastic dissipation) for various asphalt/aggregate combinations as functions of temperature, stress/strain rate, oxidative aging, and moisture exposure. The second objective of the proposed year six research is to see if the new nano-mechanical measurement techniques developed at WRI can be applied to asphalt mastics and actual aged pavement samples. The proposed experiments could lead to the development of a laboratory procedure that accurately assesses the effects of long term aging on the asphalt aggregate interface in terms of changes in fracture energy especially with respect to the dissipative portion of this energy.

Specifically WRI will work in conjunction with TAMU to provide fracture energy, broken down into surface energy and visco-plastic components, as inputs for performance predictive modeling. Working with TAMU various asphalt/aggregate combinations will be selected and fracture energy will be measured for a range of variables as specified by TAMU to provide data with which to test and validate their performance model. These data will be used to provide plastic-deformation energy that can be used with micro-calorimeter based surface free energy measurements to provide a more complete fracture energy input. Surface energy measurements from these tests can be used to validate and cross-check values measured with the micro-calorimeter. Reliable measured inputs of the plastic dissipative component of fracture energy and how this component changes with aging are essential to the success of performance predictive modeling efforts, and are also needed to validate these models.

We believe that the AFM-based nano-mechanical testing techniques developed at WRI can also be applied to the analysis of asphalt mastic fracture surfaces. When used in pavements, asphalt binders are mixed with fine filler material and larger aggregate particles and then compacted in place. The mixture of fine filler and asphalt binder (referred to as mastic) in turn bonds the larger aggregate particles into a single mass. In the pavement the asphalt binder begins to age as the result of a slow oxidation process. Only the asphalt ages, but it is commonly believed that the fine filler particles and even aggregate surfaces can influence the aging of the asphalt binder. It is the mechanical properties of this mastic component (like the mortar in a brick wall) that control the durability of the pavement. The measured surface energy and visco-plastic characteristics of binders as they age in the form of mastics may prove to be a better input for pavement performance models when compared to these values measured for neat asphalts.

For the proposed work small cylindrical samples (~6-10 mm diameter) of selected aggregate materials will be prepared by core drilling aggregate slabs. The small cylindrical aggregate samples will then be broken normal to the cylinder axis. The broken aggregate cylinder will then be heated to a specified temperature and ‘glued’ back together using mastic prepared from asphalt mixed with the fine powdered aggregate generated by the core drilling process and a controlled application of bonding pressure and temperature. The prepared cylindrical samples will be aged under various conditions of time, temperature, and humidity and then broken on mastic joint exposing fracture surfaces for AFM mechanical analysis and imaging. Alternatively, similar small cylindrical samples could be removed from thin slices of actual pavement cores. These small samples, representative of actual pavements after some known degree of real environmental exposure, could then be broken and the fracture surfaces analyzed as proposed for the laboratory prepared surrogates.

AFM-based nano-mechanical measurements on the fracture surfaces of prepared samples will show how surface energy and the energy lost to visco-plastic dissipation within the mastic change in relation to controlled sample conditioning (i.e. aging, moisture, temperature, and stress rate). These measurements can be compared with similar measurements made on neat asphalts (without fine filler materials) to determine the effect of the fine filler particles on the measured visco-plastic dissipation. The AFM-based values can be used either directly as inputs for performance models, or used for comparison and/or validation for fracture energy values determined using other methods. Nano-mechanical measurements on the fracture surfaces of field derived samples can be used to validate performance models and performance model inputs as well as providing insight into how important mechanical properties change as a pavement ages in a particular service environment.

In addition, AFM imaging of the fracture surfaces will attempt to identify structural features that tend to be associated with either ductile or brittle behavior. Understanding the morphological changes associated with the ductile/brittle transition of an interface could represent a first step toward specifically modifying asphalt binders for use in mixes that provide improved performance with respect to cracking susceptibility.

Deliverables

The proposed research will deliver a convenient micro/nano-scale cyclic direct tension test applicable to laboratory or field samples. This test will provide for the quantitative measurement of fracture energy in terms of its surface energy and visco-plastic dissipative components as well as the effects of fine filler materials, aging, and moisture on these important properties. Testing and validation of the proposed methodology will continue throughout the duration of the project, and the refined and validated test method including hardware configuration and data collection and analysis technique will be reported as the final product.

The second deliverable generated by the proposed research will be fracture energy inputs, broken down into surface energy and visco-plastic dissipative components, for advanced pavement performance predictive models being developed by other consortium partners. The exact description and timing of this deliverable will be worked out in conjunction with consortium partners who are directly involved in the modeling effort.

Table for Decision Points and Deliverables

Type of Deliverable	Description	Original Delivery Date	Revised Delivery Date	Reason for change
Test Method	A method to determine surface roughness of aggregate and fines based on AFM	12/30/11	3/30/12	Development of measurement technique has taken longer than initially expected
Test Method	A method to determine ductile –brittle properties via AFM measurements	12/30/11	12/30/11	N/A
Performance Model Input Data	Fracture energy in terms of surface energy and visco-plastic components	Work out with ARC partners	N/A	N/A
Test Method	AFM –based micro/nano-scale cyclic direct tension test	end of year six work	N/A	N/A

Cited References

Capella, B., S.K. Kaliappan, and H. Sturm, 2005, Using AFM Force-Distance Curves to Study the Glass-to-Rubber Transition of Amorphous polymers and Their Elastic-Plastic Properties as a Function of Temperature. *Macromolecules*, 38, 1874-1881.

Chizhik, S.A., Z. Huang, V.V. Gorbunov, N.K. Myshkin, and V.V. Tsukruk, 1998, Micromechanical Properties of Elastic Polymeric Materials As Probed by Scanning Force Microscopy. *Langmuir*, 14, 2606-2609.

Clifford, C.A., and M.P. Seah, 2005, Quantification issues in the indentation of nanoscale regions of homopolymers using modulus measurement via AFM nanoindentation. *Applied Surface Science*, 252, 1915-1933.

Fischer-Cripps, A.C., 2000, A review of analysis methods for sub-micron indentation testing. *Vacuum*, 58, 569-585.

Moeller, G., 2009, AFM Nanoindentation of Viscoelastic Materials with Large End-Radius Probes. *Journal of Polymer Science,* 47, 1573-1587.

CATEGORY M4: MODELING

Work Element M4c: Unified Continuum Model (TAMU)

Major Findings & Status

The moisture-induced damage model has been finalized and implemented in PANDA. This moisture damage constitutive model considers the degradation in the cohesive and adhesive properties of asphalt mixtures because of water and vapor diffusion. This decomposition of moisture damage into cohesive and adhesive degradation mechanisms allow one to conduct both micromechanical and macromechanical computer simulations of moisture damage. Micromechanical simulations are useful for guiding the material design of susceptible asphalt mixtures, whereas macromechanical simulations are useful in predicting the fatigue damage and rutting performance of asphalt pavements due to presence of moisture.

The consistency of the formulated continuum-based moisture damage model with the laws of thermodynamics has been verified. However, until now, the moisture-damage model has only been verified and calibrated against many small-scale pull-off experiments of aggregate-mastic systems. A systematic procedure has been developed for identifying the material parameters associated with the moisture damage model.

Issues Identified During the Previous Year and Their Implications on Deliverables

Due to the lack of comprehensive mechanical experimental data that report the behavior of asphalt mixtures due to moisture diffusion, the moisture-induced damage model as part of PANDA has not been fully validated against mixture-level experimental data for moisture-induced degradation. However, this issue will be solved due to the ARC 2x2 comprehensive testing (see Table V3c.3) that will be used for further calibration and validation of the PANDA implemented moisture-induced damage model. Much of the work involved with testing the ARC 2x2 matrix will be completed in Year 5 as defined in the Year 5 work plan.

21-Month Extension Work Plan

The main focus of the 21-month extension period work plan is placed on satisfactory completion of the experimental validation of the moisture damage model using the materials from the ARC 2x2 matrix validation plan (see Table V3c.3). Please refer to task V3c for the validation plan. Therefore, during years five the 21-month extension period, the moisture-induced damage model as part of PANDA will be fully validated and documented in the comprehensive report on PANDA.

Table for Decision Points and Deliverables

Date	**Deliverable**	**Description**
10/12	Journal Paper	Validation of the moisture-damage model against the ARC 2x2 experiments on asphalt mixtures
3/13	Final Report	Include the details of the PANDA moisture-damage model into the PANDA comprehensive report.

TABLE OF DECISION POINTS AND DELIVERABLES FOR THE MOISTURE DAMAGE PROGRAM AREA

Name of Deliverable	Type of Deliverable	Description	Original Delivery Date	Revised Delivery Date	Reason for change
M1b-2: Work of Adhesion at Nano-Scale using AFM (WRI). ***This subtask has been combined with M2a-2: Work of Cohesion at Nano-Scale using AFM (WRI)***	Test Method	A method to determine surface roughness of aggregate and fines based on AFM	12/30/11	3/30/12	Development of measurement technique has taken longer than initially expected
	Test Method	A method to determine ductile –brittle properties via AFM measurements	12/30/11	12/30/11	N/A
	Performance Model Input Data	Fracture energy in terms of surface energy and visco-plastic components	Work out with ARC partners	N/A	N/A
	Test Method	AFM –based micro/nano-scale cyclic direct tension test	end of year six work	N/A	N/A
M4c: Unified Continuum Model (TAMU)	Journal Paper	Validation of the moisture-damage model against the ARC 2x2 experiments on asphalt mixtures	10/12		
	Final Report	Include the details of the PANDA moisture-damage model into the PANDA comprehensive report.	3/13		

PROGRAM AREA: FATIGUE

CATEGORY F1: MATERIAL AND MIXTURE PROPERTIES

Work Element F1b: Viscoelastic Properties

Subtask F1b-1: Nonlinear viscoelastic properties of asphalt materials under cyclic loading (TAMU)

Major Findings & Status

The main objective of this subtask was to determine a constitutive model that accurately characterizes the viscoelastic response of asphalt materials subjected to a three dimensional stress state. This is important because the accuracy of any micromechanical model of an asphaltic material (analytical or computational) is contingent upon the accuracy of the constitutive model that describes the material response.

During the previous years we were able to:

- demonstrate that the asphalt binder exhibits interaction non linearity, i.e., the stiffness of the binder significantly changes when subjected to a combination of shear and normal stresses (which is common in asphalt mixtures),
- identify a constitutive model that can represent this form of nonlinear response as well as a systematic procedure using the DSR and cone and plate geometry to obtain material constants for this model, and
- validate the model under different loading history.

Issues Identified During the Previous Year and Their Implications on Deliverables

The test methods and modeling was successful and the results are expected to be useful for analytical and computational models of mortars or fine aggregate matrix (asphalt binders and fine aggregates). However, this approach needs to be extended to model the basic linear and nonlinear viscoelastic properties of mortars that can be used for analytical and computational models of asphalt mixtures.

21-Month Extension Work Plan

The work plan for year six is to further validate the results obtained thus far and extend this procedure for mortars or FAM. The analytical and experimental methods will also be documented in an AASHTO format so that they can be readily replicated by any other laboratory. More specifically the following tasks will be accomplished to achieve this.

- Thus far, the properties of the asphalt binder (as a function of the overall stress state) were measured using the DSR. The proposed test method and model were also validated using the DSR with different load configurations. This validation will be completed using a combination of shear and compressive stresses with a different test geometry configured for use with a universal loading frame. The material properties for the constitutive model will be determined using the DSR but will be applied to predict the response of the binder in this different loading geometry. *This will provide a rigorous validation for the significance of interaction effects as well as the constitutive model that accommodates these effects.*

- The test method and model will be applied to mortar or FAM specimens. Tests that simultaneously apply a shear and normal force will be conducted using a universal loading frame. Combinations of the two core binders and one core aggregate will be used for these tests. A series of creep-recovery, monotonic and cyclic tests will be conducted analogous to the protocol developed for binders.

- Results from the creep-recovery tests will be analyzed using the non-linear viscoelastic model to determine parameters for the constitutive model. Comparing predicted results using the model to the measured material response under these loading conditions will be used to validate the constitutive model for mortars.

- A computational model will be used with the proposed constitutive material model to demonstrate and highlight the *importance of accounting for the interaction effects* in determining the performance of asphalt composites. The model will be at a material scale and will be comprised of coarse aggregates with a mortar matrix. The constitutive behavior for the mortar will account for interaction effects as described above. This will also serve as an example application or demonstration for future engineers or researchers.

- The test procedure, constitutive model, and analytical methods to obtain material parameters that account for the interaction effects will be documented in the final report along with Appendices for the procedures in an AASHTO format.

Table for Decision Points and Deliverables

Type of Deliverable	**Description**	**Original Delivery Date**	**Revised Delivery Date***	**Reason for change**
Four journal papers	A constitutive model that accounts for the nonlinearity and three-dimensional stress state of the material including a method to obtain model constants for asphalt binders.	12/30/08 3/31/10 9/30/10 12/31/11	Complete Complete 3/31/11 No change	
Models and algorithm		3/31/09 6/30/10 12/31/11	3/31/12	
Draft report		12/31/08 12/31/11		
Final report		6/30/08 3/31/12		
Procedure in AASHTO format	A test and analysis procedure in AASHTO format to measure and model the linear and nonlinear viscoelastic properties of asphalt binders and mortars incorporating the effect of interaction.	7/31/13		Proposed.

* From year 5 work plan.

Subtask F1b-2: Viscoelastic properties under monotonic loading **(TAMU)**

Major Findings & Status

A method was developed during Year 4 to separate the recoverable and irrecoverable responses using creep-recovery experimental measurements at various temperatures and stress levels. This method has been and is being used during Year 5 to analyze experimental data from the ALF experiments and obtain the parameters of the PANDA model.

21-Month Extension Work Plan

We will continue to use this method in the analysis of the experimental data from the ARC mixtures testing. A MatLab code is under development to separate the viscoelastic and viscoplastic deformations from a repeated creep-recovery test automatically. Then, the MatLab code can be used to identify the viscoplastic material parameters automatically.

Work Element F1c: Aging (TAMU)

Unified Continuum Model for Aging

Major Findings & Status

A phenomenological oxidation aging model has been developed and implemented into PANDA. The model takes into consideration oxygen diffusion and formation of carbonyl in the asphalt mixture. A thermo-oxygen transport model has been developed and coupled to PANDA. The model is verified qualitatively against a wide range of experimental trends. Furthermore, how aging affects the viscoelastic, viscoplastic, damage, and healing properties has been investigated thoroughly. It has been shown that the aging model predicts well the effect of oxidation hardening on the various mechanical properties of asphalt mixtures. Moreover, the developed aging model has been calibrated and validated against existing experimental data from previous FHWA projects; mainly the experimental results documented in report FHWA/TX-05/0-4468.

Issues Identified During the Previous Year and Their Implications on Deliverables

Due to the lack of comprehensive mechanical experimental data that report the behavior of asphalt mixtures due to oxidation aging, the aging model as part of PANDA has not been fully validated against mixture-level experimental data for oxidation aging. However, this issue will be solved due to the ARC 2x2 comprehensive testing (see Table V3c.2).

21-Month Extension Work Plan

The main focus of the sixth year work plan is on the experimental validation of the aging model using the materials from the ARC 2x2 matrix validation plan (see Table V3c.2). Much of this effort will be completed during Year 5 as presented in the Year 5 work plan. However, it will be necessary to complete some of the validation testing during the 21-month extension period as well as the reporting. Please refer to task V3c for the validation plan. Therefore, during year six, the oxidation aging model as part of PANDA will be fully validated and documented in the comprehensive report on PANDA.

Table for Decision Points and Deliverables

Date	Deliverable	Description
11/12	Journal Paper	Validation of the oxidation aging model against the ARC 2x2 experiments on asphalt mixtures
3/13	Final Report	Include the details of the PANDA aging model into the PANDA comprehensive report.

Work Element F1c: Aging Field Validation (TAMU)

Major Findings and Status

Asphalts oxidize in pavements, leading to embrittlement of the binder and decreases in pavement resistance to damage such as fatigue or age-related cracking. Recent developments have produced a thermal and oxygen transport model of binder oxidation in pavements.

This model draws on laboratory measurements such as 1) both fast-rate and constant-rate binder oxidation kinetics, 2) oxygen diffusivity in binders and the effect of aggregate fines on diffusivity, and 3) air voids distribution in mixtures. Part of the kinetics characterization has been to explore oxidation reaction mechanisms and to search for correlations between the fast-rate and constant-rate kinetics.

By using these elements of binder oxidation, a thermal and oxygen transport model has been developed that shows excellent promise for a priori predictions of binder oxidation in pavements. Thus, given a pavement location, binder kinetics, and a mixture morphological model (air voids and binder distribution), one can calculate estimates of binder oxidation in pavements at locations around the country, or globe.

Issues Identified During the Previous Year and Their Implications on Deliverables

A primary issue that remains with pavement oxidation modeling is field validation. Pavement sites for which cores are available over time need to be evaluated to determine binder oxidation as a function of time and depth. Ideally, these would be pavement sites for which binder is available and thus for which complete reaction kinetics can be determined.

21-Month Extension Work Plan

A significant part of the year six work plan will be to conduct field validation. The critical point will be to identify additional field sites for which there are cores available and then obtain access to them. Then, once cores are obtained, detailed measurements of the cores will be required to determine air voids distribution and binder oxidation, both as a function of depth.

A second effort of the year six plan will be to merge the pavement binder oxidation model with mixture mechanics models. With this capability in place, calculations of mixture performance over time, including both the effects of fatigue and binder oxidation, can be made. This merging of both mechanical and chemical changes to the mixture properties is essential to making accurate performance prediction.

Table for Decision Points and Deliverables

Type of Deliverable	Description	Original Delivery Date	Revised Delivery Date	Reason for change
journal pub	Field validation of a pavement binder oxidation model	4/1/2013		
journal pub	Combining a pavement binder oxidation model with mixture micromechanics models	4/1/2013		
journal pub	Determination of oxidation kinetics from binder recovered from pavement cores	4/1/2013		
final report	Pavement Oxidation Model: Field validation and incorporation in PANDA	4/1/2013		

Work Element F1d: Healing (TAMU)

Subtasks F1d-4: Test methods to measure properties related to healing

Major Findings & Status

The main objective of this subtask was to understand the healing mechanism and its affect on material performance at different length scales.

During the previous years we were able to:

- hypothesize and partially validate a mechanism and concomitant mathematical model for healing at a micrometer length scale in asphalt binders,
- identify the potential chemical and physio-chemical properties that influence the rate of healing in asphalt binders,
- develop a test method using the DSR to measure and compare the inherent healing characteristics of different asphalt binders and evaluate the influence of aging and temperature on these properties,
- develop a test method using the DSR to measure and compare the healing characteristics of different types of asphalt mortar or fine aggregate matrix (binder with fine aggregate) at a continuum scale and demonstrate that the results from this test method were a material related property.

Issues Identified During the Previous Year and Their Implications on Deliverables

A test method to measure the overall healing characteristics of asphalt composites was developed and validated. Although the procedure is based on the same viscoelastic continuum damage theory that is currently being used for mixture characterization with the Asphalt Materials Performance Tester (AMPT), the results obtained from this method are dimensionless and can be used in any other continuum damage based approach. While the procedure was developed and partially validated using mortars or fine aggregate matrix subjected to cyclic shear in torsion, it can easily be extended to asphalt mixtures. Two aspects related to this procedure need to be developed in order for it to be used on a routine basis. First, the procedure must be validated for use with asphalt mixtures subjected to direct tension (or push-pull) loading. Second, possible methods or surrogate tests must be investigated in order to reduce the overall testing time and specimens. These issues can be addressed in the sixth year work plan.

21-Month Extension Work Plan

The work plan for year six would be to extend the continuum based procedure from mortars or FAM to full asphalt mixtures and present it in an AASHTO format so that can readily be used by any other laboratory. The test procedure to measure the intrinsic healing property of asphalt binder will also be finalized and presented in an AASHTO format. Finally, researchers will also determine ways to reduce the number of tests required to determine the healing characteristics of asphalt mixtures. More specifically, the following tasks will be conducted to accomplish this.

- Two different asphalt mixtures following a dense gradation will be used for the testing. The mixtures will be subjected to direct tension or push-pull loading configuration. The test protocol will be very similar to the one that is currently being used for the AMPT to evaluate the fatigue cracking resistance of asphalt mixtures. The only modification to this protocol will be the introduction of rest periods to characterize healing. The rest periods introduced will be analogous to the format used to test FAM specimens in the tests conducted thus far. The viscoelastic continuum damage theory will be used to quantify percentage healing as a dimensionless quantity but based on the internal state variable that represents damage.
- The dimensionless healing characteristics measured using the procedure described above will be validated by subjected test specimens to a randomized sequence of loading and rest periods. Results will also be analyzed to predict the gain in number of load cycles to failure due to the healing during the rest periods.
- Preliminary work will also be conducted to demonstrate the feasibility of using shift factors to accommodate the influence of aging and temperature. This will be done by conducting both mixture and binder tests at different temperatures and possibly aging conditions.
- A detailed test procedure to quantify the intrinsic healing in asphalt binders using the DSR will be documented in AASHTO format. This procedure can be used either to determine the intrinsic healing of binders as a material property input for micromechanics models or as a material property to screen or rank binders based on their inherent ability to self-heal.
- A detailed test procedure to quantify the overall healing in asphalt mixture composites as a continuum using direct tension tests will be documented in AASHTO format. The procedure will include experimental as well as analytical methods to characterize the

overall healing in asphalt mixtures. Documentation will also include ways in which this healing function could be used to (i) rank healing characteristics of different mixtures along with fatigue characteristics, and (ii) utilize the healing characteristics in continuum based computational models such as PANDA.

Table for Decision Points and Deliverables

Type of Deliverable	**Description**	**Original Delivery Date**	**Revised Delivery Date***	**Reason for change**
Six journal papers	A mathematical model for selfhealing at the micron scale, partial validation of this model, measurement of properties related to this model, measurement of overall healing as a function of damage and rest period, and micro to nano scale evaluation of properties that influence fracture and self-healing	12/31/08 09/30/09 3/31/10 09/30/10 09/30/11 12/31/11	Complete Complete Complete Complete Complete No change	
Models and algorithm		6/30/11	3/31/12	
Final report		12/31/08 12/31/11		
Procedure in AASHTO format	A test and analysis procedure in AASHTO format to: (i) measure the intrinsic healing of asphalt binders with potential application as a material selection tool and (ii) measure the overall healing in asphalt composites with potential applications as a mixture selection tool and required input for continuum damage models.	7/31/13		Proposed.

* From year 5 work plan.

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

Major Findings & Status

At this point, a novel micro-damage healing model for asphalt mixtures has been developed and numerically implemented into PANDA. The healing model has been validated against uniaxial compression and tension fatigue data from the Nottingham and ALF database on asphalt mixtures at various temperatures (see Abu Al-Rub et al. 2010; Darabi et al. 2011a, 2011b).

21-Month Extension Work Plan

The main focus of the six year work plan is on further validation of the micro-damage healing model against the ARC 2x2 matrix validation plan. This effort was begun in Year 5 but will be completed during the 21-month extension period. Special emphasis will be placed on relating the associated material parameters to fundamental properties (e.g. surface energy, bond strength, length of the healing process zone) based on micro-mechanical arguments. Please refer to task V3c for the validation plan.

Table for Decision Points and Deliverables

Date	Deliverable	Description
6/12	Journal Paper	Validation of the micro-damage healing model against the ARC 2x2 testing
3/13	Final Report	Include the details of the PANDA aging model into the PANDA comprehensive report.

Cited References

Abu Al-Rub, R.K., M.K. Darabi, D. Little, and E. Masad, 2010, A Micro-damage Healing Model that Improves Prediction of Fatigue Life in Asphalt Mixes. *International Journal of Engineering Science*, 48, 966-990.

Darabi, M.K., R.K. Abu Al-Rub, E.A. Masad, and D.N. Little, 2011a, A Thermodynamic Framework for Constitutive Modeling of Time- and Rate-dependent Materials, Part II: Numerical Aspects and Application to Asphalt Concrete. *International Journal of Plasticity* (submitted).

Darabi, M.K., R.K. Abu Al-Rub, and D.N. Little, 2011b, A continuum damage mechanics framework for modeling micro-damage healing. *International Journal of Solids and Structures* (submitted).

CATEGORY F2: TEST METHOD DEVELOPMENT

Work Element F2c: Mixture Testing Protocol (TAMU)

Major Findings and Status

The background for this work element is described in Year 5 work plan under work element E1a and is comprised of four components: analytical micromechanical models of binder properties, analytical micromechanical models of modified mastic systems, analytical models of micromechanical properties of asphalt mixtures, and analytical models of asphalt mixture response and damage. The last component of work will be integrated into the PANDA model and this is explained under work element F3c. In Year 5 laboratory mixture testing protocols are being verified, and fracture mechanics analysis of asphalt mixtures in compression methods are being verified and validated. These are described in detail in the June, 2011, quarterly report. This report describes how mixture testing protocols and the proposed strain decomposition method for characterizing the asphalt mixture in compression are being verified by conducting tests on 16 asphalt mixture specimens that have two binder types, two air void contents and two aging conditions. Results indicate that the proposed testing protocols can obtain consistent and reasonable material properties. The strain decomposition has been successfully performed on each asphalt mixture specimen and yields viscoplastic and viscofracture strains that are respectively used in the characterization of permanent deformation and cracking of the asphalt mixture. A fracture mechanistic model is also being verified that will be able to analyze the growth of the cracks in the tertiary stage, based on which the damage density is obtained to address the effect of the cracks on the permanent deformation during the viscoplastic modeling. Results indicate that the cracks in the tertiary stage can yield an increasing true stress which, in turn, leads to extra plastic deformation when an asphalt mixture is subjected to a controlled compressive load with a constant amplitude.

21-Month Extension Work Plan

While most of the verification work will be completed in year 5 as planned, the massive amount of verification and validation testing required at TAMU under the ARC program makes it difficult to plan for and complete all testing with the available equipment. Primarily for this reason some of the verification testing planned for year 5 must be completed in the extension period as will the reporting and documentation of that work. Therefore, the extension period work plan for work element F2c will be to complete this intensive work. The reader is referred to work element F2c in the June, 2011, quarterly report for further details.

During Year 6, work on characterization of the fine aggregate matrix (FAM) using the DMA and final validation of this work will be completed. The deliverables of this work will be included the 508 report that addresses moisture damage and will consist of the following: 1. DMA testing protocol (This is one of two protocols that will be presented using the DMA. The first has already been completed and is based on a slightly different methodology – see work element M1c.); 2. Suction diffusion model including wind speed to model wetting of asphalt layers under different levels or relative humidity; 3. Aggregate surface area method to determine asphalt content in FAM; 4. Method to moisture condition specimens in DMA; 5. Mechanical model to obtain fundamental fracture properties; 6. Repeated direct tension (RDT) method as substitute or replacement for torsional DMA testing; and 7. Data analysis to demonstrate significance of water vapor diffusion on moisture damage of FAM and full asphalt mixtures.

Table for Decision Points and Deliverables

Type of Deliverable	Description	Original Delivery Date	Revised Delivery Date	Reason for change
Journal paper and dissertation	Characterize permanent deformation of FAM under different conditions of relative humidity	3/31/12		
Journal paper	Self-consistent micromechanics model of asphalt mixtures	3/31/12		
Journal paper	Crack size distribution in asphalt mixtures	3/31/12		
508 report contribution	Moisture damage	12/31/11		
508 report contribution	Fatigue	3/30/12		

Work Element F2d: Tomography and Microstructural Characterization (TAMU)

X-Ray Computed Tomography

Major Findings & Status

The X-ray computed tomography system is used as a tool measure the damage in asphalt mixtures. These measurements are then used to determine the damage functions incorporated in the continuum model (F3c.2).

21-Month Extension Work Plan

X-ray CT will be used to scan the test specimens in work element F3c.2, and the developed image and analysis techniques will be utilized to analyze damage directional distribution.

Asphalt Binder Phase Analysis

Major Findings or Status

There have been two significant findings related to the micro-characterization of asphalt binders based on mapping of physical properties of asphalt phases using Atomic Force Microscopy (AFM). The first finding includes results of statistical analysis of the AFM phases and creep measurements formerly presented for binders AAB, AAD, and ABD, which reveal statistically significant differences amongst phase detection microscopy (PDM)-separated asphalt phases. Furthermore, the results verify statistically significant changes in the properties of these phases due to aging. The second finding includes the extraction of viscoelastic properties of each asphalt phase and composite viscoelastic properties before and after aging, which are compared to macro-scale elastic and viscoelastic properties. For conciseness, and to present an example of these results, which have not yet been reported in quarterly reports, **select results** from asphalt binder AAD are presented with some detail, followed by a summary of significant findings related to **all binders** (original and aged binders AAB, AAD, and ABD).

Figure F2d.1 shows formerly presented phase images of asphalt AAD before and after aging to serve as reference for the following results. The terms Phase 1, Phase 2, and Phase 3 are used interchangeably with Continuous Phase, Dispersed Phase, and "Bee Structure" Phase, respectively as depicted in Figure F2d.1. Furthermore, the "Bee Structure" Phase is considered to be a sub-phase of the dispersed phase, and therefore, the two phases are often referred to as the dispersed phase(s).

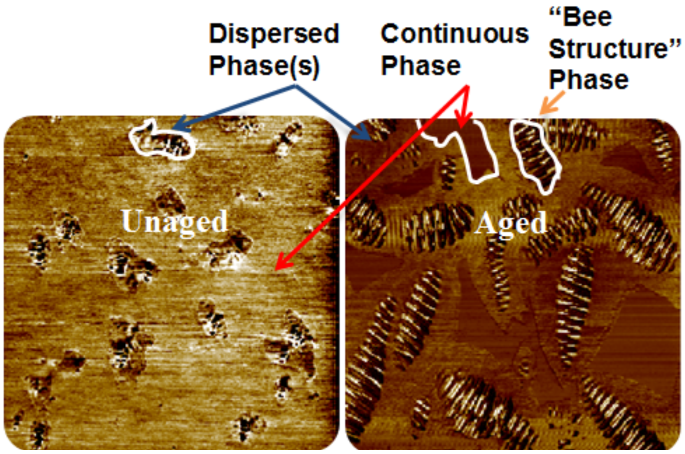
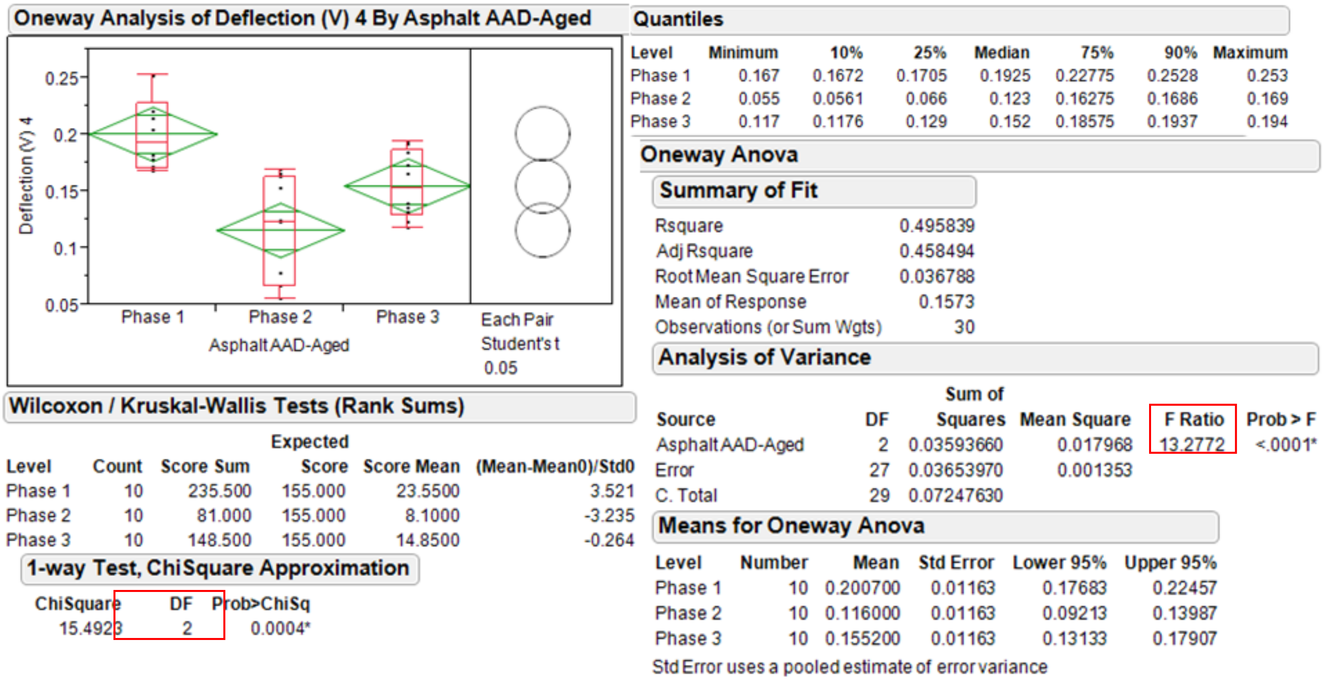


Figure F2d.1. Asphalt AAD phase images before and after aging.

Statistical Analysis of AFM Creep Data

Comparison of Multiple Populations of Asphalt Phases

Figure F2d.2 gives the analysis of variance (ANOVA) f-test results for aged asphalt AAD creep measurement comparisons. Due to the presence of non-normality and outliers in the data, the more robust Wilcoxon/Kruskal Wallis Sum Rank test was also computed to validate p-value calculated from the more powerful ANOVA f-test. The p-value should be interpreted as such: a p-value ≤ 0.05 indicates a statistically significant difference amongst populations with 95% confidence; furthermore, a p-value ≤ 0.001 indicates a statistically significant difference amongst populations with 99.9% confidence. The confidence interval is highlighted to show whether or not the value of zero (no difference amongst the populations) falls within the 95% confidence interval. Therefore, for the analysis presented, **low p-values** (i.e. ≤ 0.05) and **confidence intervals that do not enclose the value of zero** are **ideal**.



Oneway Analysis of Deflection (V) 4 By Asphalt AAD-Aged

Quantiles

Level	Minimum	10%	25%	Median	75%	90%	Maximum
Phase 1	0.167	0.1672	0.1705	0.1925	0.22775	0.2528	0.253
Phase 2	0.055	0.0561	0.066	0.123	0.16275	0.1686	0.169
Phase 3	0.117	0.1176	0.129	0.152	0.18575	0.1937	0.194

Oneway Anova

Summary of Fit

Rsquare	0.495839
Adj Rsquare	0.458494
Root Mean Square Error	0.036788
Mean of Response	0.1573
Observations (or Sum Wgts)	30

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Asphalt AAD-Aged	2	0.03593660	0.017968	13.2772	<.0001*
Error	27	0.03653970	0.001353		
C. Total	29	0.07247630			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Phase 1	10	0.200700	0.01163	0.17683	0.22457
Phase 2	10	0.116000	0.01163	0.09213	0.13987
Phase 3	10	0.155200	0.01163	0.13133	0.17907

Std Error uses a pooled estimate of error variance

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

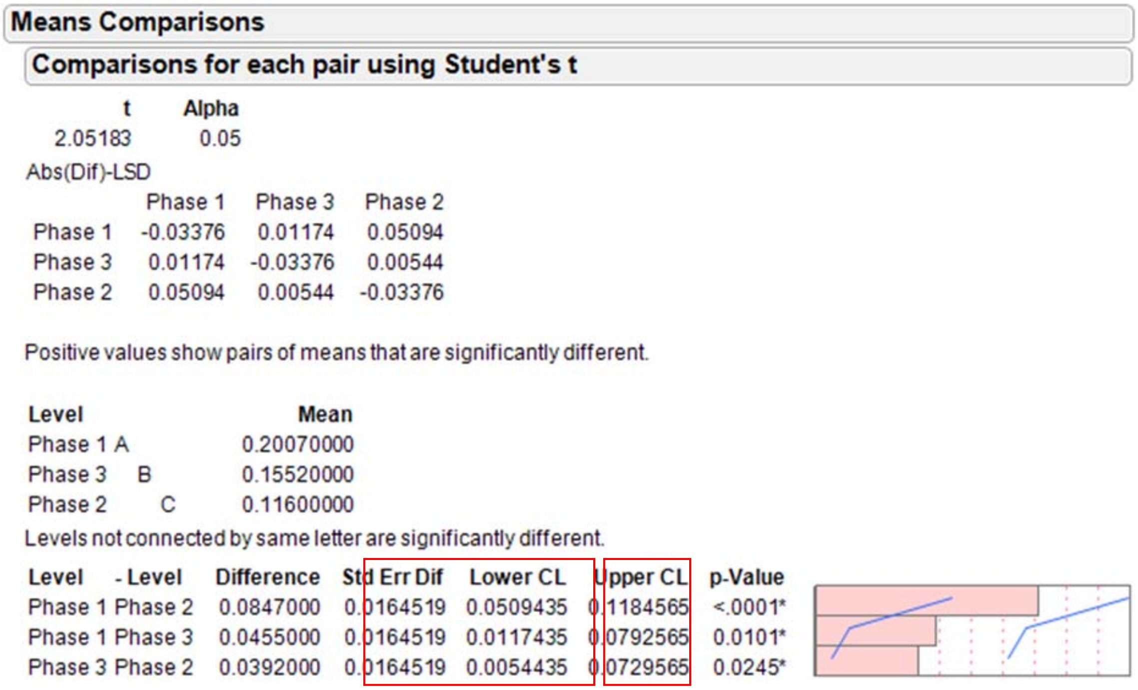
Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
Phase 1	10	235.500	155.000	23.5500	3.521
Phase 2	10	81.000	155.000	8.1000	-3.235
Phase 3	10	148.500	155.000	14.8500	-0.264

1-way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
15.4923	2	0.0004*

Figure F2d.2. ANOVA test and Wilcoxon Sum Rank test for Aged Asphalt AAD.

The null hypothesis being tested for Aged Asphalt AAD is that the maximum creep deflections for the three asphalt phases are equal, $H_0\colon \mu_1 = \mu_2 = \mu_3$ versus the alternate hypothesis that **at least one** of the population means differs from the others. Based on the hypothesis test of equal means for three phases of **Aged Asphalt AAD**, the **null hypothesis** is **rejected** at the α = 0.0004 level (99.96% confidence level). Based on rejection of the null for the three phases, Fisher's LSD analysis, presented in Figure F2d.3, was performed to determine which phases are different.



Means Comparisons

Comparisons for each pair using Student's t

t	Alpha
2.05183	0.05

Abs(Dif)-LSD

	Phase 1	Phase 3	Phase 2
Phase 1	-0.03376	0.01174	0.05094
Phase 3	0.01174	-0.03376	0.00544
Phase 2	0.05094	0.00544	-0.03376

Positive values show pairs of means that are significantly different.

Level				Mean
Phase 1	A			0.20070000
Phase 3		B		0.15520000
Phase 2			C	0.11600000

Levels not connected by same letter are significantly different.

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
Phase 1	Phase 2	0.0847000	0.0164519	0.0509435	0.1184565	<.0001*
Phase 1	Phase 3	0.0455000	0.0164519	0.0117435	0.0792565	0.0101*
Phase 3	Phase 2	0.0392000	0.0164519	0.0054435	0.0729565	0.0245*

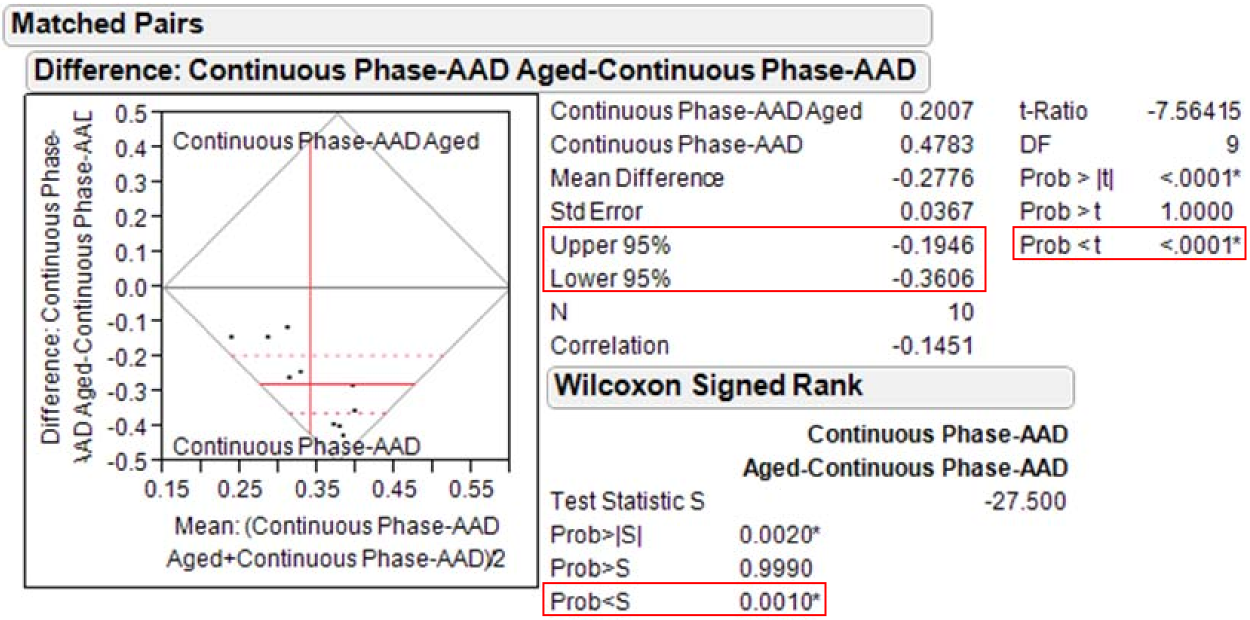
Figure F2d.3. Fisher's LSD analysis for Aged Asphalt AAD.

The most accurate and informative statement that can be made regarding the hypothesis test for the three phases of **Aged Asphalt AAD** is that the **equality of means hypothesis** is **rejected** at the α = 0.0001 level (99.99% confidence level) for the Phase 1-Phase 2 comparison, α = 0.010 level (99% confidence level) for the Phase 1-Phase 3 comparison, and α = 0.025 level (97.5% confidence level) for the Phase 3-Phase 2 comparison; furthermore, there is 95% confidence that the mean creep deflection of Phase 1 is between 0.05V and 0.12V (42% to 100%) greater than the mean creep deflection of Phase 2, the mean creep deflection of Phase 1 is between 0.01V and 0.08V (6.3% to 50%) greater than the mean creep deflection of Phase 3, and the mean creep deflection of Phase 3 is between 0.005V and 0.07V (4% to 58%) greater than the mean creep deflection of Phase 2.

Matched Pairs Analysis (Before and After Aging) of Individual Populations of Asphalt Phases

While analysis of multiple theoretical populations focused on properties of different phases in a given asphalt binder, the following matched pairs analysis focused on identifying whether or not a decrease in creep deflection (increase in stiffness) is statistically evident within a given phase, i.e. continuous phase (Phase 1) or dispersed phase (Phase 2), after aging.

The matched pairs analysis plots the mean deflection measurement before and after an effect (aging in this case) versus the difference in mean deflection before and after aging as presented in Figure F2d.4 for the continuous phase of Asphalt AAD. For the given analysis, the vertical red line indicates the average deflection measurement value, regardless of whether the measurement was taken before or after aging; whereas, the horizontal red line gives the difference that is detected due to the before and after effect. These lines essentially provide a convenient way to approximate the percentage change that is evident in the matched pairs analysis. The horizontal dotted red lines depict the 95% confidence interval of the difference. The null hypothesis being tested for each phase is that the maximum deflection after aging is greater than or equal to the maximum deflection before aging, H_0: $\mu_{after} - \mu_{before} \geq 0$ versus H_a: $\mu_{after} - \mu_{before} < 0$. In support of rejecting the H_0 in favor of H_a to make inferences that an increase in stiffness is evident due to aging, the majority of individual data points would ideally fall on the negative side of zero, indicating lower deflection (higher stiffness) after aging; furthermore, in order to make inferences using a confidence interval of the population difference at the $\alpha = 0.05$ level (95% confidence level), zero cannot fall within the 95% confidence bands.



```
Matched Pairs
Difference: Continuous Phase-AAD Aged-Continuous Phase-AAD

Continuous Phase-AAD Aged    0.2007     t-Ratio    -7.56415
Continuous Phase-AAD         0.4783     DF                9
Mean Difference             -0.2776     Prob > |t|  <.0001*
Std Error                    0.0367     Prob > t     1.0000
Upper 95%                   -0.1946     Prob < t    <.0001*
Lower 95%                   -0.3606
N                                10
Correlation                 -0.1451

Wilcoxon Signed Rank
                              Continuous Phase-AAD
                          Aged-Continuous Phase-AAD
Test Statistic S                           -27.500
Prob>|S|          0.0020*
Prob>S            0.9990
Prob<S            0.0010*
```

Figure F2d.4. Matched pairs analysis for asphalt AAD-Continuous Phase.

The most accurate and informative statement that can be made regarding the hypothesis test, H_0: $\mu_{after} - \mu_{before} \geq 0$ for the **continuous phase** of **Asphalt AAD** is that the **null hypothesis** is **rejected** at the $\alpha = 0.001$ level (99.9% confidence level); furthermore, there is 95% confidence that the mean creep deflection of the continuous phase is between 0.19V and 0.36V (40% to 75%) smaller after aging than the mean creep deflection prior to aging.

Overall, the t-tests and ANOVA f-tests (accompanied by the Wilcoxon/Kruskal Wallis Sum Rank test) provided at least 95% confidence that differences in individual phase properties existed in five of the six asphalt binders that were tested. There was a lack of statistical evidence to find a difference between the phase properties of Aged Asphalt AAB. Fisher's LSD analysis revealed with 95% confidence that each of the three phases in Aged Asphalt AAD had distinctively different properties. Matched pairs analysis provided at least 95% confidence that 11 of 12 continuous and dispersed asphalt phases that were studied reveal a decrease in maximum creep deflection (increase in stiffness) due to aging; this finding strongly supports the notion that observed increases in asphalt stiffness during aging are not only due to the presence of higher percentages of the stiffest phase after aging but also due to increased stiffness of the continuous and dispersed phases due to aging.

Viscoelastic Properties of Asphalt Phases

Theory

A typical AFM nanoindentation creep experiment performed in this study consists of contact between a an asphalt thin film and an AFM tip with known properties and geometry while a load, P, is applied and the corresponding penetration depth, h, is recorded with respect to time, t. A depiction of the AFM indention test geometry into an asphalt thin-film is shown in Figure F2d.5. The elastic-viscoelastic correspondence principle, which is commonly employed to convert elastic analytical solutions to viscoelastic solutions based on the relationship between elastic and Laplace transformed viscoelastic field equations, was used to extract viscoelastic properties from the AFM creep measurements.

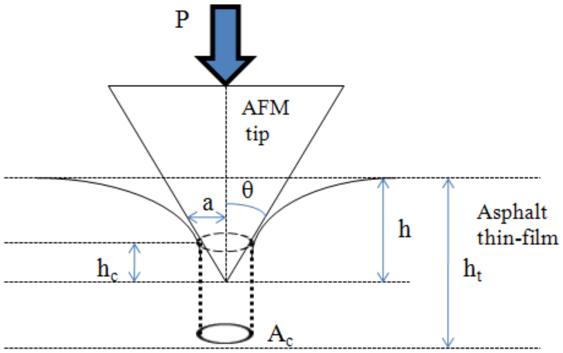


Figure F2d.5. Geometry of AFM indention test. P is the indentation load, h_t is the asphalt film thickness, h is the indentation depth, h_c is the contact depth, A_c is the projected contact area, and a is the contact radius (Adapted from Vandamme [1]).

The general solution for a rigid axisymmetric indenter into an isotropic solid is given by the Galin-Sneddon solution and reduced to the following equation [2-3].

$$h^2(t) = \left(\frac{\pi}{2tan\theta}\right)\left[\frac{P(t)(1-v^2)}{E}\right] \tag{1}$$

Where θ is the half-angle of the indenter, E is the elastic Young's modulus, and ν is the Poisson's ratio.

The viscoelastic Young's modulus under constant creep loading was fitted using the prony series model relationship given in (2).

$$E(t) = E_0 + \sum_{j=1}^{M} E_j exp\left(-\frac{t}{k_j}\right) \tag{2}$$

A range of composite elastic Young's modulus values were derived from each of the individual asphalt phases using the series/parallel bounds method, given in Equation 3. The composite bounds provide modulus ranges for two-phase media such as the system of continuous and dispersed asphalt phases and also provides the simplest solution for placing bounds on the composite elastic Young's modulus [4].

$$\frac{1}{\frac{v_1}{E_1}+\frac{v_2}{E_2}} \leq E^* \leq E_1 v_1 + E_2 v_2 \tag{3}$$

Where E and v are the respective Young's modulus and volume fraction of Phase 1 and Phase 2 as denoted.

Composite Viscoelastic Young's Modulus

Figure F2d.6 emphasizes two significant results regarding the viscoelastic Young's modulus. The first result, shown on the left side of each figure (Graph I), is the bounds for the composite viscoelastic Young's modulus [E(t)] of the unaged and aged Asphalt AAD. Graph I also highlights the viscoelastic Young's modulus value (E_1) from the unaged and aged asphalts at a specific point in time (approximately four seconds) under constant load, which corresponds to the same highlighted areas in the graph on the right side of the figure (Graph II). Graph II illustrates the relationship between individual phase modulus values, phase volume concentration, and the resulting composite E(t) values given in Graph I. Furthermore, the volume concentration of each phase before and after aging gives a unique depiction of the microstructural shift that occurs during the aging process. Graph II essentially provides information which distinguishes this AFM nanoindentation experiment from an experiment using a non-imaging, larger radius nanoindenter tip, such as a Berkovich tip or a spherical tip. Although the small-radius conical AFM tip is not as robust for collecting force measurements as the large-radius tips, the tips offer the ability to collect semi-quantitative viscoelastic properties that can be associated with different phases depicted in high resolution phase images; furthermore, viscoelastic properties extracted from age-altered phases of the same respective asphalt provides important information regarding the link between microstructural change and changes in composite viscoelastic properties.

The E(t) values at approximately four seconds (E_1 values) and composite E_1 bounds are given in Table F2d.1. The range of bounds are a function of the magnitude of difference between the moduli values of the multi-phase media for each asphalt; the bounds of the composite moduli range from less than one percent for aged Asphalt ABD to roughly 30 percent for Asphalt ABD. Furthermore, the coefficient of variance (COV) of the E_1 values (based on ten different measurements taken from each phase) ranged from 10 to 30 percent for the different asphalts.

The elastic Young's modulus (E(t) values at t=0 or the E_2 values given in Table 1) obtained from this study ranged from 0.73 MPa to 2.95 MPa and 5.48 MPa to 28.17 MPa for the unaged and aged asphalt composites, respectively. It was noted that aging of Asphalt ABD resulted in a substantial increase in composite elastic Young's modulus (approximately 16 times greater than the elastic Young's modulus prior to aging). In comparison, the increase in elastic Young's modulus due to aging of Asphalts AAB and AAD were approximately two and eight times greater than the respective values prior to aging. The elastic Young's modulus values from this study were compared to bulk values reported by Lu and Isacsson [5] to establish a relationship between nano-scale and bulk Young's modulus values for asphalt. Furthermore, Young's modulus values determined from this study were also compared to nanoindentation Young's modulus values reported by Terefter et al. and Jäger and Lackner [6-7].

Lu and Isacsson reported bulk complex modulus values for various asphalts (B1-B7) at 25°C ranging from 0.044 MPa to 0.839 MPa and 0.090 MPa to 1.37 MPa for unaged asphalts and RTFO-aged asphalts, respectively. Terefter et al. tested virgin asphalt binder and polymer modified binders but was unable to obtain meaningful results for a virgin asphalt binder using the Oliver and Pharr method. The reported Young's modulus values for polymer modified performance grade PG 70-22 and PG 76-28 binders were 0.76 MPa and 5.22 MPa, respectively. Jäger and Lackner reported Young's modulus values for B50/70 binder at 10°C ranging from 1.5 GPa to 2.5 GPa (1,500 Mpa to 2,500 Mpa). Young's modulus values for aged asphalt binders were not included in either study [6-7]. For the purpose of comparing Young's modulus values to other values obtained via nanoindentation, differences in the methods and equipment used to obtain the values are highlighted. For instance, the nanoindentation Young's modulus values reported by Terefter et al. and Jäger and Lackner were collected using a nanoindenter fitted with a spherical tip and Berkovich tip, respectively, which place the obtained Young's modulus values at larger length scales than the values obtained in this study. AFM imaging tips have a tip radius of approximately 8 nm, whereas a Berkovich tip has a radius of approximately 150 nm. Terefter et al. used a spherical tip with a nominal tip radius of 10µm (10,000 nm), so values reported in [7] were actually collected on the micrometer length scale rather than the nanometer length scale. As previously reported, several of the PDM-identified asphalt phases were as small as 1 µm to 5 µm in diameter, so it is clear that a tip radius larger than one of these phases would fail to capture the Young's modulus value for the isolated phase but rather a composite value of the phase, the surrounding phase, and the interfacial bond between the two phases. It should also be distinguished that the bulk values reported by Lu and Isaccson were short-term aged using the thin-film oven test (TFOT); whereas, aged asphalt specimens that were tested in this study were long-term aged using the rolling thin-film oven test (RTFOT) and the pressure aging vessel (PAV).

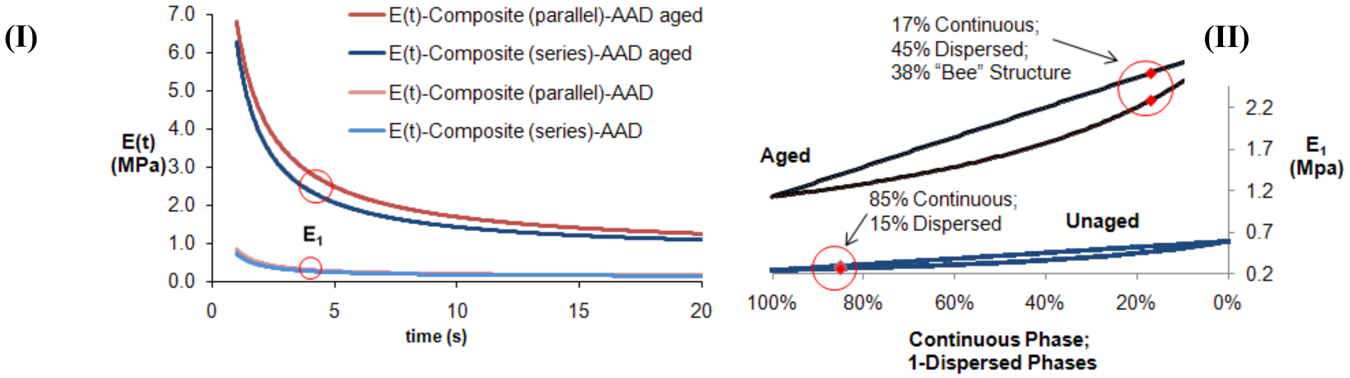


Figure F2d.6. (I) Bounds for the composite relaxation modulus [E(t)] of unaged and aged Asphalt AAD and (II) the relationship between individual phase modulus, phase distribution, and composite E(t) values.

Table F2d.2. E(t) values at approximately four seconds (E_1 values) and composite E_1 bounds.

	E_1 (MPa)			Composite E_1 (MPa)			
Asphalt Binder	**Phase 1**	**Phase 2**	**Phase 3**	**Series (lower)**	**Parallel (upper)**	**St. Dev.**	**Coeff. of var (COV)**
AAB	**52% .65**	**48% 1.25**	**-**	**0..85**	**0.94**	**0.22**	**0.25**
AAB-aged	**20% 1.33**	**70% 2.04**	**10% 1.89**	**1.83**	**1.88**	**0.56**	**0.30**
AAD	**5% .19**	**15% 0.54**	**-**	**0.21**	**0.24**	**0.03**	**0.13**
AAD-aged	**17% 1.08**	**45% 3.88**	**38% 2.02**	**2.17**	**2.70**	**2.68**	**0.28**
ABD	**48% 0.23**	**52% 0.79**	**-**	**0.36**	**0.52**	**0.08**	**0.19**
ABD-aged	**41% 8.76**	**59% 10.02**	**-**	**9.46**	**9.50**	**0.99**	**0.10**

Summary and Conclusions

The overall importance of these findings is that the application of AFM imaging and nanoindentation to collect creep measurements in this study resulted in validation of the statistical significance of the asphalt micro-phases and original AFM creep data; furthermore, semi-quantitative viscoelastic properties have been obtained and associated with AFM phase images. The viscoelastic Young's modulus values extracted from age-altered phases of the same respective asphalts have provided important relationships between microstructural changes depicted in the images and changes in composite viscoelastic properties obtained from the measurements. Based on comparison of the composite viscoelastic Young's modulus values obtained from this study to values obtained at larger length scales, it was concluded that modulus values appear to decrease in magnitude as the length scale increases, which agrees with similar results reported by Jones [8] in the nanoindentation study of cement paste. Possible causes for higher modulus values could be due to tighter molecular clustering at the nano-scale or due to weaknesses between phase interfaces as theoretically depicted by Kringos et al. [9].

<u>Issues Identified During the Previous Year and Their Implications on Deliverables</u>

There were no significant issues that will impact deliverables scheduled for the 21-month extension period.

<u>21-Month Extension Period</u>

<u>*Task 1*</u>

The chemistry and micro-rheology of the microstructures within the asphalt binder influence its macroscopic properties such as stiffness, viscoelasticity and plasticity, adhesion, fracture and healing. By developing a clearer understanding of the micromechanical behavior or micro-rheology of the asphalt binder and linking that behavior to its chemical makeup and macroscopic properties, one can engineer asphalt binders and modifiers for asphalt binders that will result in improved mechanical properties and eventually longer-lasting and better performing pavements.

The focus of this task will be to link previously obtained physical properties of AFM phases to chemical properties and determine how the relationship is influenced by aging. Associations will be made between asphalt chemistry and asphalt micromechanical properties through asphalt chemical mapping using methods such as soft x-ray beamline testing and AFM testing with functionalized AFM tips. These methods will result in the diffusion of atoms and molecular species and carbonyl grouping of the same asphalts in which physical properties have been extracted. The fabrication and testing of synthetic asphalt binders and individually extracted asphalt components will also significantly aide in validating the relationship between micromechanical properties and chemical composition. Special focus will be placed on viscoelastic properties and associated patterns of particular asphalt phases, which give a strong indication that weak zones somehow form during the molecular bonding and re-organization of phases as the binder ages. This suggests that while asphalt becomes stronger and more stable during this process, the formation of inevitable weak zones hinders composite performance properties and, thus, induces pavement distress. The application of AFM imaging, nanoindentation, and chemical mapping of asphalt binder will be presented as a potential method to understand and modify weaknesses amongst phase interfaces while improving the fatigue and fatigue healing characteristics of asphalt binders.

Task 2

Closed form solutions for nanoindentation that exist in the literature do not provide accurate values for large deformation, and non-uniform tip geometry. This is due to the assumption that uniform tip geometry exists, and during indentation only small strains occur. However, through the finite element method (FEM) large strains along with changes in geometry can be accounted for, and a more accurate solution can be obtained. FEM can also be used to study sharp conical indenters for which analytical solutions may prove to be inaccurate. In this work, a finite element model is being developed to compare with the closed form solution for different geometry, loading, material behavior, and indentation depth. Correction factors will be given for large deformation indentation where the closed form expressions provide an inaccurate solution. The finite element model will then be extended to include viscoelastic material properties such as that of asphalt.

Some of the various assumptions that are made during and AFM indentation test include conical or spherical tip geometry, small deformations, and homogeneous and isotropic material response. During the next year various finite element models will be developed to study the effects of AFM tip geometry, and complex constitutive behavior of asphalt with application to AFM indentation. These constitutive models will include plasticity, viscoelasticity, and viscoplasticity. The results of the finite element simulations of different material models mentioned will be compared to AFM indentation test data. The purpose of these comparisons is to more accurately understand the recorded data during an AFM test and provide calibration factors to obtain data that is numerically more precise than the data that can be calculated with analytical expressions available in the literature [10-11].

Task 3

Asphalt is currently assumed to be a homogenous material. However, composite behavior of asphalt binder has already been observed through AFM imaging and indentation testing [12]. The images obtained have shown the presence of different phases, and creep measurements have shown that micromechanical properties corresponding to each phase are also different. A finite element model consisting of multiple viscoelastic phases in agreement with experimental images and data will be analyzed and the indentation response will be compared to that of a uniformly distributed homogeneous material. This will show the difference in response of a composite asphalt binder as opposed to one containing a single phase. This in turn will help characterize asphalt more accurately and describe its mechanical response (e.g., composite elastic modulus, composite viscoelastic creep compliance) under any stimuli.

Task 4

Fatigue damage is directly related to number of load cycles and plastic strain. Therefore, understanding the plastic behavior of the asphalt binder is of high interest. Further AFM tests will be performed to study the effect of aging on the plasticity of asphalt binder. AFM images have shown the existence of beehive structures in aged asphalt samples [12]. These structures may exhibit different plastic response under loading compared to an unaged sample. The beehive regions will be indented and the residual deflection will be measured. This will be compared to the residual deflection of an unaged sample for the same type of test. The comparison will show whether the beehive regions are a physical representation of increased plastic response. This will help characterize aging along with the effects of aging on fatigue damage of asphalt binder.

Task 5

During an AFM indentation test, the measurements taken are affected by the surface van der Waals force interactions between the AFM tip and the asphalt sample. These forces are both of attractive and repulsive in nature at various times during the test. This van der Waals attraction and repulsion as a function of the distance between the tip and the sample is referred to as the Lennard-Jones Potential [13]. At the nanoscale these forces can be significant enough to affect the measured data. The next phase of this work will involve the inclusion of the Lennard-Jones Potential into a finite element model.

All finite element modeling will be done using an open source finite element code or a commercial software such as ABAQUS. The development of an open source finite element model will provide with a tool to accurately carry out AFM indentation tests without having to run the experiments. This will prove to be cost effective in terms of time, resources, and expenditures. Also, the commercialization of such code will prove to be an effective tool for analyzing indentation for research and design purposes. A complete package will include complex constitutive behavior, will account for non-uniform tip geometry, and also include surface interactive forces. The end product will determine the material response under loading.

For example, it will be able to quantify the plastic response and predict fatigue damage. This will result in the proper selection of binder, which will lead to an effective pavement design with long service life. This in turn will save millions of dollars that otherwise would be spent for maintenance and rehabilitation each year.

Task 6

Work closely with WRI on their work elements using the AFM for microstructural characterization (i.e., work elements M1b-2: Work of Adhesion at the Nano-Scale and M2a-2: Work of Cohesion at the Nano-Scale as well as on work element F3a-8: Calculation of Asphalt Molecular Structures and Correlation to Experimental Physico-Chemical Properties of SHRP Asphalts (WRI and TU Delft University).

Type of Deliverable	**Description**	**Original Delivery Date**	**Revised Delivery Date**	**Reason for change**
Journal Paper	Two journal papers have been submitted to ASCE on the physical properties of asphalt phases before and after aging and on the statistical analysis of physical properties of asphalt phases			
Journal Paper	Application of AFM Imaging and Nano-Indentation and Chemical Mapping on Selecting Methods of Nano-Modification	6/30/12		
Journal Paper	Constitutive Models of Viscoelasticity, Viscoplasticity and Plasticity of Asphalt Binder Phases	9/30/12		
Journal Paper	Using Nano-Indentation and AFM Imaging as a Tool for Binder Selection	12/30/12		
508 Report	Characterization of Asphalt Binders using Atomic Force Microscopy	3/30/13		

Cited References

[1] Vandamme, M,, 2008, “The nanogranular origin of concrete creep: a nanoindentation investigation of microstructure and fundamental properties of calcium–silicate–hydrates.” Massachusetts Institute of Technology.

[2] Galin, L., I. Sneddon, and H. Moss, 1961, "Contact problems in the theory of elasticity." Raleigh (NC): Dept. of Mathematics, School of Physical Sciences and Applied Mathematics, North Carolina State College.

[3] Sneddon, I.N., 1965, Relation between load and penetration in axisymmetric Boussinesq problem for punch of arbitrary profile. *Int J Eng Sci*, 3, 47–57.

[4] Hashin, Z., 1983, Analysis of Composite Materials. *Journal of Applied Mechanics*, 50, 481-505.

[5] Lu, X., and U. Isacsson, 2002, Effect of aging on bitumen chemistry and rheology. *Construction and Building Materials*, 16, 15-22.

[6] Jäger, A., R. Lackner, and J. Eberhardsteiner, J., 2007, Identification of viscoelastic properties by means of nanoindentation taking the real tip geometry into account. *Meccanica*, 42, 293-306.

[7] Tarefder, R.A., A.M. Zaman, and W. Uddin, 2010, Determining Hardness and Elastic Modulus of Asphalt by Nanoindentation. *International Journal of Geomechanics*, 106-116.

[8] Jones, C.A., 2011, "Contact Mechanics Based on Mechanical Characterization of Portland Cement Paste." Ph.D. Dissertation. Texas A&M University, College Station, TX.

[9] Kringos, N., A. Schmets, T. Pauli, and T. Scarpus, 2009, A Finite Element Based Chemo-Mechanical Model to Simulate Healing of Bitumen. *Proc.*, International Workshop on Chemo-mechanics of Bituminous Materials, Delft, Netherlands.

[10] Fischercripps, A., 2004, A simple phenomenological approach to nanoindentation creep. *Materials Science and Engineering A*, *385*(1-2), 74-82.

[11] Vandamme, M., & F. Ulm, 2006, Viscoelastic solutions for conical indentation. *International Journal of Solids and Structures*, 43(10), 3142-3165.

[12] Allen, R.G., 2010, "Structural Characterization of Micromechanical Properties in asphalt using atomic force microscopy." Master's Thesis, Texas A&M University.

[13] Johnson, K., 1998, Mechanics of adhesion. *Tribology International*, 31(8), 413-418.

CATEGORY F3: MODELING

Work Element F3a: Asphalt Microstructural Model

Overview

Asphalt concrete provides an important example of a material whose properties are governed by hierarchical scales. Viscoelastic properties of neat asphalts are influenced by crude oil source (Petersen et al. 1994) through their detailed molecular compositions (nm). Microstructural phase domains are potentially induced by wax precipitation (Pauli et al. 2011) and by blending asphalt with polymer modifiers (μm), RAP, and/or warm-mix additives. Adding fillers to binder leads to mastic (particle smaller than 0.075 mm + binder) with yet different rheology. The mastic binds together mm-to-cm aggregate to form asphalt mixture.

The chemistry within asphalts is rich and still poorly-defined, while desired macro scale properties are well-posed. Over the past two decades, pavement design has been advanced by incorporating well-defined experiments into material specifications (Superpave approach [Kennedy et al. 1994]), and by applying numerical models, such as the Mechanistic-Empirical Pavement Design Guide (ARA Inc. 2004). The rather limited understanding of the quantitative aspects of the interplay among chemical, physical, and mechanical phenomena involved in pavement performance currently inhibits developing a fully mechanistic approach. For example, Superpave lab methods for defining "good" asphalts for use in the field often fail when applied to polymer-modified asphalts (Shenoy 2002). Quantifying and incorporating such chemical effects, with increasing guidance from computation, will be crucial for rational and targeted design of high-performance asphaltic concrete, particularly as petroleum sources of asphalt raw materials become scarcer due to decreasing supplies worldwide.

Hence, this work element aims at developing (1) a fundamental understanding of the mechanisms and (2) practical methods to assess binder, mastic, and full mixture characteristics that impact failure modes including fatigue, self-healing, and moisture damage properties in a coupled multiscale model.

Major Findings and Status

Molecular Mechanics/Dynamics of Model Asphalts and Physicochemical and Mechanical Properties (URI)

New model asphalt systems have been proposed that contain molecules with more realistic distributions of polarity and molecular weight than prior molecular models. Manuscripts that describe the first of these systems and its dynamics are being prepared for publication as peer-reviewed journal articles. Molecule relaxations of the revised AAA-1 system show a common activation energy, and the temperature dependence of relaxation time suggests zero shear viscosities that are comparable to reported values for asphalts.

Comparisons among models of different asphalt compositions (AAA-1, AAK-1, AAM-1) are being pursued at URI through molecular dynamics simulations between 7/2011 and 3/2012, with completion expected by the end of ARC year 5. In addition, a paper has been published (Li and Greenfield 2011) that describes modifications to side group locations in proposed asphaltene structures. The modifications alleviate a so-called "pentane effect" in high energy configurations and thus provide more realistic asphaltene structures. This realism is important for increasing confidence in the simulation results about how chemical and phase environments affect asphaltene, resin, and maltene behaviors.

Molecular Mechanics/Dynamics to Phase-Field Modeling of Asphalt Composition (VT, URI, WRI)

Phase-field models can cover length scales from microscopic (e.g., microscopic phase-field models) to macroscopic (e.g., coarse grained phase-field models) (Wang et al. 2010). In other words, we can focus on either individual microstructures or the macroscopic behavior of mixtures. As an extra bonus, the phase-field method has been successfully applied to the modeling of fracture, where the order parameter is used to distinguish the solid and the void phases (Spatschek et al. 2011). Recently, Corson et al. (2009) conducted phase-field simulation of crack propagation under thermal loading. Thus the phase-field method seems to be a versatile tool that covers several topics that we are interested in: phase separation, thermal stress, and cracking.

Work on extracting phase-field parameters from molecular dynamics simulations is in progress. A literature review has been conducted to look into the methods on computing free energies and other parameters related to fatigue resistance from the trajectory information derived from molecular dynamics simulations.

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

Phase-Field to Continuum Mechanics (WRI, TUDelft)

Collaboration between the Delft University of Technology Healing Consortium and Western Research Institute as part of the ARC program has resulted in a first generation Finite Element Driven Phase Field Model (FEDFP) of fatigue and self-healing in a hypothetical binary-phase asphalt binder system (Kringos et al. 2009a; 2009b). This model, on the one hand, demonstrates that multi-phase materials may be more prone to developing stress risers at phase boundaries resulting, for example, in thermal fatigue and crack propagation under certain conditions (e.g., low temperature climate). On the other hand, this model also demonstrates the added potential for a binder to heal by exhibiting phase transition phenomena (or memory loss of damage) in addition to the current mechanisms of visco-elastic-plastic recovery (Voyiadjis et al. 2010; Kim et al. 2001) and surface energy behavior (Lytton et al. 2001).

A constitutive equation which defines the net entropy production, σ, of the damage-healing process (Voyiadjis et al. 2010) is defined by,

$$\sigma = \frac{\partial \psi^d}{\partial \zeta^d} : \dot{\zeta}^d + \frac{\partial \psi^p}{\partial \zeta^p} : \dot{\zeta}^p + \frac{\partial \psi^h}{\partial \zeta^h} : \dot{\zeta}^h \geq 0 \qquad \text{(F3a.1)}$$

or more generally by

$$\sigma = \sum_{\alpha=1}^{r} \frac{\partial \psi^{\alpha}}{\partial \zeta^{\alpha}} : \dot{\zeta}^{\alpha} \geq 0 \tag{F3a.2}$$

Here $\partial \psi^{\alpha} / \partial \zeta^{\alpha}$ defines the derivative in the work or free energy, ψ , per thermodynamic variable or structure parameter, ζ , for processes: $\alpha = p, d, h, ..., r$ (i.e., *d*-damage, *p*-plastic flow, *h*-healing,…, etc.), where $\dot{\zeta}^{\alpha} = \partial \zeta / \partial t$ is the time rate of change in the thermodynamic variable. Kringos et al. (2009a; 2009b), consider a configurational free energy term of phase structuring of wax species for example, derived based on the Cahn-Hilliard model of diffuse interfacial thermodynamics (Cahn and Hilliard 1958) to define the healing term,

$$\sigma = \frac{\partial \psi^{h}}{\partial \zeta^{h}} : \dot{\zeta}^{h} \geq 0 \tag{F3a.3}$$

Details of this work will be available for publication in (Pauli 2011/2012; Kringos 2011; Kringos et al. 2011).

Issues Identified During the Previous Year and Their Implications on Deliverables

None

21-Month Extension Work Plan

(WRI, URI, VT)

Year 6 of the proposed research continues the development of molecular-, chemo-mechanics, and continuum mechanics based multi-scale models capable of predicting the mechanical performance of unmodified asphalts, modified (polymer, RAP, warm-mix, sulfur extended, etc.) asphalts, and full binder-aggregate systems as they relate particularly to fatigue, self healing and moisture damage.

Molecular Mechanics/Dynamics of Model Asphalts and Physicochemical and Mechanical Properties (URI)

On molecular scales, the chemical compounds that constitute asphalt pack into condensed phase(s) of an overall density just over 1 g/cm^3. The objective on this scale (nm) is to understand the intermolecular correlations and the rates that molecules in asphalts rearrange. Results from this scale provide chemically specific guides for parameter choices at longer scales.

Molecular dynamics simulations of chemically distinct model asphalts are being conducted in years 1-5. Work extending into year 6 will interpret the results to determine the effects of temperature and asphalt chemistry on single-molecule relaxations. Stress correlations at high temperature will be used to relate these results to complex modulus. The simulation interpretations will guide the magnitudes of composition-dependent free energies that are used in the phase field calculations described below. The extension to year 6 will enable more thorough relationships between chemistry and mechanics and between chemistry and free energy to be quantified.

Deliverable: The nanometer scale calculations will deliver quantitative results for the effects of chemical and phase environment on single molecule relaxation rates. These results will be written up as a research article for a peer-reviewed journal while the draft report is reviewed.

Molecular Mechanics/Dynamics to Phase-Field Modeling of Asphalt Composition (VT, URI, WRI)

The versatile phase-field method will be used to simulate several problems associated with asphalt binder phase behavior. First, phase-field modeling of phase separation and mixing of asphalt molecular phases will be considered. By considering the binder as a mixture of several molecular components, the phase-field model will be used to predict phase separation as temperature decreases and mixing as temperature increases. Model parameters will come from experimental measurements of physicochemical and rheological properties of asphalt binder composition and free energy and mechanical theories, some of which may be described from MD simulations. The challenge here will be to upscale atomic and nano-scopic behavior of molecules to phase behavior of larger numbers of molecules interacting to comprise phases, which may include wax crystallization. Secondly, thermal stress for a given asphalt composition will be calculated. The asphalt binder can be considered as an elastic solid, in which different components contribute differently to elastic moduli and thermal expansion coefficients.

Deliverables: Phase Field Theory (PFT) models of phase behavior in asphalt binders, where model inputs are derived from physicochemical and rheological properties of asphalt binder composition based on free energy and mechanical theories of fluid flow and viscoelastic behavior.

Phase-Field to Continuum Mechanics (VT, URI, WRI)

Phase-field methods will be utilized in the simulation of cracking. In this part of the work, the interplay between solid-phase and void-phase are considered in terms of a single phase field variable used to identify solid and void phases. In the future we may pursue the modeling of crack propagation in multi-component solids. These three steps will be developed separately. If possible, these three will be connected together to obtain a systematic understanding of the asphalt binder.

Deliverables: A Micro scale FEM computational method that takes the PFT inputs to assess the fatigue, healing, and moisture damage effects at mesoscale (mastic scale). This will serve as a platform for multiscale FEM modeling for future work.

Methods to model fatigue process using phase field methods, and methods to characterize nano-to-meso scale structure of binder and mastics, which may include AFM and Nano CT, will contribute to model input parameters at all scales.

An Experimental Method for Evaluating Fatigue of Binder and Mastics (VT, WRI)

A cyclic direct tension testing method to evaluate the fatigue, healing and moisture damage properties of binder and mastics developed during previous years will be refined. Test methodologies which can provide rheological and mechanical properties of binder and mastics for model inputs and validation will be developed.

Cited References

ARA Inc., 2004, Guide for Mechanistic-Empirical Design, Technical Report 1-37A, NCHRP.

Cahn, J. W., and J. E. Hilliard, 1958, Free Energy of a Nonuniform System. I. Interfacial Energy. *J. Chem. Phys*., 28, 258.

Corson, F., M. Adda-Bedia, H. Henry, and E. Katzav, 2009, Thermal Fracture as a Framework for Quasi-static Crack Propagation. *Int. J. Fract.,* 158, 1-14.

Kennedy, T. W., G. A. Huber, E. T. Harrigan, R. J. Cominsky, C. S. Hughes, H. Von Quintus, and J. S. Moulthrop, 1994, SHRP-A-410, *Superior Performing Asphalt Pavements (Superpave): The Product of the SHRP Asphalt Research Program*, National Research Council, Washington, DC.

Kim, Y. R., H.-H. Lee, and D. N. Little, 2001, Microdamage Healing in Asphalt and Asphalt Concrete, Volume IV: A Viscoelastic Continuum Damage Fatigue Model of Asphalt Concrete with Microdamage Healing, Publication No. FHWA-RD-98-144. U. S. Department of Transportation, Federal Highway Administration, McLean, VA.

Kringos N., Exploring the Kinetics of Phase Decomposition to Understand Behavior of Bitumen, *under review*, 2011.

Kringos, N, T. Pauli , A. Schmets and T. Scarpas, Demonstration of a New Computational Model to Simulate Healing in Bitumen, *submitted*, AAPT, 2011.

Kringos, N., A.J.M. Schmets, T. Pauli, and T. Scarpas, 2009a, A Finite Element Based Chemo-mechanical Model to Simulate Healing of Bituminous Materials. In: N. Kringos (ed.), Chemo-mechanics of bituminous materials, June 2009, Delft, The Netherlands, 69-75. ISBN 978-94-90284-04-6.

Kringos, N., A. Scarpas, T. Pauli, and R. Robertson, 2009b, A Thermodynamic Approach to Healing in Bitumen. In: A. Loizos, M. N. Partl, T. Scarpas and I.L. Al-Qadi, eds., 7th int. RILEM symposium on advanced testing and characterization of bituminous materials. May 2009, Rhodes, Greece. The Netherlands: CRC Press/Balkema, 123-132. ISBN: 978-0-415-55854-9.

Lytton, R. L., C. W. Chen and D. N. Little, 2001, Microdamage Healing in Asphalt and Asphalt Concrete, Volume III: A Micromechanics Fracture and Healing Model for Asphalt Concrete, FHWA-RD-98-143. Federal Highway Administration, U. S. Department of Transportation, McLean, VA.

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

Pauli, T., Development of an Understanding of Healing and Cracking in Bitumen on Micro-scale, PhD thesis, TUDelft University, *under review*, 2011/2012.

Pauli, A.T., R.W. Grimes, A.G. Beemer, T.F. Turner, and J.F. Branthaver, 2011, Morphology of Asphalts, Asphalt Chromatographic Fractions and Model Wax-doped Asphalts Studied in Thin-films by Atomic Force Microscopy. *International Journal of Pavement Engineering*, 12(4), 291-309.

Petersen, J.C., R.E. Robertson, J.F. Branthaver, P.M. Harnsberger, J.J. Duvall, S.S. Kim, D.A. Anderson, D.W. Christensen, H.U. Bahia, 1994, SHRP-A-367, *Binder Characterization and Evaluation, Volume 1*. Strategic Highway Research Program, National Research Council, Washington, DC.

Shenoy, A., 2002, Model-fitting the Master Curves of the Dynamic Shear Rheometer Data to Extract a Rut Controlling Term for Asphalt Pavements. *J. Testing Eval.*, 30, 95-102.

Spatschek, R., E. Brener, and A. Karma, 2011, Phase field modeling of crack propagation. Philosophical Magazine, 91, 75-95.

Voyiadjis, G.Z., A. Shojaei and G. Li, 2010, A Thermodynamic Consistent Damage and Healing Model for Self Healing Materials. *International Journal of Plasticity, Article in Press*, doi:10.1016/j.ijplas.2010.11.002.

Wang, Y., and J. Li, 2010, Phase Field Modeling of Defects and Deformation. *Acta Materialia*, 58, 1212-1235.

Table for Decision Points and Deliverables

Type of Deliverable	Description	Original Delivery Date	Revised Delivery Date	Reason for change
Free energy models	Approaches to interpret MD simulation results and experimental data to quantify the composition and temperature dependence of free energy.	Q1-2010	Dec 2012	NIST co-PI involvement is no longer possible.
Draft Final Report	Molecular dynamics results for multiple asphalt chemistries	Q3-2011	May 2013	Additional simulation interpretations
Final Report	Molecular dynamics results for multiple asphalt chemistries		Dec. 2013	
Literature articles	Descriptions of model asphalts and their dynamics for research peers and practitioners	Q1-2010	Dec. 2013	Unanticipated need to analyze single-molecule structures to revise asphaltene
Source Code	Phase-Field Model	Q2-2011	Jan 2013	NIST co-PI involvement is no longer possible. VT began on this task late 2010
Draft Final Report	Progress Toward a Multi-scale Model of Asphalt Pavement.	Q1-2012	May 2013	
Final Report	Progress Toward a Multi-scale Model of Asphalt Pavement.		Dec. 2013	
Draft Final Report	Test Methods which Provide Model Parameter Input	Q1-2012	May 2013	
Final Report	Final Report: Test Methods which Provide Model Parameter Input		Dec. 2013	
New Direct Tension Fatigue Test	Method for Fatigue of Binder and Mastics: A direct tension cyclic tension test that can provide direct evaluation of fatigue for binder and mastic. It can also provide model validation and model parameter inputs.	Q1-2012	Jan 2013	

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

Major Findings & Status

Table F3c.1 describes the significant advancements we have made in qualification, verification, calibration and validation of the PANDA model and its components (Figure F3c.1).

Table F3c.1 Qualification, Verification, Calibration and Validation of the PANDA Models.

Modeling Phase	Objective (after Oberkampf et al. 2004 and Dave and Buttlar 2010).	Progress
Qualification	Determination of adequacy of the conceptual model to provide an acceptable level of agreement for the domain of intended application.	PANDA models were developed and mathematically formulated to capture important mechanisms of asphalt mixture performance. These mechanisms were formulated based on laboratory and field experiences. The PANDA model has components for: • Viscoelasticity and viscoplasticity (Masad et al. 2007, Masad et al. 2009, Saadeh and Masad 2010, Huang et al. 2011a, 2011b, and Abu Al-Rub et al. 2011a) • Mechanical damage (Darabi et al. 2011a, 2011b) • Moisture damage-adhesive and cohesive (Abu Al-Rub et al. 2010b, paper is under preparation). • Healing (Abu Al-Rub et al. 2010a) • Aging (paper is under preparation). We have conducted significant parametric analysis and simulations of simple, uniform stress tests to determine the suitability of PANDA in representing the various mechanisms listed above.
Verification	The process of determining that a model implementation accurately represents the developer's conceptual description of the model and the solution to the model.	The PANDA model and all its components have been implemented in finite element. The verification was achieved through comparing analytical solutions for uniaxial tests with the PANDA finite element results. The references are the same as those mentioned in the Qualification part.

Calibration	Determination and adjustment of model parameters based on comparison with experimental measurements.	• We have carried out initial calibration of the viscoelastic-viscoplastic components of the mode using a database at TAMU with three aggregates and one binder (Masad et al. 2007, Saadeh and Masad 2010). • We have also used the Nottingham database extensively for the calibration of the PANDA model in terms of viscoelasticity, viscoplasticity, damage and healing (Huang et al. 2011a, Abu Al-Rub et al. 2010a, Darabi et al. 2011a, 2011b). The Nottingham database and tests used in the calibration were presented in earlier ARC progress reports and included in the validation document that was submitted by the ARC to the FHWA. • In the ALF database, we used the various loading test (VL) and the constant loading period and stress test (CLT) to determine and calibrate the model parameters. A journal paper documenting this work is currently being prepared. • The moisture damage model has been calibrated against many pull-off experiments of a mastic-aggregate systems. Two journal papers documenting this work are currently being prepared. • The aging oxidative hardening model has been calibrated using existing experimental data from previous FHWA projects; mainly the experimental results documented in report FHWA/TX-05/0-4468.
Validation	The process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.	• The model has been validated against a large set of laboratory experimental data from the Nottingham database (Abu Al-Rub et al 2010a, Huang et al 2011a, Darabi et al 2011a, 2011b). • We have used a number of tests including accelerated loading from the Nottingham database in the model validation (Abu Al-Rub et al. 2011). • In the ALF experiments, the model validation was achieved by comparing the model results with experimental measurements of creep recovery tests with various stress levels and loading times (VLT).

21-Month Extension Work Plan

Please refer to task V3c for the validation plan.

Table for Decision Points and Deliverables

Date	Deliverable	Description
3/13	PANDA-UMAT subroutine	Provide the PANDA-UMAT subroutine as part of Abaqus software
3/13	Final Report	Include the details of the PANDA constitutive models into the PANDA comprehensive report.
4/13	PANDA Workshop	Workshop on PANDA models, calibration, validation, and using the PANDA standalone finite element software and the PANDA-UMAT within the commercial finite element software Abaqus.

Cited References

Abu Al-Rub, R., M. Darabi, D. Little, and E. Masad, 2010a, A Micro-damage Healing Model that Improves Prediction of Fatigue Life in Asphalt Mixes. *International Journal of Engineering Science*, 48, 966-990.

Abu Al-Rub, R.K., E.A. Masad, and M.A. Graham, 2010b, “Physically-based Model for Predicting the Susceptibility of Asphalt Pavements to Moisture-Induced Damage,” Final Report submitted to Southwest University Transportation Center, Report # SWUTC/09/476660-0012-1.

Abu Al-Rub, R., M. Darabi, C.W. Huang, E. Masad, and D. Little, 2011a, Comparing Finite Element and Constitutive Modeling Techniques for Predicting Rutting of Asphalt Pavements. *International Journal of Pavement Engineering* (in press).

Abu Al-Rub, R.K., M.K. Darabi, T. You, E.A. Masad, D. Little, 2011b, A Unified Continuum Damage Mechanics Model for Predicting the Mechanical Response of Asphalt Mixtures and Pavements. *International Journal of Roads and Airports* (Under Review).

Darabi, M., R. Abu Al-Rub, E. Masad, C.W. Huang, and D. Little, 2011a, A Thermo-Viscoelastic-Viscoplastic-Viscodamage Constitutive Model for Asphaltic Materials. *International Journal of Solids and Structures*, 48, 191-207.

Darabi, M.K., R.K. Abu Al-Rub, E.A. Masad, and D. Little, 2011b, Thermodynamic Based Model for Coupling Viscoelastic, Viscoplastic, and Viscodamage Constitutive Behavior of Asphalt Mixtures. *International Journal for Numerical and Analytical Methods in Geomechanics* (in press).

Huang, C. W., E. Masad, A. Muliana, and H. Bahia, 2007, Nonlinearly Viscoelastic Analysis of Asphalt Mixes Subjected to Shear Loading. *Mechanics of Time Dependent Materials*, 11 (2), 91-110.

Huang, C.W., R.K. Abu Al-Rub, E.A. Masad, D. Little, and G. Airey, G., 2011). Numerical Implementation and Validation of a Nonlinear-Viscoelastic and Viscoplastic Model for Asphalt Concrete Mixes. *International Journal of Pavement Engineering*, 12 (4), 433-447.

Huang, C.W, R. Abu Al-Rub, E. Masad, and D. Little, 2011b, Three-Dimensional Simulations of Asphalt Pavement Deformation Using a Nonlinear Viscoelastic and Viscoplastic Model. *Journal of Materials in Civil Engineering*, ASCE, 23 (1), 56-68.

Masad, E., C.W. Huang, J. D'Angelo, and D. Little, 2009, Characterization of Asphalt Binder Resistance to Permanent Deformation Based on Nonlinear Viscoelastic Analysis of Multiple Stress Creep Recovery (MSCR) Test. *Journal of the Association of Asphalt Paving Technologists,* 78, 535-566.

Masad, E., S. Dessouky, and D. Little, 2007, Development of an Elasto-Visco-Plastic Microstructural-Based Continuum Model to Predict Permanent Deformation in Hot Mix Asphalt. *International Journal of Geomechanics*, ASCE, 7 (2), 119-130.

Saadeh, S., and E. Masad, 2010, On the Relationship of Microstructure Properties of Asphalt Mixtures to their Constitutive Behavior. *International Journal of Materials and Structural Integrity*, 4 (2), 186-214.

TABLE OF DECISION POINTS AND DELIVERABLES FOR THE FATIGUE PROGRAM AREA

Name of Deliverable	**Type of Deliverable**	**Description**	**Original Delivery Date**	**Revised Delivery Date**	**Reason for change**
***F1b-1: Nonlinear viscoelastic properties of asphalt materials under cyclic loading* (TAMU)**	Four journal papers	A constitutive model that accounts for the nonlinearity and three-dimensional stress state of the material including a method to obtain model constants for asphalt binders.	12/30/08 3/31/10 9/30/10 12/31/11	Complete Complete 3/31/11 No change	
	Models and algorithm		3/31/09 6/30/10 12/31/11	3/31/12	
	Draft report		12/31/08 12/31/11		
	Final report		6/30/08 3/31/12		
	Procedure in AASHTO format	A test and analysis procedure in AASHTO format to measure and model the linear and nonlinear viscoelastic properties of asphalt binders and mortars incorporating the effect of interaction.	7/31/13		Proposed.
F1c: Aging (TAMU)	Journal Paper	Validation of the oxidation aging model against the ARC 2x2 experiments on asphalt mixtures	11/12		
	Final Report	Include the details of the PANDA aging model into the PANDA comprehensive report.	3/13		

Name of Deliverable	**Type of Deliverable**	**Description**	**Original Delivery Date**	**Revised Delivery Date**	**Reason for change**
F1c: Aging Field Validation (TAMU)	journal pub	Field validation of a pavement binder oxidation model	4/1/2013		
	journal pub	Combining a pavement binder oxidation model with mixture micromechanics models	4/1/2013		
	journal pub	Determination of oxidation kinetics from binder recovered from pavement cores	4/1/2013		
	final report	Pavement Oxidation Model: Field validation and incorporation in PANDA	4/1/2013		
Subtasks F1d-4: Test methods to measure properties related to healing	Six journal papers	A mathematical model for selfhealing at the micron scale, partial validation of this model, measurement of properties related to this model, measurement of overall healing as a function of damage and rest period, and micro to nano scale evaluation of properties that influence fracture and self-healing	12/31/08 09/30/09 3/31/10 09/30/10 09/30/11 12/31/11	Complete Complete Complete Complete Complete No change	
	Models and algorithm		6/30/11	3/31/12	
	Final report		12/31/08 12/31/11		
	Procedure in AASHTO format	A test and analysis procedure in AASHTO format to: (i) measure the intrinsic healing of asphalt binders with potential application as a material selection tool and (ii) measure the overall healing in asphalt composites with potential applications as a mixture selection tool and required input for continuum damage models.	7/31/13		Proposed.

Name of Deliverable	**Type of Deliverable**	**Description**	**Original Delivery Date**	**Revised Delivery Date**	**Reason for change**
Subtask F1d-8: Coordinate Form of Healing Parameter with Micromechanics and Continuum Damage Models (TAMU)	Journal Paper	Validation of the micro-damage healing model against the ARC 2x2 testing	6/12		
	Final Report	Include the details of the PANDA aging model into the PANDA comprehensive report.	3/13		
F2c: Mixture Testing Protocol (TAMU)	Journal paper and dissertation	Characterize permanent deformation of FAM under different conditions of relative humidity	3/31/12		
	Journal paper	Self-consistent micromechanics model of asphalt mixtures	3/31/12		
	Journal paper	Crack size distribution in asphalt mixtures	3/31/12		
	508 report contribution	Moisture damage	12/31/11		
	508 report contribution	Fatigue	3/30/12		

Name of Deliverable	**Type of Deliverable**	**Description**	**Original Delivery Date**	**Revised Delivery Date**	**Reason for change**
F2d: Tomography and Microstructural Characterization (TAMU)	Journal Paper	Two journal papers have been submitted to ASCE on the physical properties of asphalt phases before and after aging and on the statistical analysis of physical properties of asphalt phases			
	Journal Paper	Application of AFM Imaging and Nano-Indentation and Chemical Mapping on Selecting Methods of Nano-Modification	6/30/12		
	Journal Paper	Constitutive Models of Viscoelasticity, Viscoplasticity and Plasticity of Asphalt Binder Phases	9/30/12		
	Journal Paper	Using Nano-Indentation and AFM Imaging as a Tool for Binder Selection	12/30/12		
	508 Report	Characterization of Asphalt Binders using Atomic Force Microscopy	3/30/13		

F3a: Asphalt Microstructural Model	Free energy models	Approaches to interpret MD simulation results and experimental data to quantify the composition and temperature dependence of free energy.	Q1-2010	Dec 2012	NIST co-PI involvement is no longer possible.
	Draft Final Report	Molecular dynamics results for multiple asphalt chemistries	Q3-2011	May 2013	Additional simulation interpretations
	Final Report	Molecular dynamics results for multiple asphalt chemistries		Dec. 2013	
	Literature articles	Descriptions of model asphalts and their dynamics for research peers and practitioners	Q1-2010	Dec. 2013	Unanticipated need to analyze single-molecule structures to revise asphaltene
	Source Code	Phase-Field Model	Q2-2011	Jan 2013	NIST co-PI involvement is no longer possible. VT began on this task late 2010
	Draft Final Report	Progress Toward a Multi-scale Model of Asphalt Pavement.	Q1-2012	May 2013	
	Final Report	Progress Toward a Multi-scale Model of Asphalt Pavement.		Dec. 2013	
	Draft Final Report	Test Methods which Provide Model Parameter Input	Q1-2012	May 2013	
	Final Report	Final Report: Test Methods which Provide Model Parameter Input		Dec. 2013	
	New Direct Tension Fatigue Test	Method for Fatigue of Binder and Mastics: A direct tension cyclic tension test that can provide direct evaluation of fatigue for binder and mastic. It can also provide model validation and model parameter inputs.	Q1-2012	Jan 2013	

Name of Deliverable	**Type of Deliverable**	**Description**	**Original Delivery Date**	**Revised Delivery Date**	**Reason for change**
F3c: Development of Unified Continuum Model (TAMU)	PANDA-UMAT subroutine	Provide the PANDA-UMAT subroutine as part of Abaqus software	3/13		
	Final Report	Include the details of the PANDA constitutive mdoels into the PANDA comprehensive report.	3/13		
	PANDA Workshop	Workshop on PANDA models, calibration, validation, and using the PANDA standalone finite element software and the PANDA-UMAT within the commercial finite element software Abaqus.	4/13		

PROGRAM AREA: ENGINEERED MATERIALS

CATEGORY E1: MODELING

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

Major Findings and Status

Mixture healing properties of asphalt mixtures have been proven to depend on the internal stress that develops within the mixture. This internal stress is dependent on mixture properties. A methodology has been developed and validated by which internal stress that is the driving force for healing is measured and quantified. In addition fracture properties of asphalt mixtures using the overlay tester have been quantified and validated.

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

21-Month Extension Work Plan

The majority of this work will be completed during year 5; however, due to the extensive verification and validation program some of the work will extend into year 6.

In order to characterize the healing properties of an asphalt mixture, the damage density of crack growth in the creep phase of the revised creep and recovery test must be determined first. This is because the damage density at the end of the creep phase is the starting point of the healing process. The extent of healing that an asphalt mixture specimen can have depends on the amount of the cracking damage that is generated under the destructive loading. The first step in determining the damage density of the crack growth has been discussed above, and the following steps are planned to be studied in the next quarter, including: 1) calculate the pseudo strain and reference modulus; 2) determine the true creep strain and true creep stress of damaged asphalt mixtures from the destructive test; 3) determine the damage density and average crack size and the number of cracks from the destructive test. While the majority of this work will be completed in year 5, some portions will extend into the initial months of the extension period, and full documentation will be completed in the reporting period.

Currently, the actual crack growth in the OT test can be calculated. The next step will be the application of the Pseudo displacement principle to find the A and n, Paris' law's fracture parameters, as well as B and m values for healing properties. Subsequently, the same approach will be applied to the field cores with the different stiffness gradients. This method will allow us to determine the fracture and healing properties of both lab-compacted samples as well as cores taken from aged asphalt layers in the field. Once again, while the majority of this work will be completed in year 5, some portions will extend into the initial months of the extension period, and full documentation will be completed in the reporting period.

Table for Decision Points and Deliverables

Type of Deliverable	Description	Original Delivery Date	Revised Delivery Date	Reason for change
Dissertation	Characterization of fatigue cracking and healing of asphalt mixtures	5/30/12		
Dissertation	Viscoelastic and fracture properties with respect to time and depth in field-aged and laboratory asphalt specimens	5/30/12		
508 report contribution	Moisture damage	12/31/11		
508 report contribution	Fatigue	3/30/12		

Work Element E1c: Warm and Cold Mixes

Subtask E1c-1: Warm Mixes (UWM, UNR)

Major Findings and Status

In the past 2-3 years the research team has shown that aggregate gradation, viscosity and lubricity are all important properties that are critical for studying effect of warm mix additives, the concentration needed, and the allowable reduction in production and compaction temperatures. Development and modifications of the lubricity procedure in the past year were made in an effort to improve controlling normal force and measurement of torque during testing. The literature review conducted identified methodologies for evaluating the lubricating properties of Newtonian and non-Newtonian fluids. These methods will be evaluated further using the data collected from the Asphalt Lubricity test pending completion of the experimental plan.

As part of work element E1c-1, investigation of binder viscosity for the determination of WMA production temperatures using AASHTO 312 (Temperature-Viscosity plots) was conducted.

Although for unmodified binders, the procedure seems to be acceptable, it was fund unsuitable for modified binders. For modified binders, after review of the NCHRP recent project on mixing and compaction temperate, a simplified method for defining mixing and compaction temperatures of modified asphalt based on viscosity at low shear rates (LSV) was developed for evaluation of the impacts of WMA additives on the production temperatures of modified binders.

Efforts related to the evaluation of the effects of WMA additives and reduced aging temperatures on asphalt binder and mixture performance focused on the evaluation of appropriate binder aging methods and methods to estimate allowable temperature reductions to prevent significant reductions in performance. The RTFO aging method depends on both temperature and viscosity to short term age the binder in the laboratory, thus the contribution of reduced temperature to the decrease in performance at lower aging temperatures is still not specifically quantified. Efforts are being made to isolate viscosity and temperature using the TFOT method. To isolate the effects of oxidation and reduce testing time, a thin film binder aging method is currently under development.

Collaborative efforts have continued with the University of Nevada-Reno on moisture damage testing. Mix designs from the materials shipped from WI were verified, appropriate HMA and WMA mixing and compaction temperatures were determined, and WMA additive mixing procedures were recommended. Bitumen bond strength testing has been conducted at UW Madison on aggregate plates prepared from the Reno aggregate.

The research team was informed by WisDOT that there are a significant number of WMA projects planned for the 2011 construction season and that they are willing to partner with the research team. To date, no specific projects have been identified, but it is expected there will be projects for the fall of 2011. The progress of this task is conditional upon WisDOT collaboration.

Issues Identified During the Previous Year and Their Implications on Deliverables

Asphalt lubricity testing was delayed due to some hardware and procedure modifications, through which the test method was revised 3 times. The research team continues to work with the Wisconsin Department of Transportation (WisDOT) to provide field projects for evaluation of WMA placed in Wisconsin. WisDOT has repeatedly confirmed interest in trying Warm Mix in one or two projects in each district in Wisconsin. These opportunities did not materialize in 2011 yet but planning for 2012 could prove more productive. The research team will continue to work with WisDOT and, if possible, incorporate results into this task.

21-Month Extension Work Plan

Anticipated Scope of Year 6 Work

Year 6 activities in this task will be focused on addressing specific knowledge gaps directly related to the development of a WMA mix design guideline. The suggested topics for additional study under this task are listed under the following subtasks:

Subtask E1c-1-Y6-I: Guideline for Determination of Acceptable WMA Production Temperatures

This task will focus on developing guidelines for recommending allowable reduction (or verifying supplier recommendation), in WMA production and compaction temperatures depending on type of additive, amount of additive, and binder properties.

It has been shown that viscosity alone is not a sufficient criterion for determination of WMA mixing and compaction temperatures. Lubricity has been proven to be an important parameter complementing viscosity in this regard. Also aggregate gradation is very important. It is anticipated that the lubricity test methodology will be fully determined by the end of year 5, thus in year 6 this subtask will focus on developing a guideline for the determination of WMA mixing and compaction temperature based on the lubricity test, Low Shear Viscosity (LSV) and Phase Angle, and aggregate gradation.

The research team at UW has collected some initial data for 2 warm mix modifiers and developed an initial model for the N92 (Number of gyrations to 92% Gmm) as a function of viscosity (measured by rotational viscometer), coefficient of friction (measured by the lubricity test), and gradation as defined by a sigmoidal function. The current WMA production temperature determination method proposed by the UW team uses models based on data from the Lubricity test, viscosity measurements and aggregate gradation. The models will be further developed and validated for use as a guideline.

The team will also evaluate and implement recent findings on the difference of level of aging between binders used in WMA and HMA applications, and the resulting adjustment of WMA binder performance grading required.

Efforts to define specification limit values for the selected test procedures will be in coordination with Subtask *E1c-1-Y6-II*, to ensure compatibility with WMA mixture design criteria and specification, such as proper aggregate coating and mix compactability.

Subtask E1c-1-Y6-II: Evaluation of WMA Mix Design Guideline

The NCHRP 9-43 interim report includes a draft AASHTO standard specification for WMA mix design, which modifies current HMA mix design procedures most notably with the addition of coating and compactability criteria.

This subtask will focus on the evaluation and possible modification of the current WMA coating criteria based on AASHTO T195, as well as evaluate the N92 compactability criteria for suitability as WMA mix design criteria. 2-D imaging techniques recently developed and utilized by the UW team will be employed to enhance quantification of aggregate coating.

Based on the results of this subtask, suitable criteria and their respective specification limits will be defined and suggested as revisions to the current WMA design guideline where appropriate.

Subtask E1c-1-Y6-III: Development of WMA Performance Tests for Design Specification

This task will focus on the development and selection of suitable WMA performance testing procedures, most notably suggesting procedures and specifications for rutting and moisture damage resistance. Design limits will be determined for test procedures currently under development at UNR for WMA mixture performance evaluation such as the E* compression ratio, dynamic modulus and Flow Number, and developed into standard specifications to be included in the WMA mix design guideline developed in this task.

Subtask E1c-1-Y6-IV: Development of WMA Mix Design Adjustment Methods

This subtask will focus on the determination of appropriate mix design alteration methods in cases when the WMA mix design does not meet criteria. It will investigate adjusting the dosage of the WMA additives, mixing parameters and adjustment of binder performance grading accounting for WMA level of binder aging, among other factors. The effect of such adjustments will be determined and used to propose a WMA mix design correction method for mixes not meeting design criteria.

(Cont. from Yr. 5) Subtask E1c-1v: Field evaluation of mix design procedures and performance recommendations

In this subtask the work started in Year 3 in conjunction with NCHRP 9-43 will continue. The research team has completed testing aimed at comparing laboratory and field produced WMA mixes. Results will be summarized pending publication of the NCHRP 9-43 final report. University of Nevada-Reno continues evaluating the mechanical properties of the WMA sections in Manitoba. Results of the Manitoba project will be reviewed to identify additional recommended practice. The University of Wisconsin team will continue to work with the Wisconsin Department of Transportation (WisDOT) to coordinate sampling and testing for WMA projects placed in Wisconsin.

Table for Decision Points and Deliverables

Type of Deliverable	Description	Original Delivery Date	Revised Delivery Date	Reason for change
Draft AASHTO	Standard Specification for the Lubricity test	3/12	N/A	N/A
Draft Guideline	WMA Mixing and Compaction Temperature Guideline	9/12	N/A	N/A
Draft Guideline	Guideline for adjustment of WMA Binder Performance Grade	1/13	N/A	N/A
Draft Guideline	WMA Mix Design Procedure	6/13	N/A	N/A
Journal Paper	Evaluation of WMA Mixtures Design Parameters on Performance	7/12	N/A	N/A
Journal Paper	Mixture Design for WMA	7/13	N/A	N/A

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

Major Findings and Status

A literature review outlining the current state-of-practice and specification guidelines pertaining to Cold Mix Asphalt (CMA) and Cold In-place Recycling (CIR) has been completed. Based on the knowledge gaps outlined in the literature review, researchers began an evaluation of current laboratory coating and compaction procedures for CMA and CIR. Aggregate gradation, aggregate moisture content, residual asphalt content, and mixing schedule were all found to influence the aggregate coating experience in the laboratory. Imaging software was used to objectively assess the coating. No standard or acceptance criteria are given in the literature for aggregate coating, and all recommendations made are subjective. Since no standard gradation requirements for CMA and CIR are given in the literature, this too will need to be addressed further.

Compaction conditions, namely compaction pressure and number of gyrations was shown to influence the volumetric properties of CMA and CIR samples in the lab. Since no unified compaction procedure exists for CMA and CIR, there is a need for a standardized procedure. In the last year, compactions were completed using a modified gyratory compactor that allows excess moisture to drain from the samples. In addition the curing time after compaction was shown to heavily influence the volumetric properties of the CMA and CIR samples. All these conditions will be evaluated in Year 6 and will be used propose a standardized compaction and mixture deign procedure. There is currently no field acceptance criteria or volumetric data found in the literature; there is therefore the need to use field data to develop criteria for the standard design method.

Issues Identified During the Previous Year and their Implications on Future Work

None.

21-Month Extension Work Plan

Anticipated Scope of Year 6 Work:

Year 6 work emphasis will be on the completion of a protocol for a mix design method for CMA and CIR. The outcome will be a guideline that offers users a step-by-step mix design procedure that provides: a specification for selecting appropriate aggregates for CMA and CIR in terms of reactivity and mineralogy; specification for selecting an aggregate gradation and pairing of a selected emulsion with aggregate moisture content for optimum coating; a laboratory mix compaction specification that includes compaction pressure, number of gyrations, sample curing time and conditions, recommended volumetric properties, and required performance testing.

Subtask E1c2-Yr6-I: Protocol for Selecting Aggregates and Emulsions for CMA

This element will consider the methodology in choosing the correct aggregates (gradation, moisture content, coating etc.) and emulsions (residual asphalt content, optimum emulsion content etc.) for use in CMA. Initial work on coating procedures has provided insight into gradation and aggregate moisture requirements for coating. Image analysis has successfully been used to provide a subjective evaluation of laboratory coating. Evaluation of the effect of aggregate mineralogy on coating can be completed using such methods as pH testing and zeta potential measurements.

Subtask E1c2-Yr6-II: Evaluation of CMA Laboratory Compaction Methods and Curing Conditions

This element will evaluate the use of the Superpave gyratory compactor (SGC) for compacting CMA specimens. This element will expand on ASTM 7229 which does not directly specify a method to evaluate coating samples, number of gyrations for compaction, compaction pressure, and sample curing time. Preliminary work using a modified SGC has demonstrated that the sample volumetrics are highly dependent on compaction pressure and number of gyrations. Acceptance criteria for HMA pavements include density and surface smoothness. However, testing has shown that the volumetric (density) properties (VMA, VFA etc) of CMA samples are highly dependent on when the evaluation takes place. This is a direct result of the moisture loss over time that the CMA samples experience. Field compaction and curing conditions for established CMA pavements will be evaluated in order to match them to laboratory compaction and curing conditions. This work will be tasked to UWMARC.

Early stability and moisture sensitivity of CMA pavements are also primary concerns in the field and will be evaluated based on curing conditions on the lab. This mixture testing work will be done in collaboration with UNR.

Subtask E1c2-Yr6-III: Field Trials of CMA Mixtures

Laboratory performance testing will allow for the recommendation of trial field sections of CMA. Practical performance tests should be tailored to the predominant CMA pavement distresses noted in the field. Possible tests are IDT, Marshall Stability, and flow number. Based on the performance evaluation of these sections, final decisions can be made regarding choosing appropriate design guidelines. This work will be a collaborative effort between UNR and UWMARC.

Subtask E1c2-Yr6-IV: Protocol for Selecting Emulsions for CIR

This element will develop a standard procedure for identifying the appropriate emulsion grade to be used in the design and construction of the CIR mixture. The selection of the emulsion will be based on the following factors: coating and workability. The selected emulsion will also have a PG that is appropriate for the location of the project.

Subtask E1c2-Yr6-V: Mix Design Procedure for CIR

The objective of this element is to develop a mix design method for CIR. The following performance indicators were identified as critical to CIR mixtures:

- Mixing/coating
- Compaction/air-voids
- Early raveling
- Early stability
- Moisture sensitivity
- Fatigue cracking – (long-term property)
- Thermal cracking – (long-term property)

It is believed that the first three indicators; mixing/coating, compaction, and raveling can be assessed through the measurements of the temperature-susceptibility of the emulsion. In other words, the mix design process should be able to identify optimum mixing and compaction temperatures for the emulsion that will lead to good performance on these three indicators. The following experimental plan is being conducted during year five to verify this concept for the first three indicators.

Mix	**Gradation**	**Emulsions**			**Mixture Tests**
		CMS-2S	**Special**	**Tests**	
CIR	Non-graded	3 levels	3 levels	Viscosity vs. temperature (70 – 140^{o}F)	− Coating vs. temp − Compaction vs. temp − Sweep test vs. temp
	Graded	3 levels	3 levels		
	Fine	3 levels	3 levels		

The data generated from the above experiment will used to develop a full mix design method for CIR mixtures that will cover remaining performance indicators of CIR mixtures.

Table of Decision Points and Deliverables

Type of Deliverable	Description	Original Delivery Date	Revised Delivery Date	Reason for change
Journal Paper	Effect of Aggregate Mineralogy on CMA coating	1/2012	N/A	N/A
Final Report	Evaluation of laboratory aggregate coating procedure.	6/2012	N/A	N/A
Journal Paper	Evaluation of field acceptance criteria and performance of CMA	8/2012	N/A	N/A
Journal	Guidelines for performance testing of CMA	8/2012	N/A	N/A
Standard	Mix Design method for CMA	5/2013	N/A	N/A
Standard	Laboratory Compaction and curing Procedure for CMA	5/2013	N/A	N/A
Final Report	Mix Design Method for CIR Mixtures	8/2013	N/A	N/A

CATEGORY E2: DESIGN GUIDANCE

Work Element E2b: Design System for HMA Containing a High Percentage of RAP Materials (UNR, UWM, NCAT)

Major Findings and Status

Three major parts of the design system has been completed: a) estimating the RAP binder properties without extraction and recovery, b) determining the properties of RAP aggregates, and c) laboratory mixing process of asphalt mixtures containing RAP materials.

The estimation of the RAP binder properties is based on the testing of RAP mortar in the BBR for low temperature grade and in the DSR for the intermediate and high temperature grades. The process is based on the following concept: for a specific project location, the required PG of the virgin binder is identified for the combination of RAP binder and percentage of RAP materials to be used in the mix. Based on this relationship, the mix design engineer will be able to identify: a) the appropriate RAP content for a given virgin binder grade or b) the appropriate virgin binder grade for a given RAP content.

The determination of the properties of RAP aggregates is based on an extensive laboratory experiment that identified the most applicable method of extraction for the determination of aggregates properties. The evaluated RAP aggregates properties included: gradation, Superpave consensus properties, Superpave source properties, and specific gravities and absorption. The developed system is ready for implementation as an AASHTO Standard Practice (will be finalized in year five) to be incorporated into an overall mix design method.

The laboratory mixing process consisted of identifying the most appropriate method for mixing RAP materials with virgin aggregates and binder as part of the mix design process. The laboratory experiment evaluated the following methods:

- Method A: The virgin aggregate, the virgin asphalt binder and the RAP material are all heated to the appropriate mixing temperature as dictated by the virgin asphalt binder grade.
- Method B: The virgin aggregate is superheated in accordance with NAPA's recommendations from Information Series 123. The virgin asphalt binder is heated to the appropriate temperature dictated by the PG. The RAP material is only dried and added at the ambient temperature.
- Method C: The virgin aggregate is superheated in accordance with NAPA's recommendations from Information Series 123. The virgin asphalt binder is heated to the appropriate temperature dictated by the PG. The RAP material is wetted to the appropriate moisture content and added at the ambient temperature.

The properties of laboratory mixtures were compared with the properties of field mixtures obtained from two projects in Utah. The measured properties included; binder properties, volumetrics, and dynamic modulus master curves. Method A produced the mixture with a dynamic modulus that most closely resembled the modulus measured for the field mixtures at 70°F. Based on the findings from this experiment, it was recommended that Method A be instituted in the laboratory for mixing HMA mixtures containing RAP materials. It proved to be the simplest method without requiring excessive superheating temperatures which can be difficult to reach and maintain in the laboratory setting. It was also recommended that the RAP material be batched for individual samples where the amount of RAP material required to heat is small and preheating for 30 – 45 minutes is sufficient.

Issues Identified During the Previous Year and Their Implications on Deliverables

The three systems that have been developed have only been validated on laboratory produced mixtures and limited field mixtures; one project in Manitoba and two projects in Utah. It is recommended that the developed systems be validated and verified on additional field projects to ensure their applicability over a wide range of RAP and virgin materials. The proposed work plan for the additional field projects is described under the Work Plan for Year 6.

21-Month Extension Work Plan

The following research activities will be completed during year six:

- Conduct extensive field and laboratory evaluation of 3 – 5 field projects throughout the U.S. that include high RAP contents with both un-modified and polymer-modified asphalt binders. The NCAT Mobile laboratory will be used to evaluate the properties of the mixtures during the construction of the 3 – 5 field projects. Materials and mixtures will be sampled during construction and used in laboratory evaluation of the mixtures. All the measured properties on field and laboratory mixtures will be incorporated in the ARC Materials Database.

- Validate and verify the RAP binder evaluation system using materials from the 3 – 5 field projects. The low temperature PG grade of the RAP binder evaluation system has already been verified against the TSRST on two field projects and showed good agreement. During year six, the low temperature PG will be verified against the TSRST and the high temperature PG will be verified against the Flow Number test on the 3 – 5 field projects. Based on the results of these verification efforts the RAP binder evaluation system will be finalized and an AASHTO Standard will be developed to be included in the overall mix design method.
- Further develop the RAP binder evaluation system to predict the blended binder viscosity characteristics at commonly used mixing and compaction conditions for both neat and polymer-modified HMA mixtures. In addition, extend this application of the RAP binder evaluation system to mixtures containing warm mix additives. Validate and verify the developed system on the 3 – 5 field projects.
- Validate and verify the laboratory mixing procedure on the 3 – 5 field projects. Repeat the laboratory mixing experiment that was conducted in year five on mixtures from the 3 – 5 field projects. Based on the findings of this effort a laboratory mixing method for asphalt mixtures containing RAP materials will be finalized and an AASHTO standard will be developed and included in the overall mix design method.
- Conduct an extensive review of the state-of-practice for RAP fractionation and validation guidelines. It is hypothesized that different portions of a RAP stockpile gradation will blend differently with the same virgin binder. The objective of this effort is to document the benefits of fractionation practices and effects on mixture workability, effective binder grades, and aggregate properties.
- Develop an AASHTO standard for a complete mix design procedure for asphalt mixtures containing RAP materials that covers the following steps:
    - RAP binder evaluation system
        - Selection of appropriate virgin binder PG for a given RAP content or
        - Selection of appropriate RAP content for a given virgin binder PG
    - RAP aggregate evaluation system
    - Laboratory mixing procedure
    - Laboratory compaction procedure
    - Volumetric mix design criteria
    - Selection of design binder content
    - Evaluation of moisture sensitivity
    - Evaluation of performance characteristics

Table for Decision Points and Deliverables

Type of Deliverable	Description	Original Delivery Date	Revised Delivery Date	Reason for change
AASHTO Standard	RAP Binder Evaluation System	12-31-2012		
Research Report	Evaluation of Field Projects Containing RAP Materials	06-30-2013		
AASHTO Standard	Mix Design Method for Asphalt Mixtures Containing RAP Materials	08-31-2013		
Research Draft Final Report	Mix Design Method for Asphalt Mixtures Containing RAP Materials	06-30-2013		
Research Final Report	Mix Design Method for Asphalt Mixtures Containing RAP Materials	12-31-2013		

Subtask E2b-2: Compatibility of RAP and Virgin Binders

Major Findings and Status

Over the course of this program a number of techniques have been employed in a unique approach to determine the extent of mixing and the overall compatibility of RAP and virgin binders. Initially, work was performed to extract RAP samples using different solvent systems: one was a mixture of toluene and ethanol (85:15 by volume) and the other was cyclohexane. Cyclohexane provides the best approximation of the solvent characteristics of petroleum asphalt in a simple, organic solvent. This work, in most instances, demonstrated that use of cyclohexane did result in the extraction of slightly less asphalt from the RAP.

The fact that the cyclohexane extractions resulted in lower asphalt extraction yields in most cases is interesting in that it could be a good indicator of how virgin and RAP binders interact in practice. Several tests were performed on each of the extracted samples to determine whether the extracted binders were different chemically and physically. Indeed, the cyclohexane extracted RAP binder was less stiff than the toluene:ethanol extracted analogues as determined using dynamic shear rheometry. The chemical composition of the binders was also evaluated using the Asphaltene Determinator (AD), a quick and automated method of separating binders into fractions based on solubility. In general, the AD results indicate that the cyclohexane extracted binders were lower in asphaltene content, particularly the toluene soluble fractions. All of this data is in support of the hypothesis that binder mixing is not complete when RAP is blended with virgin materials. The lower asphaltene indicates that some asphaltene materials are strongly adsorbed to the RAP aggregate and most likely do not blend with virgin binder.

In the year 4 work plan, several phases were planned: Automated Flocculation Titrimetry (AFT) to determine the compatibility of extracted and blended binders and a study of the physical blending of aggregate, RAP and virgin binder with subsequent binder. The physical blending study has been put on hold indefinitely to avoid duplicating research currently being performed by another group outside of the ARC. Pending the outcome of that study, collaboration with the outside group could make good sense for the characterization of their blended materials.

The results of the AFT (ASTM D6703-01) compatibility study, thus far, have been mixed. RAP binders from sources in Iowa, South Carolina, and California were extracted using both cyclohexane and toluene:ethanol (85:15). The extracted samples were blended at several concentrations with two different, RTFO aged ARC binders, BI-0001 and BI-0002. In most cases the results indicate an increase in asphaltene content, as expected, and indicate an increase in the polarity of the overall asphalt chemical composition. Initially, it was believed that the increase in asphaltene content was accompanied by an improvement in the solvent power of the maltenes. However, as the rheological data is obtained for this project, the stiffening that is observed indicates that the AFT parameters usually attributed to the maltenes and whole asphalt are a better indication of the total polarity of the system and not necessarily the compatibility of the blended binders. The data are mixed, but the sample set is not completely finished. Samples obtained from the NCHRP 9-12 project, in which extracted RAP binders actually softened the virgin binders, will be run as a sound baseline for using one-dimensional AFT to determine aged and virgin binder compatibility. Coupled with data that WRI has obtained outside of the scope of this project, there is a good indication that a multi-dimensional compatibility test would be best suited for determining aged and virgin binder blend compatibility used to predict performance.

The work under the current work plan for year 4 will be finished in the first quarter of 2012.

Issues Identified During the Previous Year and Their Implications on Deliverables

The long delay in delivery and installation of several new rheometers has resulted in a major backlog for sample analysis at WRI. Over the past quarter, a second shift was added that will continue part-time through the next two quarters in an attempt for the rheology lab to catch up.

21-Month Extension Work Plan

As a means to develop a better understanding of the properties of blends between RAP and virgin binders a test is needed that provides more information that one-dimensional solubility determination as in AFT (ASTM D6703-01). One need not look far for an alternative, though. he Bitumen Solubility Model, or BISOM test, was developed at Nynas Bitumen and is a modified approach to determining the internal stability, or compatibility, of a material (Redelius 2004; Hansen 2007). In fact, the AFT is still used for determining a multi-dimensional material compatibility.

The BISOM test, simply put, is a suite of Heithaus titrations of bitumen dissolved in toluene with different solvents of known Hansen solubility parameters. Each solvent that is utilized is selected to help determine particular chemical characteristics relating to the stability of the system: a measurement of polar, dispersive, and hydrogen-bonding characteristics. Three samples of an asphalt are dissolved in toluene and each is titrated in the AFT with a poor solvent that corresponds to internal chemical characteristics. For example, titration with iso-octane provides an indication of material polarity, while methyl-ethyl ketone gives an indication of the hydrogen bonding nature, and 2-ethyl-1-hexanol the dispersive characteristics. The results of the titrations can then be plotted using a program called HSP3D, developed at WRI in conjunction with Nynas to present a 3-dimensional profile of a binder system (figure E2b-2.1).

The AFT performed thus far in this study has been a one-dimensional compatibility measurement that was focused primarily on the precipitation of asphaltenes using iso-octane and only provided an indication of the polar character of the blended binders. While this works well for unmodified, virgin binders, it has shown to be deficient when determining the compatibility of the blended aged and virgin binders. This is due to the highly polar nature of aged binders which overwhelms the determination of the character of the solvent fraction.

In year 6, the materials and blends used up to this point will be tested using the BISOM method. Three dimensional analysis of their compatibility profiles will be used to help demonstrate the effects of blending aged and virgin binders and related to the physical properties of the materials. Additionally, the results will be used to help predict which aged and virgin binders are most likely to perform well when blended.

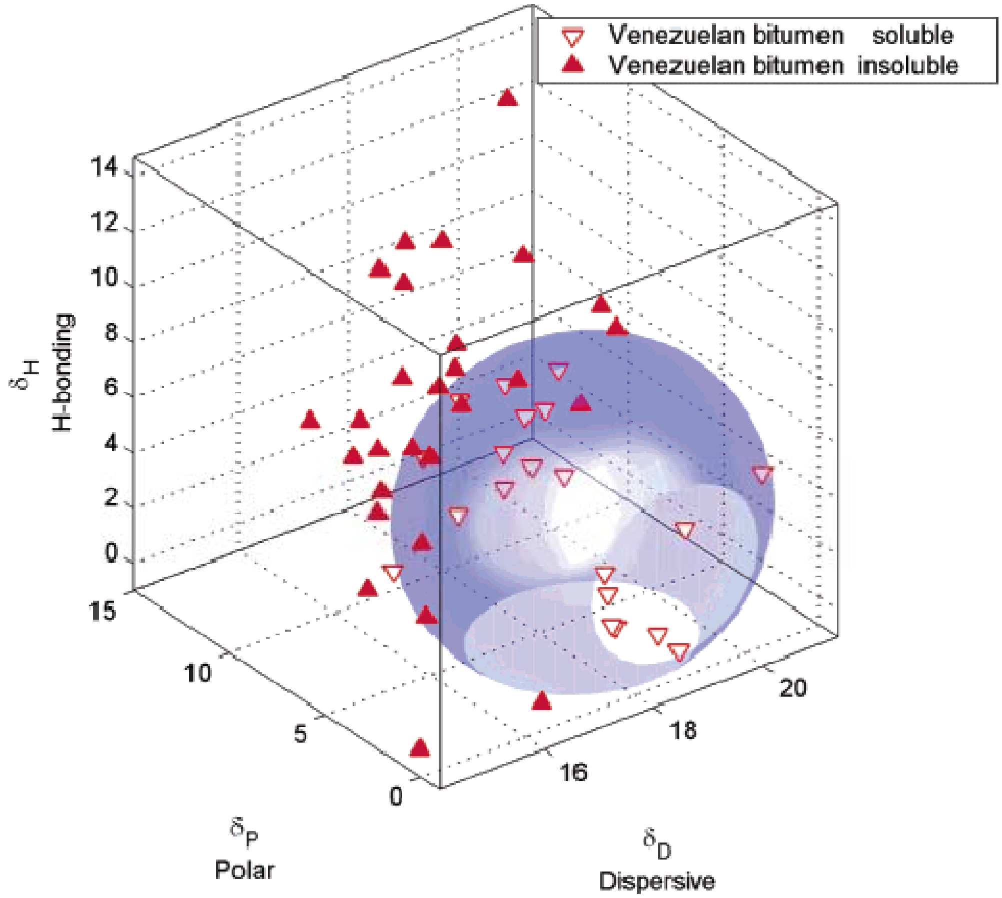


Figure E2b-2.1. Example of a 3-Dimensional solubility profile of a Venezuelan bitumen (Redelius 2004).

Table for Decision Points and Deliverables

Type of Deliverable	Description	Original Delivery Date	Revised Delivery Date	Reason for change
Report	508 report	12/31/2011	4/30/2012	Extension

Cited References

Hansen, Charles M., 2007, *Hansen Solubility Parameters of Asphalt, Bitumen, and Crude Oils, Hansen Solubility Parameters – A Users Handbook*, CRC Press, 151-175.

Redelius, P., 2004, Bitumen Solubility Model Using Hansen Solubility Parameters. *Energy and Fuels*, 18(4), 1087-1092.

Work Element E2c: Critically Designed HMA Mixtures (UNR)

Major Findings and Status

During Year 5, the 3D-Move analysis for non-uniform loading conditions that are described in the experimental plan will be completed. In addition, the evaluation of predominant frequencies in the asphalt layer will be completed.

The permanent deformation characteristics of laboratory-produced and field-produced mixtures under the testing conditions identified in the experimental plan will be completed. The impact of air-voids, gradation, and binder type on the asphalt mixture critical temperature will be summarized.

Issues Identified During the Previous Year and Their Implications on Future Work

The expansion of the experimental plan based on the recommendations of the ETGs extended the time schedule for this work element.

21-Month Extension Work Plan

Subtask E2c-3: Develop a Simple Test

Work for Year 6 will consist of completing the FN testing and analysis for ETG Flow Number Task Force.

Subtask E2c-4: Develop Standard Test Procedure

UNR team will develop a standard practice to identify the critical conditions of HMA mixtures.

Subtask E2c-5: Evaluate the Impact of Mix Characteristics

Work for Year 6 will consist of evaluating the impact of mixture characteristics on the critical condition of the HMA mixes evaluated under subtask E2c-3.

Table for Decision Points & Deliverables

Type of Deliverable	Description	Original Delivery Date	Revised Delivery Date	Reason for Change
Practice	Recommended practice to identify the critical condition of an HMA mix at the mix design stage to avoid accelerated rutting failures of HMA pavements.	12/31/11	12/31/2012	The experimental plan was expanded to incorporate the ETGs input
Draft Final Report	Report summarizing the impact of mixture characteristics on the critical condition of the HMA mixes	03/31/2012	05/31/2013	The experimental plan was expanded to incorporate the ETGs input
Final Report	Report summarizing the impact of mixture characteristics on the critical condition of the HMA mixes	11/31/2013		The experimental plan was expanded to incorporate the ETGs input

Work Element E2d: Thermal Cracking Resistant Mixes for Intermountain States (UNR, UWM)

Major Findings and Status

Field test sections were identified in year 5. The experiment to evaluate the aging characteristics (oxidation and hardening kinetics) of asphalt binders when aged in forced convection (horizontal airflow) ovens will be completed.

The laboratory testing to evaluate the impact of aggregate absorption and mixtures characteristics on the aging of the asphalt binder will be completed.

Explored the behavior of asphalt mixtures using the newly developed unified Tg-TSRST system focusing on the nature of the stress relaxation observed in isothermal conditions and the effect of thermal history on the stress buildup and isothermal relaxation.

The aging model will be developed in Year 5.

Issues Identified During the Previous Year and Their Implications on Future Work

The search for well-documented field sections with original materials did not identify a significant number of projects.

21-Month Extension Work Plan

Subtask E2d-2: Identify the Causes of the Thermal Cracking

Work for Year 6 will consist of testing the materials for the identified sections and conduct the experimental plan of subtask E2d-2.

Subtask E2d-4: Modeling and validation of the Developed System

The UNR research team leads the efforts associated with the development of a program for the prediction of critical cracking temperatures using the input variables measured from the proposed tests procedures (e.g., TSRST, Tg, SENB) that have been provided by the University of Wisconsin–Madison research team during Year 5. Work will continue with TTI to modify the viscoelastic finite element tool (VE2D) to incorporate the findings of this work element. UW-Madison will validate the developed system based on thermal cracking performance and laboratory tests on material from national pavement sites identified in the LTPP database.

Finite element modeling (FEM) of thermal loading of asphalt mixtures will be performed to determine the effects of different factors (e.g., gradation and angularity of aggregates, volumetric fraction, T_g, α_l, and α_g of binder) on the development of thermal stresses and strains. Furthermore, FEM will be used in Year 6 to investigate the relationship between glass transition of binders and mixtures.

Subtask E2d-5: Develop a Standard

Four preliminary standards will be prepared in AASHTO format for the TSRST test, T_g measurements of asphalt binders and mastics, the unified T_g-TSRST device and, the SENB test.

Table for Decision Points & Deliverables

Type of Deliverable	Description	Original Delivery Date	Revised Delivery Date	Reason for Change
AASHTO Standard	Thermal cracking characterization of mixtures by means of the unified Tg-TSRST device.	07/30/11	N/A	N/A
	SENB, binder Tg and the Tg-TSRST device.	01/31/2012	N/A	N/A
	TSRST with cylindrical specimens compacted using the SGC.	03/31/11	05/31/2012	Issues with specimens breaking at the edge.
Draft Final Report	Thermal Cracking Resistant HMA Mixtures	03/31/2012	04/30/2013	Additional work on field sections and TSRST
Final Report	Thermal Cracking Resistant HMA Mixtures	03/31/2012	10/31/2013	Additional work on field sections and TSRST

Work Element E2e: Design Guidance for Fatigue and Rut Resistant Mixtures (AAT)

Major Findings & Status

In National Cooperative Highway Research Program (NCHRP) Projects 9-25 and 9-31, models relating mixture composition to engineering and performance properties were developed. Specific models were developed for:

- Dynamic modulus
- Rutting resistance
- Fatigue cracking resistance
- Permeability

Further improvement of some of these models is needed to address specific shortcomings that were identified in subsequent validation efforts, and to expand the range of mixtures (nominal maximum aggregate size, compaction level, aggregate type, binder grade, modifier type etc.) used in the model development.

In Year 1, the NCHRP Project 9-25 and 9-31 composition to engineering property models and the data included in their development were reviewed and specific improvements were identified as summarized in Table E2e.1. Preliminary experimental designs for each of the recommend improvements were developed and presented in the Year 2 work plan. Preliminary experimental designs were developed for the Hirsch Model, the Resistivity Model, and the Continuum Damage Fatigue Model. Further development of the Permeability Model involves supplementing the current permeability database with published results from other researchers. It was planned that the experiments would be initiated in Year 2 of the project, however, testing was delayed to allow the experiment designs to be further refined based on the findings of other on-going research studies. In Year 3, final experimental designs were prepared for the Hirsch Model and the Resistivity Rutting Model experiments, and an extended uniaxial fatigue experiment was undertaken to verify that the simplified continuum damage approach developed at AAT over the past several years can be used to collapse uniaxial fatigue data gathered over a wide range of temperatures, frequencies and strains. The data from this experiment were analyzed over much of Year 4, leading to the conclusion that the damage relationship for an asphalt mixture depends on the initial stiffness of material. Models were developed to estimate the damage function from the initial stiffness of the mixture. These models can be combined with the Hirsch Model to estimate the fatigue damage function from the composition of the mixture and the properties of the binder. The effectiveness of this approach was demonstrated using full-scale pavement fatigue tests from the Federal Highway Administration Pavement Testing Facility. A final set of fatigue experiments to improve the damage relationships and to evaluate the damage tolerance of mixtures was developed. During Year 4 laboratory testing for the Hirsch Model and the Resistivity Model was initiated. Laboratory testing for the final Continuum Damage Fatigue Model experiments was started in Year 5. Much of the data from the laboratory experiments was analyzed in Year 5.

Table E2e.1. Summary of recommended improvements to the NCHRP Project 9-25 and 9-31 composition to engineering property models.

Model	Recommended Improvement	Approach
Hirsch Model for Dynamic Modulus	Curing time	Laboratory Experiment
	Low stiffness stress dependency	
	Limiting maximum modulus	
Resistivity Model for Rutting Resistance	Incorporate MSCR binder characterization	Laboratory Experiment
Continuum Damage Fatigue Model	Healing	Laboratory Experiment
	Damage tolerance	
Permeability	Expand data set	Data from Literature
	Aggregate size effect	

<u>Proposed Additional Work</u>

Based on the findings from the experiments completed to date for improving the Continuum Damage Fatigue Model some additional fatigue related research is proposed for Year 6 of the project. This additional research will focus on using a relatively simple fracture test to estimate the damage tolerance of an HMA mixture. Justification for this additional work and the work plan are described below.

From the work completed on the Continuum Damage Fatigue Model in Subtask E2e-2 and Subtask E2e-3, it is now possible to predict with reasonable accuracy the manner in which the modulus of a given HMA mixture will degrade under fatigue loading. Fatigue damage functions for HMA appear to be largely a function of modulus; however, this does not explain the significant differences in fatigue performance that exist among HMA mixes made with binders of the same performance grade that would have similar modulus values and similar fatigue damage functions. One likely reason for the difference in fatigue performance despite similar fatigue damage functions is differences in damage tolerance—that is, at what point during the fatigue process will micro-cracks and other forms of micro-damage coalesce into a large, propagating crack?

The fatigue experiments in progress in Subtask E2e-2 and associated analysis in Subtask E2e-3 include provisions for studying the damage tolerance of a variety of mixes subjected to fatigue loading. However, the development of reasonably accurate equations for damage prediction means that fatigue testing of HMA may in many cases not be necessary in order to characterize the damage function. It would therefore be useful to have a relatively simple fracture test that could be used to estimate the damage tolerance of an HMA mixture.

A variety of tests exist for evaluating the fracture properties of asphalt binders and HMA mixtures. It was determined that the most promising mixture test for rapid implementation is the FENIX test recently developed in Spain. This is a simple test performed on a thin, semi-circular HMA specimen trimmed from a gyratory specimen or field core. It is easy to perform and provides fundamental fracture properties. With appropriate grips, the test could be performed in the Asphalt Mixture Performance Tester (AMPT). A second very simple approach to this problem is to use the direct tension test on asphalt binder as an indicator of damage tolerance.

An important aspect of the proposed additional work is that the fracture tests will be performed at temperatures representing equal HMA modulus (or binder stiffness) values. This is because asphalt binder and HMA fracture properties vary enormously with temperature, and so testing at an arbitrary temperature will potentially provide very little information about the inherent fracture properties of an HMA mixture or asphalt binder—in many cases, it is simply going to provide some idea of the stiffness of the mix or binder. However, by testing at an equi-stiffness temperature, variability due to differences in temperature/flow properties are minimized, and the results will provide a much better picture of the inherent fracture properties of the HMA mix and/or asphalt binder. The proposed additional research will involve performing the FENIX test at the intermediate continuous grading temperature, and the binder direct tension test at the temperature where the m-value of the binder is 0.300.

A new subtask, Subtask E2e-6, Relationship Between Mix Fracture and Fatigue Properties, is proposed for this additional work. The major work activities for this new subtask are described below.

Implement FENIX Test

This portion of the work involves implementing the FENIX test on loading equipment available at AAT. Grips will be developed for performing the FENIX test. If possible, the test will be performed using the AMPT. Otherwise, one of AAT's servo-hydraulic frames will be used. The FENIX test was originally run at a loading rate of 1 mm/min. However, in order to ensure that good test results will be obtained at the intended test temperature (the intermediate binder grading temperature), the test will be run at a higher loading rate of 20 mm/min. As part of this task, shake down and preliminary tests will be performed as needed to refine the testing procedure.

Perform FENIX Test

In this part of the work, the FENIX test will be performed on the mixes tested as part of the associated work on refinement of the Continuum Damage Fatigue Model. Only mixes showing clear localization during fatigue testing will be evaluated using the FENIX test, since the analysis of the data will involve correlating localization during fatigue with the results of the FENIX test. As mentioned above, the initial plan will involve performing the FENIX test at the intermediate binder grading temperature at a loading rate of 20 mm/min.

Perform Binder Direct Tension Tests

Binder direct tension tests will be performed on binders used in the refinement of the Continuum Damage Fatigue Model. As with the FENIX test, only binders used in mixes showing localization during fatigue testing will be evaluated. The test will be performed at the temperature where the binder m-value is 0.300, using the standard loading rate.

Data Analysis and Reporting

The final work activity is to analyze and summarize the resulting data in tabular and graphical format. If appropriate, regression analysis will be used to quantify the relationship between the damage tolerance of the mixes and the results of the fracture tests, with the goal being to develop one or more empirical equations for predicting the point of localization during a uniaxial fatigue test. The work will be added to the final report for Work Element E2e. If appropriate, a paper will be compiled for potential publication.

21-Month Extension Work Plan

Work Element E2e is behind schedule so some of the work that was originally scheduled for completion in Year 5 will continue in Year 6. Subtasks E2e-1, Identify Model Improvements; E2e-2: Design and Execute Laboratory Testing Program; and E2e-3: Perform Engineering and Statistical Analysis to Refine Models will be completed in Year 5. Work on Subtasks E2e-4, Validate Refined Models; and E2e-5, Prepare Design Guidance will continue in Year 6 along with the proposed additional work in Subtask E2e-6, Relationship Between Mix Fracture and Fatigue Properties as described below.

Subtask E2e-4: Validate Refined Models

The Continuum Damage Fatigue Model has been validated using data from the FHWA Pavement Testing Facility. Published dynamic modulus and permeability data from various studies will be used to validate the improved Hirsch Model and the improved Permeability Model. The improved Resistivity Rutting models will be validated using data from various accelerated pavement tests: FHWA Pavement Testing Facility, NCAT Test Track, WesTrack, and MNRoad.

Subtask E2e-5: Prepare Design Guidance

All of the revised models relate important engineering properties of asphalt concrete to mixture composition. These models will be used to develop guidance for designing mixtures to resist specific forms of distress. It is envisioned that this guidance would be added to any future revision of the Mixture Design Manual for HMA developed in NCHRP Project 9-33.

Subtask E2e-6: Relationship Between Mix Fracture and Fatigue Properties

If funding for the proposed additional work is authorized, this subtask will be started and completed. The findings from this study will be included in the design guidance developed in Subtask E2e-5.

Table for Decision Points and Deliverables

Type of Deliverable	Description	Original Delivery Date	Revised Delivery Date	Reason for change
Journal Paper	Improved Continuum Damage Fatigue Model	9/1/2011	9/1/2011	No change. Paper completed and sent to Association of Asphalt Paving Technologists
Models	Improved composition to engineering property models • Hirsch Model for Dynamic Modulus • Resistivity Model for Rutting Resistance • Continuum Damage Fatigue Model • Permeability	1/1/2012	6/30/12	Testing delays
Journal Paper	Improved composition to engineering property models for HMA design	9/1/2012	9/1/2012	No change.
Model	Damage tolerance as a function of mix fracture properties	none	12/31/2012	New work
Draft Report	Draft report documenting Work Element E2e	1/1/2012	3/31/2013	Testing delays and addition of damage tolerance as a function of mix fracture properties.
Final Report	Final report documenting Work Element E2e	3/31/2012	12/31/2013	Testing delays and addition of damage tolerance as a function of mix fracture properties.

CATEGORY E3: NEW TOPICS

Work Element E3a: Effect of Extenders (such as Sulfur) and Alternative Binders (such as Bio-Binders) on Mixture Performance (UWM)

Major Findings and Status

Most of the bituminous binders used in the pavement industry are petroleum based. Nowadays bio-binders have started gaining popularity because of their renewable and environmental friendly aspect. In addition, due to the high increase in cost of binders, binder extenders have become an option to optimize cost and performance of conventional binders.

Bio-binders are used to reduce the demand for crude petroleum–derived binders. The bio-binders are produced from biomass such as agricultural crops, forest byproducts and animal byproducts, and can be used to replace 100% of the fossil binder (as a direct alternative binder), 25-75% (as a binder extender) or less than 10% (as a bitumen modifier) (Raouf and Williams 2010). Currently vegetable oil formulations (from soybean, corn, sunflower, and canola) are being investigated as possible modifiers for asphalt binders. These products include rejuvenators (extender oils), bio-polymers, and resin-like synthetic binders (FHWA 2011). Raouf and Williams (2010) used an oakwood-based bio-oil as a direct alternative binder. The author concluded that further research needed to be conducted to study the possibility of replacing the asphalt binder with 100% bio-binders. Fini et al. (2011) replaced 2-10% of the fossil binder with bio-binders from swine manure and observed a decrease in the mixing and compaction temperatures and an increase in workability.

Several projects are underway on binder extenders. Researchers have used wood byproducts, such as lignin, as binder extenders. Terrel and Rimsritong (1979) showed that mixtures produced with lignin have good qualities in terms of coating, workability, compaction, low temperature and fatigue resistance. McCready and Williams (2007) showed that the addition of lignin caused a slight increase in the stiffness at high, intermediate and low temperatures, but this increase did not affect the performance grade significantly. Sundstrom (1983) showed comparable properties for an AC20 neat binder and an AC10 modified with 30% lignin. One of the most common asphalt extender that has seen renewed interest is sulfur. Sulfur can replace up to 25% of the binder by mass while improving the mechanical performance of the mixture. The addition of a compaction enhancing additive allowed for compaction at temperatures as low as 90°C.

These new binders and extenders have not been tested widely and their effects on short and long term performance are not well documented. With the need for better binders and increased cost, better understanding of the effects of such binders or additives is critically needed.

Issues Identified During the Previous Year and Their Implications on Deliverables

None

Work Plan for Year Six

The objective of this work element is to study the effect of the asphalt extenders on binder and mixtures properties. The objective will be addressed by pursuing the following tasks:

Subtask E3a-Yr6-I: Conduct an elaborate literature review on bio-binders and extender oils.

Subtask E3a-Yr6-II: Select and investigate the mechanical properties of selected bio-binders and extenders that show high promise, and compare the results with conventional asphalt binders.

Subtask E3a-Yr6-III: Investigate the need for modification of mix design procedures when using aforementioned binders and additives, in particular the effects on mixing and compaction procedures.

Subtask E3a-Yr6-IV: Measure mechanistic and performance properties of the mixture produced with such binders and relate the results with existing published results such as the NCAT study results on sulfur extenders.

Subtask E3a-Yr6-V: Provide guidelines for use of bio-binders asphalt extenders, and define future research needs to make such binders or additives commonly used in practice.

Table for Decision Points and Deliverables

Date	**Deliverable**	**Description**
6/30/2012	Presentation on possible binders or additives	Literature review
12/31/2012	Report on detailed work plan and selected materials	Interim report on lit review and initial results
1/31/2013	Report on comparison to documented performance	Comparison with NCAT results on sulfur extenders and document performance of other materials
6/30/2013	Final Report	Guidelines for use of Bio-binders and Extenders
8/1/2013	Journal paper	Related to asphalt extenders

Cited References

Federal Highway Administration, 2011, http://www.fhwa.dot.gov/pavement/materials/pubs/hif10002/ahpm04.cfm

Fini, E., et al., Chemical Characterization of Bio Binder from Swine Manure: A Sustainable Modifier for Asphalt Binder., *Journal of Materials in Civil Engineering*, v. 1, no. 1, 256, 2011.

McCready, N. S., and C. Williams, "The utilization of agriculturally derived lignin as an antioxidant in asphalt binder", v. 46, 2007.

Raouf, M.A., and R. C. Williams, 2010, Temperature and Shear Susceptibility of Nonpetroleum Binder as Pavement Material. *Transportation Research Board of the National Academies, Washington, DC*, v. 2180, p. 9-18.

Terrel, R. L., and S. Rimsritong, 1979, Wood Lignins Used as Extenders for Asphalt in Bituminous Pavements. *Journal of the Association of Asphalt Paving Technologists*, v. 48, no. 111-134, 1979.

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

Major Findings and Status

Efforts toward characterization of emulsions have previously been conducted under the ARC subtask E1c-2. The most significant result of this work element was the introduction of a set of emulsion and residue tests for emulsions. This work was in coordination with the FHWA Emulsion Task Force (ETF). The tests include a standard method for measuring the adhesion and cohesion of the bond between asphalt and aggregate. A test method entitled the Bitumen Bond Strength (BBS) test was proposed for evaluating the adhesive properties of emulsions and residues.

During this study the Brookfield Rotational Viscometer was used to evaluate emulsion viscosity and its shear rate dependence. Based on the results, and discussions with the ETF members, a need to simulate pumping and circulating of emulsions before using in the field was identified. Ideas and experiments are underway to introduce a specific procedure to simulate such effects and propose a reliable method to measure emulsion workability for construction of chip seals, slurry seals, or for cold mix. Anionic, high-float emulsions demonstrated a high degree of shear sensitivity, indicating that these materials have the potential to be more susceptible to drops in viscosity during pumping and handling.

For the emulsion residue testing, a procedure for testing strain tolerance to evaluate later raveling; a modified PAV procedure for aging; and a DSR procedure for estimating low temperate creep stiffness and m-value were proposed.

In collaboration with the FHWA emulsion task force, the research team has defined a performance evaluation framework for emulsion residues using the DSR and the BBS devices. Testing includes both recovered and PAV aged residues. Preliminary results indicated that the MSCR test has the potential to be used as a high temperature specification. Also, the DSR and BBS procedures show high potential for covering properties related to raveling, moisture damage, fatigue, and low temperate cracking.

Issues Identified During the Previous Year and Their Implications on Future Work

None.

21-Month Extension Work Plan

The main objective of this work element in Year 6 is to recommend best methods to use in an emulsion performance grading (PG) specification that takes into account the binder properties and failure mechanisms, considering the three distinct life cycle phases of emulsions (construction, early life and end of life). The specifications should also be specific to the main types of application. It is expected that the main applications will include surface treatment, cold mixtures including cold in place recycling and full depth reclamation.

The objective will be accomplished by pursuing the following tasks:

- Evaluate residue preparation methods.
- Evaluate emulsions workability using a rotational viscometer and a coating test.
- Evaluate early and late life properties of the residue including raveling and bleeding.
- Provide performance-related specifications that specify quality in terms of long-term performance. This should cover fatigue, thermal cracking and moisture damage.

Some of the tasks will be accomplished in collaboration with the University of Nevada at Reno (UNR) and North Caroline State University (as part of NCHRP 9-50 project).

Subtask E3b-Yr6-I: Evaluation of the laboratory methods for emulsion recovery

Currently there are two standard methods to recover emulsion residue. One method requires the application of the emulsion with a film thickness of 380 microns followed by six hours curing in a forced draft oven at 60°C. The other method uses a film thickness of approximately 2 mm and requires a total of 48 hours for curing, consisting of 24 hours at 25°C and 24 hours at 60°C. Although the first method is preferred due to shorter recovery time and less aging of the residue, comprehensive laboratory testing is required to make recommendations on the suitability of the aforementioned methods.

Subtask E3b-Yr6-II: Evaluation of emulsion workability during construction

Sprayability, drain-out, fluidity and spreadability of asphalt emulsions will be investigates in this subtask. The viscosity of emulsions should allow the application of effective spray rates, while preventing run-off on the surface after spraying due to low viscosity. An optimum viscosity is required at the specific climatic conditions on site. Furthermore, the viscosity can be used as an indirect measurement of the storage stability of the emulsion. A stable emulsion should maintain a uniform viscosity while stored at ambient or slightly elevated temperatures for a period of time.

Subtask E3b-Yr6-III: Evaluation of early life emulsion properties

Loss of aggregates during the early stage is a major concern. Therefore, emulsion residues must gain sufficient bond strength and stiffness for the seal to be opened to traffic. The Bitumen Bond Strength (BBS) will be used to investigate the early life properties of emulsions. In addition moisture damage during the early service life could lead to increasing aggregate loss. Testing with the BBS system should help identify key parameters that can be used in specifications to limit aggregate loss. This task will also cover the effects of modifiers and additives claimed to improve aggregate retention.

Subtask E3b-Yr6-IV: Evaluation of late life emulsion properties

Loss of aggregates and cracking are the main distresses affecting the emulsion properties in their later stages of life. DSR tests such as the Linear Amplitude Sweep (LAS) test for fatigue will be used in collaboration with UNR to evaluate best indicators of resistance to late raveling and fatigue or thermal cracking.

Subtask E3b-Yr6-V: Provide performance–related emulsion specifications

This task will focus on developing emulsion characterization specifications based on the critical failure mechanisms, environmental and traffic conditions with regards to the application type: chip seal, ready mix (slurry seal, cape seal, micro-surfacing) and cold mix, individually. The main types of distresses that will be investigated are bleeding, raveling and stripping, aggregate loss, flushing, thermal cracking, fatigue cracking and rutting. This task will be completed in coordination with North Caroline State University (through the NCHRP 9-50 project), and UNR for Cold in Place recycling or full depth reclamation.

Subtask E3b-Yr6-VI: Evaluation of the emulsion specification against mixture performance

This task will focus on emulsion properties important for Cold Asphalt Mix. The testing will be done in collaboration with UNR and will include various types of performance testing of cold mixes in the recycled state.

Table for Decision Points and Deliverables

Date	**Deliverable**	**Description**
6/30/2012	Presentation on testing methods	Evaluation of the methods to recover emulsions
10/30/2012	Interim Report on test methods selection	Guidelines for evaluation of early and late life properties
6/30/2013	Report	Guideline for PG (emulsion) specifications
8/1/2013	Journal paper	Related to specifications
9/1/2013	Final report	

TABLE FOR DECISION POINTS AND DELIVERABLES FOR THE ENGINEERED MATERIALS PROGRAM AREA

Name of Deliverable	Type of Deliverable	Description	Original Delivery Date	Revised Delivery Date	Reason for change
Work Element E1a: Analytical and Micro-mechanics Models for Mechanical Behavior of Mixtures (TAMU)	Dissertation	Characterization of fatigue cracking and healing of asphalt mixtures	5/30/12		
	Dissertation	Viscoelastic and fracture properties with respect to time and depth in field-aged and laboratory asphalt specimens	5/30/12		
	508 report contribution	Moisture damage	12/31/11		
	508 report contribution	Fatigue	3/30/12		
E1c-1: Warm Mixes (UWM, UNR)	Draft AASHTO	Standard Specification for the Lubricity test	3/12	N/A	N/A
	Draft Guideline	WMA Mixing and Compaction Temperature Guideline	9/12	N/A	N/A
	Draft Guideline	Guideline for adjustment of WMA Binder Performance Grade	1/13	N/A	N/A
	Draft Guideline	WMA Mix Design Procedure	6/13	N/A	N/A
	Journal Paper	Evaluation of WMA Mixtures Design Parameters on Performance	7/12	N/A	N/A
	Journal Paper	Mixture Design for WMA	7/13	N/A	N/A

Name of Deliverable	**Type of Deliverable**	**Description**	**Original Delivery Date**	**Revised Delivery Date**	**Reason for change**
E1c-2: Improvement of Emulsions' Characterization and Mixture Design for Cold Bitumen Applications (UWM, UNR)	Journal Paper	Effect of Aggregate Mineralogy on CMA coating	1/2012	N/A	N/A
	Final Report	Evaluation of laboratory aggregate coating procedure.	6/ 2012	N/A	N/A
	Journal Paper	Evaluation of field acceptance criteria and performance of CMA	8/2012	N/A	N/A
	Journal	Guidelines for performance testing of CMA	8/2012	N/A	N/A
	Standard	Mix Design method for CMA	5/2013	N/A	N/A
	Standard	Laboratory Compaction and curing Procedure for CMA	5/ 2013	N/A	N/A
	Final Report	Mix Design Method for CIR Mixtures	8/2013	N/A	N/A
E2b: Design System for HMA Containing a High Percentage of RAP Materials (UNR, UWM, NCAT)	AASHTO Standard	RAP Binder Evaluation System	12-31-2012		
	Research Report	Evaluation of Field Projects Containing RAP Materials	06-30-2013		
	AASHTO Standard	Mix Design Method for Asphalt Mixtures Containing RAP Materials	08-31-2013		
	Research Draft Final Report	Mix Design Method for Asphalt Mixtures Containing RAP Materials	06-30-2013		
	Research Final Report	Mix Design Method for Asphalt Mixtures Containing RAP Materials	12-31-2013		
E2b-2: Compatibility of RAP and Virgin Binders	Report	508 report	12/31/2011	4/30/2012	Extension

Name of Deliverable	**Type of Deliverable**	**Description**	**Original Delivery Date**	**Revised Delivery Date**	**Reason for change**
E2c: Critically Designed HMA Mixtures (UNR)	Practice	Recommended practice to identify the critical condition of an HMA mix at the mix design stage to avoid accelerated rutting failures of HMA pavements.	12/31/11	12/31/2012	The experimental plan was expanded to incorporate the ETGs input
	Draft Final Report	Report summarizing the impact of mixture characteristics on the critical condition of the HMA mixes	03/31/2012	05/31/2013	The experimental plan was expanded to incorporate the ETGs input
	Final Report	Report summarizing the impact of mixture characteristics on the critical condition of the HMA mixes	11/31/2013		The experimental plan was expanded to incorporate the ETGs input
E2d: Thermal Cracking Resistant Mixes for Intermountain States (UNR, UWM)	AASHTO Standard	Thermal cracking characterization of mixtures by means of the unified Tg-TSRST device.	07/30/11	N/A	N/A
		SENB, binder Tg and the Tg-TSRST device.	01/31/2012	N/A	N/A
		TSRST with cylindrical specimens compacted using the SGC.	03/31/11	05/31/2012	Issues with specimens breaking at the edge.
	Draft Final Report	Thermal Cracking Resistant HMA Mixtures	03/31/2012	04/30/2013	Additional work on field sections and TSRST
	Final Report	Thermal Cracking Resistant HMA Mixtures	03/31/2012	10/31/2013	Additional work on field sections and TSRST

Name of Deliverable	Type of Deliverable	Description	Original Delivery Date	Revised Delivery Date	Reason for change
E2e: Design Guidance for Fatigue and Rut Resistant Mixtures (AAT)	Journal Paper	Improved Continuum Damage Fatigue Model	9/1/2011	9/1/2011	No change. Paper completed and sent to Association of Asphalt Paving Technologists
	Models	Improved composition to engineering property models • Hirsch Model for Dynamic Modulus • Resistivity Model for Rutting Resistance • Continuum Damage Fatigue Model • Permeability	1/1/2012	6/30/12	Testing delays
	Journal Paper	Improved composition to engineering property models for HMA design	9/1/2012	9/1/2012	No change.
	Model	Damage tolerance as a function of mix fracture properties	none	12/31/2012	New work
	Draft Report	Draft report documenting Work Element E2e	1/1/2012	3/31/2013	Testing delays and addition of damage tolerance as a function of mix fracture properties.
	Final Report	Final report documenting Work Element E2e	3/31/2012	12/31/2013	Testing delays and addition of damage tolerance as a function of mix fracture properties.

Name of Deliverable	**Type of Deliverable**	**Description**	**Original Delivery Date**	**Revised Delivery Date**	**Reason for change**
E3a: Effect of Extenders (such as Sulfur) and Alternative Binders (such as Bio-Binders) on Mixture Performance (UWM)	Presentation on possible binders or additives	Literature review	6/30/2012		
	Report on detailed work plan and selected materials	Interim report on lit review and initial results	12/31/2012		
	Report on comparison to documented performance	Comparison with NCAT results on sulfur extenders and document performance of other materials	1/31/2013		
	Final Report	Guidelines for use of Bio-binders and Extenders	6/30/2013		
	Journal paper	Related to asphalt extenders	8/1/2013		
E3b: Development of PG Specification for Emulsions used in Surface Treatments, Cold Mixes and Cold In Place Recycled Mixes (UWM)	Presentation on testing methods	Evaluation of the methods to recover emulsions	6/30/2012		
	Interim Report on test methods selection	Guidelines for evaluation of early and late life properties	10/30/2012		
	Report	Guideline for PG (emulsion) specifications	6/30/2013		
	Journal paper	Related to specifications	8/1/2013		
	Final report		9/1/2013		

PROGRAM AREA: VEHICLE-PAVEMENT INTERACTION

CATEGORY VP3: MODELING

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

Major Findings and Status

Nearly all of the work from the original software development proposal has been completed and several versions of the *3D-Move Analysis* software were released. The following list summarizes the major items that were completed. Since the release of the software, several items that were not part of the original software development proposal were suggested and included in the software.

- Development of 3D-Move in windows-based environment using graphical user interface (GUI) and SI and US system of units;
- Improvement in the running time for 3D-Move dynamic and static analyses;
- Inclusion of different models for specifying the master curve of asphalt mixtures (symmetrical sigmoidal function-MEPDG, non-symmetrical sigmoidal function, symmetrical sigmoidal function-AMPT, Huet-Sayegh Model, User Input-Interpolation, and Witczak model)
- Generation of contact stress distribution data (circle, ellipse and rectangle) for generic loaded areas;
- Inclusion of a database for non-uniform contact stress distribution from NATC and VRSPTA measurements and tools for interpolation of missing combinations;
- Inclusion of non-highway vehicle loading (end dump truck, fork lift);
- Specification of generic semi-trailer truck with vehicle dynamics (uniform and non-uniform contact stress distribution) and dynamic variation of loads;
- Inclusion of the pavement performance evaluation subroutine (MEPDG and VESYS models);
- Development of help and user manual for users;
- Development of an internet based User Forum to collect feedbacks, comments, issues, and concerns etc. of individuals who are evaluating and/or using 3D-Move (http://3d-move.finddiscussion.com/).
- The UNR team continued on assisting user's with issues ranging from software operations, concepts clarifications and software bugs. Software bugs were collected and solved as raised by users.

Issues Identified During the Previous Year and Their Implications on Deliverables

An Evaluation, Verification and Validation plan of the *3D-Move Analysis* software version 2.0 is scheduled to start in year 5. However, the request for additional features such as the performance evaluation subroutine delayed the release of the version 2.0 of the software. The proposed plan consists of three phases: I) Operational Evaluation, II) Verification and III) Validation. The operational plan is anticipated to help identifying potential errors, bugs, and difficulties involved in using the software for pavement analysis purposes. As a result, an action plan will be developed and executed. The second phase consists of verification of the selected *3D-Move Analysis* pavement responses with measured field data. It is anticipated that datasets that include vehicle dynamics and sufficient laboratory characterization and documentation will be identified in year 5. In phase III, the findings from phase II will be validated with an independent dataset. The completion of the verification and validation plans will have to be completed in year six.

Work Plan for Year Six

Based on the preceding findings and issues mentioned above, the following items are recommended to be completed in year 6:

- Conduct and complete the verification and validation plan. The findings will be used to enhance the *3D-Move Analysis* software.
- Include additional non-Highway vehicles such as agriculture off-road vehicles and buses with braking effect.
- Develop an artificial neural network (ANN) for non-uniform stress distributions. The latest version uses linear interpolation to calculate the non-uniform contact stress distributions at intermediate tire load from the existing databases. It is anticipated that the ANN technology may result in more realistic contact stress distributions.
- Revise and enhance the help menu for the *3D-Move Analysis* software based on the latest changes made and proposed.
- Maintain the “3D-Move Discussion Group” forum.
- Assist users with issues and questions that may arise from the use of the software.
- The development team expects that bugs may potentially show up, particularly those related to the pavement performance evaluation subroutines. The team will attempt to fix any observed bug.

TABLE FOR DECISION POINTS AND DELIVERABLES FOR THE VEHICLE-PAVEMENT INTERACTION PROGRAM AREA

Name of Deliverable	**Type of Deliverable**	**Description**	**Original Delivery Date**	**Revised Delivery Date**	**Reason for change**
VP3a: Pavement Response Model to Dynamic Loads (UNR)	Documentation	Complete the verification and validation plan	02/28/2013		
	Development	Include agriculture off-road vehicles and buses	01/31/2013		
	Development	Develop the artificial neural system (ANN) and implement the system to the software	06/30/2013		
	Documentation	Update the user help files	08//31/2013		
	Overall Model (Software)	Release the final version of the 3D-Move pavement response model	09/30/2013		
	Documentation of 3D-Move Draft Final Report	Pavement Response Model to Dynamic Loads	03/31/2013		
	Documentation of 3D-Move Final Report	Pavement Response Model to Dynamic Loads	09/30/2013		

PROGRAM AREA: VALIDATION

CATEGORY V1: FIELD VALIDATION

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

Major Findings and Status

Construction of two warm-mix asphalt sections and a control hot-mix asphalt section were completed in early September 2007 near the East Entrance to Yellowstone National Park (YNP) on U. S. Highway 14-16-20. Samples of all construction materials were obtained during construction. After construction was completed, three 500-foot monitoring sections were established in each of the three different materials and initial monitoring data was obtained on each section. The construction material samples are being used to determine the effects of the warm mix additives on asphalt and mix properties. The performance of the sections will be used to determine the important properties of the materials that relate to performance.

The annual monitoring of the YNP sections has occurred annually in September 2008, 2009, 2010 and 2011. Initially, the YNP personnel did not want conventional core samples removed from the pavement because of the effect the samples would make on the aesthetics of the road, however, a small sampling technique was approved. The small sampling technique used a masonry drill and one-inch lapidary core bit. Core sampling was permitted during the annual monitoring in September 2011.

The ARC and Manitoba Infrastructure & Transportation collaborated to plan and construct a new comparative pavement performance site in the province of Manitoba, Canada using warm-mix additives. The project was completed in July 2010. The project has sections of HMA, Advera, Sasobit, and Evotherm DAT. Extensive sampling of all construction materials was conducted and the materials were sent to the ARC researchers and to the FHWA MRL in Sparks, Nevada. The WMA site is on provincial highway 14 between the towns of Winkler and Plum Coulee. The initial monitoring of the Manitoba WMA site was performed in 2010 and the first annual monitoring occurred in August 2011.

21-Month Extension Work Plan

It is planned to monitor the YNP WMA site in September 2012 and 2013 and obtain core samples if the Park Service allows. Monitoring of the Manitoba WMA site is planned for the Fall of 2012 and the Fall of 2013. Performance data from both WMA sites will be entered into the ARC database along with data obtained on core samples.

Work Element V1b: Construction and Monitoring of Additional Comparative Pavement Performance Sites (WRI)

Major Findings and Status

The ARC and Manitoba Infrastructure &Transportation collaborated to plan and construct a new comparative pavement performance site in the province of Manitoba, Canada using two different amounts of RAP (15 and 50%) with two different asphalt grades (150/200 and 200/300 pen). Construction on the RAP comparative pavement performance site was completed in October 2009. Extensive sampling of all construction materials was conducted and the materials were sent to the ARC researchers and to the FHWA MRL in Sparks, Nevada. The RAP site is on provincial highway 8 about 10 km north of Gimli. Annual monitoring and sampling occurred in 2010 and 2011.

Additional comparative pavement performance sites are being sought with the emphasis placed on states where existing LTPP SPS-5 and SPS-9 sections are going out of service. Currently, Kansas DOT has great interest in constructing a comparative performance site using a high level of RAP and two different asphalt sources. The projects that have been identified for possible selection are not LTPP sites going out of service, however discussion of this matter will be a subject for future discussions as the plans move forward.

There is also interest in constructing a high-RAP comparative performance project in Indiana in cooperation with Rieth-Riley Construction. Rieth-Riley Construction is discussing the idea with Indiana DOT.

21-Month Extension Work Plan

It is planned to continue to pursue construction of comparative pavement performance sections that include material variation with state DOT’s, agencies having LTPP sections going out of service, and local agencies. The ARC will collaborate with LTPP on construction of any new sites. Contact will continue with Kansas DOT and Rieth-Riley Construction regarding high-RAP sites.

Performance monitoring and sampling of the comparative pavement sections in Arizona, Kansas, Minnesota, and the RAP sections in Manitoba are planned for in 2012 and 2013. Recall that during 2010, FHWA and WRI agreed to consolidate the performance monitoring of the comparative pavement performance sites under the Fundamental Properties of Asphalts and Modified Asphalts III contract with the sites under the ARC contract. Thus, the Arizona, Kansas, Minnesota, and Manitoba RAP sites will all be monitored and reported under this work element.

All performance data from the comparative pavement performance sites in Arizona, Kansas, Minnesota, and Manitoba will be entered into the ARC database. Data from any new sites will also be entered into the ARC database.

Table for Decision Points and Deliverables

Type of Deliverable	Description	Original Delivery Date	Revised Delivery Date	Reason for change
Topical report	Topical report on construction and monitoring activities	June 2013		

CATEGORY V2: ACCELERATED PAVEMENT TESTING

Work Element V2a: Accelerated Pavement Testing including Scale Model Load Simulation on a Small Test Track (WRI)

Major Findings and Status

The Asphalt Research Consortium (ARC) acknowledges that accelerated performance testing is a viable method that can be used to validate the new test methods and predictive models that will be developed during the ARC agreement term. The most important aspect of accelerated pavement testing is the cost of construction of sections. Generally, the party that is interested in the testing is responsible for the cost of construction, which can run into the hundreds of thousands of dollars. Other factors that are important in the acquisition of accelerated testing are: the availability of a facility, cost of data acquisition, cost-share possibilities, and others. The cost-benefit analysis and the availability of adequate resources will need to be carefully weighed. One disadvantage of accelerated testing is little or no influence of environmental factors which are known to influence pavement performance.

There are several accelerated testing facilities that may be of use. The ARC researchers are committed to pursue accelerated testing during the agreement at locations such as the FHWA ALF at Turner-Fairbank Highway Research Center, the NCAT Test Track at Auburn University, the Minnesota Road Research Facility (MnRoad), the Accelerated Testing facility at Florida DOT, etc. The one-third scale model load simulator at Texas A&M may also be a possibility for accelerated testing.

21-Month Extension Work Plan

The ARC will continue to look for partners to pursue accelerated performance testing to compare materials for validation of test methods and performance prediction models.

Work Element V2b: Construction of Validation Sections at the Pecos Research & Testing Center (WRI)

The Pecos Research & Testing Center (RTC) is a collaboration between Texas A&M / Texas Transportation Institute and industry. Accelerated performance testing at the Pecos site will most likely need an industry sponsor or industry support to make the cost reasonable.

CATEGORY V3: R&D VALIDATION

Work Element V3c: Validation of PANDA (TAMU)

Major Findings & Status

Please refer to the details presented in work elements M4c, F1c, F1d-8, and F3c in this document and in previous work plans and quarterly reports. These work elements outline what has already been accomplished in the development of the constitutive models that are implemented in PANDA. The work has been completed in validating PANDA against the Nottingham and the FHWA accelerated loading facility (ALF) comprehensive experimental databases. For more details, please refer to Year 5 work plan [see also Abu Al-Rub et al. (2010a,b); Huang et al., (2011); Darabi et al. (2011a,b,c)]. The validation included comparisons with: (a) extensive laboratory experimental data; and (2) field accelerated loading rutting and fatigue damage performance data (see Year 5 work plan for details of the types of tests used for validation). Systematic procedures for identifying every single material parameter in the constitutive models implemented in PANDA have been developed. Moreover, accurate and robust numerical integration algorithms for implementing the highly complex constitutive models have been developed, implemented, and tested in PANDA. The predictions showed that PANDA has well predictions with experimental measurements.

Issues Identified During the Previous Year and Their Implications on Deliverables

One issue that is affecting the ability to fully calibrate the viscoplastic constitutive model against the ALF experimental data is the lack of sufficient experimental data on the different asphalt mixtures in the ALF database. Currently, the main emphasis is placed on identifying some of the important viscoplastic material parameters based on flow number tests on the ALF four mixtures. This issue is avoided in the ARC 2x2 testing.

Year Six Work Plan

In year six, PANDA validation will be completed against the 2 x 2 ARC matrix that is comprised of two binders and two aggregates with significantly different mineralogical properties. This matrix is comprised of a relative pure calcium carbonate limestone from Hanson, Inc. aggregate producers and a siliceous gravel from Wyoming. The two binders are a NuStar Energy Venezuelan asphalt (ARC-B1-001) and a Valero Refining, Benicia, California, California Valley crude (ARC-B1-003). The four asphalt mixtures that will be used in validation are being subjected to the testing matrix described in Year 5 work plane and recalled here (see Tables V3c.1 to V3c.3). However, some of the information and tests are being revised based on the findings of the verification work that we accomplished during Year 5.

Table V3c.1 ARC Tests on specimens without aging or moisture conditioning.

Test	Temperature, C	Confining Stress, kPa	Deviatoric Stress	Frequency, Hz	Loading Time, sec	Unloading Time, sec	Note
Dynamic Modulus Test (DMT) @ various temperatures and confinements (control the strain under 50-70με).	AASHTO TP 62	0	AASHTO TP 62	AASHTO TP 62			Same specimen is used at all temperatures and frequencies
Repeated Creep recovery test (RCRT) and various stress levels (RCRT-VS)	5, 19, 40, 55	0, 70, 140, 500	Starts at 103 kPa and increases by a ratio $1.1^{(n-1)}$, where n is number of cycles (See Table A).		0.4	10 (the final value will determined based on pilot testing)	The loading time in the VS test is 0.4 sec and then following around 10 sec resting time. The resting time should be modified depends on the material behavior. The resting time can be determined by measuring the slope of relaxation strain becomes 0.
Repeated Creep recovery test (RCRT) and various loading times (RCRT-VLT).	5, 19, 40, 55	0, 70, 140, 500	840		Starts at 0.1 sec and increases by a ratio $1.2^{(n-1)}$, where n is number of cycles.	10	

Repeated Creep recovery test (RCRT) and various rest times (RCRT-VRT).	5, 19, 40, 55	0, 70, 140, 500	840		0.1	Starts at 0.9 sec and increases by a ratio $1.2^{(n-1)}$, where n is number of cycles.	
Repeated Creep recovery test (RCRT) and various stress levels and loading times (RCRT-VST).	5, 19, 40, 55	0, 70, 140, 500	To be determined		To be determined	To be determined	Validation tests
Tension Constant Actuator Displacement Cyclic Fatigue Test (S-VECD Protocol)	5, 19, 40	0	Strain is variable with N_f target of approximately 1,000 and 10,000	10			
Tension Repeated Creep recovery test (RCRT) and various rest times (RCRT-VRT)	19	0	Strain is chosen based on S-VECD tests to yield reasonable cycles to failure		0.1	Starts at 0.9 sec and increases by a ratio $1.2^{(n-1)}$, where n is number of cycles. When rest period becomes too long the rest period will be reset to 0.9 and repeated	

Table V3c.2 ARC tests on specimens with aging but no moisture conditioning.

Test	Temperature, C	Confining Stress, kPa	Deviatoric Stress	Frequency, Hz	Loading Time, sec	Unloading Time, sec	Aging Period, Months	Percent Air Voids, %	Note
Dynamic Modulus Test (DMT) @ various temperatures and confinements (control the strain under 50-70με).	AASHTO TP 62	0	AASHTO TP 62	AASHTO TP 62	N/A	N/A	6, 12	7, 10	Same specimen is used at all temperatures and frequencies
Repeated Creep recovery test (RCRT) and various stress levels (RCRT-VS)	19, 40	0	Starts at 103 kPa and increases by a ratio $1.1^{(n-1)}$, where n is number of cycles (See Table A).		0.1	10 (the final value will determined based on pilot testing)	6, 12	7, 10	The loading time in the VS test is 0.1 sec and then following around 10 sec resting time. The resting time should be modified depends on the material behavior. The resting time can be determined by measuring the slope of relaxation strain becomes 0.
Tension Constant Actuator Displacement Cyclic Fatigue Test (S-VECD Protocol)	19, 40	0	Strain is variable with N_f target of approximately 1,000 and 10,000	10			6, 12	7, 10	

Tension Repeated Creep recovery test (RCRT) and various rest times (RCRT-VRT)	19	0	Strain is chosen based on S-VECD tests to yield reasonable cycles to failure		0.1	Starts at 0.9 sec and increases by a ratio $1.2^{(n-1)}$, where n is number of cycles. When rest period becomes too long the rest period will be reset to 0.9 and repeated	6, 12	7, 10	

Table V3c.3 ARC tests on specimens without aging but with moisture conditioning.

Test	Temperature, C	Confining Stress, kPa	Deviatoric Stress	Frequency, Hz	Loading Time, sec	Unloading Time, sec	Aging Period, Months	Note
Dynamic Modulus Test (DMT) @ various temperatures and confinements (control the strain under 50-70με).	AASHTO TP 62	0	AASHTO TP 62	AASHTO TP 62	N/A	N/A	6, 12	Same specimen is used at all temperatures and frequencies
Repeated Creep recovery test (RCRT) and various stress levels (RCRT-VS)	19, 40	0	Starts at 103 kPa and increases by a ratio $1.1^{(n-1)}$, where n is number of cycles (See Table A).		0.1	10 (the final value will determined based on pilot testing)	6, 12	The loading time in the VS test is 0.1 sec and then following around 10 sec resting time. The resting time should be modified depends on the material behavior. The resting time can be determined by measuring the slope of relaxation strain becomes 0.
Tension Constant Actuator Displacement Cyclic Fatigue Test (S-VECD Protocol)	19, 40	0	Strain is variable with N_f target of approximately 1,000 and 10,000	10			6, 12	

Tension Repeated Creep recovery test (RCRT) and various rest times (RCRT-VRT)	19	0	Strain is chosen based on S-VECD tests to yield reasonable cycles to failure		0.1	Starts at 0.9 sec and increases by a ratio $1.2^{(n-1)}$, where n is number of cycles. When rest period becomes too long the rest period will be reset to 0.9 and repeated	6, 12	
Tension Constant Actuator Displacement Uniaxial Tension Test	5, 19, 40	0	Strain rate to be determined				6, 12	

In addition to the testing described in Table V3c, a protocol for characterization of engineering properties that has been advanced under work element F2 is a also being performed on the ARC 2x2 matrix. This protocol can either be used as a standalone product for use by engineers to characterize asphalt mixtures or as a fast and accurate input for PANDA. This is in effect an alternative characterization protocol compared to that summarized in Table V3c. this alternative protocol is comprised of the steps summarized below:

1. Undamaged Properties Characterization

The undamaged engineered properties of asphalt mixture include anisotropic viscoelasticity and microstructural inherent anisotropy, which consist of corresponding testing protocols, characterizing models and material property outputs.

1.1 Anisotropic Viscoelasticity

- Testing protocols include: 1) uniaxial compressive creep test, 2) indirect tensile creep test, and 3) uniaxial tensile creep test, all of which can be completed in one day on a single sample with no sample-to-sample variability.
- Constitutive models include: 1) generalized Kelvin viscoelastic model, and 2) new master curve models for the magnitude and phase angle of the complex modulus and complex Poisson's ratio.
- Material properties obtained include master curves for magnitude and phase angle of the compressive complex modulus and complex Poisson's ratio in both vertical and horizontal directions, and master curves for magnitude and phase angle of the tensile complex modulus and complex Poisson's ratio.

1.2 Microstructural Inherent Anisotropy

- Testing protocol is: a new proposed lateral surface scanning test to obtain the aggregate characteristics including size, orientation and aspect ratio.
- Characterizing models are: a modified vector magnitude (Δ') which can quantify the inherent anisotropy and a micromechanical relationship between Δ' and the vertical to horizontal modulus ratio (E_{11}/E_{22}).
- Material properties are the modified vector magnitudes which can be programmed into the PANDA program and modify the normal stress to yield more accurate prediction.

2. Damaged Properties Characterization

The damaged engineered properties of an asphalt mixture contain viscoplasticity for permanent deformation characterization and viscofracture for cracking characterization, which include a strain decomposition technique, a comprehensive viscoplastic fracture model and corresponding model parameter acquisition method.

2.1 Strain Decomposition Technique

- Testing protocol is: destructive dynamic modulus test.
- Strain decomposition technique is proposed using employing the pseudo strain concept and extended elastic-viscoelastic correspondence principle. This technique has

advantages of completely separating each of the strain components without the need for a recovery testing period.

- Material properties are: destructive dynamic modulus and phase angle, and the separated elastic strain, viscous strain, plastic strain, viscoplastic strain and viscofracture strain.

2.2 Viscoplasticity for Permanent Deformation Characterization

- Testing protocols include: uniaxial and triaxial compressive strength test.
- Viscoplastic fracture model include a modified Perzyna's viscoplastic model incorporated with a modified extended Drucker-Prager yield surface, a non-associated flow rule, a strain hardening function and an anisotropic damage density function.
- Data acquisition method includes 1) relationships between yield surface and plastic potential parameters with the material properties including cohesion, internal friction angle and inherent anisotropy, and 2) determination of viscosity and rate dependent parameters and strain hardening parameters based on the separated viscoplastic strain.
- Interface with PANDA: the data acquisition method presented here provides a quick and reliable method to determine the viscoplastic and damage models' parameters in PANDA program (see Appendix).

2.3 Viscofracture for Cracking Characterization

- Testing protocols: the separated viscofracture strain data is sufficient and no more tests are needed.
- Viscofracture model is an anisotropic damaged density function based on modified Paris' law which can be derived from the force balance equation and the dissipated pseudo fracture strain energy balance equation.
- Data acquisition for viscofracture model is accomplished by using the separated viscofracture strain data.

Moreover, field validation using WesTrack field data from either National Center for Asphalt Technology (NCAT) test sections, MnRoad test sections or Long Term Pavement Performance Data (LTPP) test sections will be conducted. The WesTrack test section provide the best potential for immediate results in that materials are readily available at the Material Reference Laboratory (MRL) in Reno, Nevada, as are detailed results of laboratory testing and field data. Dr. Jon Epps, Senior Research Fellow at Texas Transportation Institute (TTI) and former principal investigator of the WesTrack project, will help coordinate the collection and proper use of these data toward model validation. The plan for validation of PANDA from WesTrack data will be completed during the last quarter of year 5. ARC researchers will work closely with NCAT officials through Dr. Jon Epps and with Mr. Eric Weaver of FHWA to identify sections at the NCAT test track and sections in the LTPP data base that can provide the materials for testing (if necessary) and the field data to make inclusion of NCAT and/or LTPP sections in the field validation plan.

Table V3c.4 Westrack Test Sections.

Original 1995 Construction										**1997 Rehabilitation**		
Design Air Void Content %	**Aggregate Gradation Design**											
	Fine			**Fine Plus**			**Coarse**			**Coarse**		
	Design Asphalt Contents (%)											
	4.7	5.4	6.1	4.7	5.4	6.1	5.0	5.7	6.4	5.1	5.8	6.5
4	▨	4	18	▨	12	21/9	▨	23	25	▨	39	55
8	2	1/15	14	22	19/11	13	8	5/24	7	38	35/54	37
12	3/16	17	▨	10	20	▨	26	6	▨	56	36	▨

Notes: Numbers shown in each cell represent actual test section numbers,
Six cells were eliminated due to the construction impracticality

Table for Decision Points and Deliverables

Date	**Deliverable**	**Description**
10/12	Journal Paper	Paper documents the calibration and validation of PANDA based on the ARC laboratory testing
3/13	Journal Paper	Paper documents the validation of PANDA against other existing databases.
3/13	Final Report	Documentation of PANDA constitutive models, calibration, and Validation

Finally, the University of Illinois at Urbana-Champaign (UIUC) will work with TAMU during the 21-month extension period as a subcontractor to help calibrate and validate PANDA. Their role will be to run PANDA for various cases and serve as an external review of the efficacy of PANDA and its "user-friendliness" and to suggest adaptations that might be necessary to improve PANDA. A primary role of UIUC will be to perform testing defined in Table V3c.1 for materials for which they have performance data from their accelerated loading facility at the Advanced Transportation Research and Engineering Laboratory (ATREL) and use this information to help validate PANDA.

Cited References

Abu Al-Rub, R.K, M.K. Darabi, D. Little, and E. Masad, 2010a, A Micro-damage Healing Model that Improves Prediction of Fatigue Life in Asphalt Mixes. *International Journal of Engineering Science*, 48, 966-990.

Abu Al-Rub, R.K., M.K. Darabi, T. You, E.A. Masad, and D. Little, 2011b, A Unified Continuum Damage Mechanics Model for Predicting the Mechanical Response of Asphalt Mixtures and Pavements. *International Journal of Roads and Airports*, 1 (1), 68-84.

Huang, C.W., R.K. Abu Al-Rub, E.A. Masad, D. Little, and G. Airey, 2011, Numerical Implementation and Validation of a Nonlinear-Viscoelastic and Viscoplastic Model for Asphalt Concrete Mixes. *International Journal of Pavement Engineering*, 12 (4), 433-447.

Darabi, M., R. Abu Al-Rub, E. Masad, C.W. Huang, D. Little, 2011a, A Thermo-Viscoelastic-Viscoplastic-Viscodamage Constitutive Model for Asphaltic Materials. *International Journal of Solids and Structures*, 48, 191-207.

Darabi, M.K., R.K. Abu Al-Rub, E.A. Masad, and D. Little, 2011b, Thermodynamic Based Model for Coupling Viscoelastic, Viscoplastic, and Viscodamage Constitutive Behavior of Asphalt Mixtures. *International Journal for Numerical and Analytical Methods in Geomechanics* (in press).

Darabi, M.K., R.K. Abu Al-Rub, E.A. Masad, and D.N. Little, 2011c, A Thermodynamic Framework for Constitutive Modeling of Time- and Rate-dependent Materials, Part II: Numerical Aspects and Application to Asphalt Concrete. *International Journal of Plasticity* (submitted).

PANDA Standalone Finite Element Software

Major Findings and Status

Work has been started in March 1st of 2011 on the development of the standalone finite element software PANDA (**P**avement **A**nalysis using a **N**onlinear **D**amage **A**pproach) that can be used for predicting the fatigue damage and rutting performance of asphalt pavements under different loading and environmental conditions. Therefore, there are two PANDA deliverables: (1) PANDA-UMAT which is a user material subroutine written in Fortran and links to the well-known finite element software Abaqus and a Fortran complier; and (2) PANDA standalone finite element software that can be simply installed on a regular PC without the need for any additional software. PANDA is intended to include highly efficient and robust finite element algorithms that implement two-dimensional (2D) and three-dimensional (3D) displacement-based finite elements. These elements are used to calculate the total deformations that are then passed to the material constitutive models. The material constitutive model is then used to calculate the corresponding stress and desired internal state variables (e.g. viscoelastic strain, viscoplastic strain, crack density, etc). This calculated information is then passed back to the main finite element code in order to check the satisfaction of the stress equilibrium equation.

The process of PANDA development includes first coding its main engine which is used for solving the highly nonlinear equations incrementally. This engine is based on the Newton-Raphson iterative process and used to achieve the needed accuracy in calculating the loads and deformations. It includes the global assembly of the stiffnesses, nodal degrees of freedom, and nodal loads matrices, and solves the set of simultaneous equations for the nodal displacements using the method of modification. The method of modification is coded for the modification of the banded nanosymmetrical matrices in their condensed form, and it computes the bandwidth and average bandwidth of the stiffness matrix and then solves based on the Gauss elimination/back substitution method with no column pivoting. Once the main engine is developed, then a code is written for a finite element by defining its number of nodes, nodal degrees of freedom, and number of Gaussian integration points.

At this point, the whole plan of PANDA development has been created by searching the literature for the best practices in creating standalone finite element codes. This plan has already been finalized and initiated by programming the main engine for solving the nonlinear system of equations based on the finite element method. Moreover, five different elements are already coded and implemented in PANDA (see Figure V3c.1). Those include three 2D elements and two 3D elements. The 2D elements can be used for solving plane stress, plane strain, and axisymmetric problems, whereas the 3D elements can be used for conducting the 3D rutting and fatigue damage performance simulations. Furthermore, a very important part of the code has been programmed which calculates the stiffness matrix of each element and modifies the element's stiffness matrix for the boundary conditions. Then, it assembles the global stiffness matrix and locates the position of the element matrices in the global matrix. The predictions from these elements are validated by comparing the results with the corresponding ones from the commercial finite element software Abaqus. The finite element code is written using Fortran 90.

Finally, a Fortran subroutine is coded that includes an extensive library of tensor operations that are useful in the implementation of complex material constitutive models. This tensor library is essential for the numerical implementation of the ARC developed constitutive models into the developed stand-alone software.

Issues Identified During the Previous Year and Their Implications on Deliverables

None

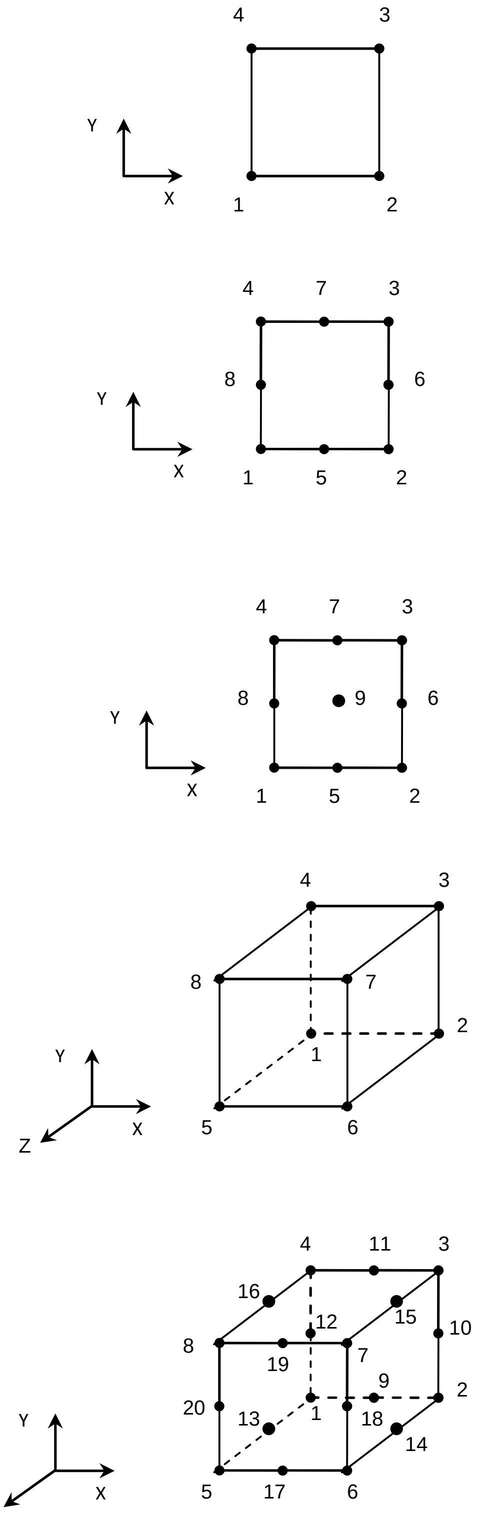


Figure V3c.1. Implemented 2D and 3D elements in PANDA.

21-Month Extension Work Plan

The focus of the 21-month extension period for the standalone PANDA software includes the following activities:

(1) Development of a friendly user interface of PANDA. During year 5, the main finite element code has been developed where the user creates the input file using keywords and commands, and views the output as a text that can be transferred to plotting software for viewing the results. However, in year 6, the user will be given the option of either to use commands and keywords to create the input file (similar to the well-known finite element program Abaqus) or to use a friendly user interface for creating the finite element model (i.e. geometry, boundary conditions, and mesh) (i.e. a pre-processing) and view the output as colored contours (i.e. post-processing). Both options will be attractive for users; the keywords and commands option will be attractive to advanced users and researchers, whereas the friendly user interface will be attractive for beginners and pavement engineers.

(2) Create within the user friendly interface pavement structures that can be directly used by a user to conduct the needed 2D and/or 3D rutting and fatigue damage performance simulations.

(3) Implement in PANDA other continuum-based constitutive models that are developed as part of the ARC, or constitutive models that are commonly being used by the asphalt research community. For example, the user will have the option to use different fatigue damage models (e.g. TAMU fatigue damage model or Schapery's fatigue damage model) or use different micro-damage healing models. In fact, this will be a very important task since it will document the deliverables of the ARC in an interactive manner where the user will be able to have a hand-on and a better grasp of the major modeling outcomes of the ARC.

(4) Finish the preparation of the user and theory manuals of PANDA. The user manual will provide detailed steps for installing and using PANDA standalone finite element software and will provide several tutorial examples. The theory manual will document the finite elements that are implemented in PANDA and the details of the implemented constitutive models and the procedures of calibrating these models.

(5) Provide training for interested users through a three day workshop as detailed below. This workshop was planned for to be held during the second quarter of year five; however, the decision was made to postpone this workshop until the standalone finite element software is available. Also, the cost associated with planning more than workshop is very high. Therefore, the workshop is planned to be held during the last quarter of year six.

PANDA Training and User Workshop

Objective

The objective is to outline the content of a training workshop that the TAMU's ARC researchers will offer during the last quarter of the sixth year of the ARC project. This workshop will present and provide training on PANDA-UMAT and PANDA standalone finite element software. The training will be offered using experimental data that the participants will analyze in order to obtain the parameters of the constitutive models in PANDA.

Overview

The ARC will deliver a mechanistic fatigue damage, aging, moisture, and healing constitutive models in the form of a PANDA User MATerial Computational Code (PANDA-UMAT) subroutine within the finite element software Abaqus. However, due to the need for buying a license for Abaqus software and a Fortran program complier as well as the difficulty in using Abaqus for conducting fatigue damage and rutting performance simulations, the decision was made to create the PANDA standalone finite element software. This software can be used more effectively by researchers and pavement engineers for conducting performance simulations. Moreover, researchers will have the flexibility to incorporate new and improved modeling techniques for pavements using the PANDA standalone software. Both PANDA-UMAT and PANDA standalone software incorporate several material constitutive models to define the behavior (thermo-nonlinear-viscoelastic, thermo-viscoplastic, mechanical damage, moisture damage, fatigue damage, fracture, aging, and micro-damage healing) of asphalt mixtures. These constitutive relationships will contribute to the overall ability of the mechanistic model to make reliable predictions of the appearance of important forms of damage to asphalt pavements. The final deliverables of the continuum damage modeling effort will be as follows:

(1) The first part is a computational material code written in Fortran programming language that is easily linked to the well-known finite element and commercially available software Abaqus. This subroutine – called **PANDA-UMAT** (i.e. PANDA as a User MATerial computational code) in Abaqus – will include the finite element implementation of state-of-the-art constitutive equations of the ARC continuum damage material model. The developed computational code PANDA-UMAT will be used to predict the constitutive behavior (viscoelastic response, permanent deformation, fatigue damage, moisture damage) of the asphalt mixture in an asphalt pavement structure. This computational code can be used to simulate the asphalt mixture behavior under various mechanical and environmental loading conditions.

(2) The second part is a set of geometrical finite element models for different pavement structures that will be prepared within Abaqus software and will be provided along with the computational code PANDA-UMAT. This set of finite element structural models will include precise and robust finite element meshes, boundary conditions, loading conditions, and two-dimensional versus three-dimensional models. These structural models will be provided as CAE (Computer Aided Engineering) visual files within the Abaqus environment such that the user can choose to directly use these files to run

performance simulations of a specific pavement structure without the need to create the model. However, the user will also have the flexibility to modify the provided structural models or even create completely new ones.

The standalone finite element software PANDA. This software can be installed on any PC without the need for any additional software to run. PANDA can be used to simulate 2D plane stress, plane strain, axisymmtric, and 3D boundary value problems. It includes robust finite element algorithms for numerically integrating highly nonlinear equations. It also includes three 2D elements and two 3D elements that give the user the flexibility to obtain accurate and inexpensive finite element simulations. PANDA implements the various continuum-based fatigue damage, rutting, moisture damage, aging, and micro-damage healing constitutive models that are developed within ARC as well as models that are commonly used by the asphalt research community.

(3) The third part is a user and theory manuals that include:

- a theory manual which documents the constitutive equations of the continuum damage model included in the developed computational algorithms used to implement these equations in finite element codes.
- guidelines to estimate or measure the material constants associated with the constitutive equations in PANDA-UMAT and PANDA.
- description of different pavement structures (boundary conditions, method of applying repeated loading).
- Steps for installing and using the PANDA standalone finite element software.

Description of the Workshop

The workshop will be for three days and it will include formal lectures and interactive training sessions as follows:

1. Description of the material constitutive model (4 hours): this part will include presentations of the theoretical background of the materials models and their components. This will encompass descriptions the viscoelastic and viscoplastic models as well as the internal state variables and functions that describe aging, healing, mechanical damage, and moisture damage.

2. Numerical implementation of the model (2 hours): this part will include description of the numerical techniques and programming of the material models in finite element codes.

3. Identification of the model parameters (2 hours): this session will describe the experimental methods that are used to identify the model parameters. In addition, the analytical methods and programs that are used to extract these parameters from the experimental results will be described.

4. Structural model (2 hours): this session will include description of the method used to generate pavement structure models in the standalone finite element software PANDA, loading conditions and boundary conditions.

Interactive session on the use of the PANDA-UMAT (4 hours): this session will include hands-on experience with using PANDA-UMAT within the commercial finite element program Abaqus to predict pavement performance. The training will cover the modules for inputting the model parameters, generate the structural model and predict performance. This session will utilize experimental measurements and data that are used in the ARC for the purpose of the verification of the PANDA-UMAT. Therefore, the workshop participants will have the chance to examine how changes in the material response and model parameters for a known experimental set (e.g. ALF data) impact the performance of the pavement structure under realistic loading and boundary conditions.

Interactive session on the use of the PANDA standalone finite element software (8 hours): this two 4 hours sessions will include hands-on experience with using the PANDA standalone software to predict pavement performance and compare the results to that obtained using PANDA-UMAT. The training will cover installing PANDA and using it for creating finite element models and analyze the computational results. This session will utilize experimental measurements and data that are used in the ARC for the purpose of the verification of the PANDA. Therefore, the workshop participants will have the chance to examine how changes in the material response and model parameters for a known experimental set (e.g. ALF data) impact the performance of the pavement structure under realistic loading and boundary conditions.

<u>Table for Decision Points and Deliverables</u>

Date	**Deliverable**	**Description**
3/13	PANDA standalone software	Provide the standalone finite element software
3/13	PANDA standalone software user and theory manuals	Detailed manuals that explain the constitutive models in PANDA and how to install and use the finite element program.
4/13	PANDA Workshop	Workshop on PANDA models, calibration, validation, and using the PANDA standalone finite element software and the PANDA-UMAT within the commercial finite element software Abaqus.

Work Element V3e: Performance Monitoring Sections and Field Validation of New ARC Products and Uniformity of PG+ Specifications (UWM)

<u>Major Findings and Status</u>

In Year 5, the research team created and populated a database of measured binder and mixture properties as a result of an on-going collaboration with the Western Cooperative Test Group (WCTG) and the Rocky Mountain Asphalt User-Producer Group (RMAUPG). Field performance of sections constructed with the binders and mixtures will become available once/twice every year after significant distresses are observed in these pavement projects. Currently, the research team has access to nine binders and mixtures that have been placed in different projects around the United States. The information collected from these sections can be used to validate the findings of the Asphalt Research Consortium (ARC) and to improve Superpave PG+ specifications. Some of the products which have been tested are the Linear Amplitude Sweep (LAS), Single Edge Notched Beam (SENB), and the Bitumen Bond Strength (BBS) tests.

The WCTG/RMAUPG database includes information on binder performance using current PG specification, PG+ and new testing methods developed in the ARC project. The database was expanded to include mixture testing and pavement performance properties. PG and PG+ test results, as well as information from corresponding field projects were provided by WCTG members. Approximately 40 laboratories around the country are helping in collecting relevant data and running the tests. The participation in monthly testing is on a volunteer basis and thus the number of participating laboratories varies every month. Significant work has been done to improve the data collection system used in the monthly round-robin binder testing. It is important to note that as a result of the WCTG-RMAUPG-ARC collaboration, a valuable database is now available for validation and evaluation of current and new technologies and products. This collaboration is helping achieve one of the major objectives of ARC, which is to complement the current PG specification system with new fundamental tests such as MSCR, LAS, SENB, among others and to move away from non-fundamental tests, such as ductility and elastic recovery tests.

Efforts were also directed towards evaluating ARC products (e.g., LAS and SENB) using the Long Term Pavement Performance (LTPP) materials and performance database. The LAS and SENB test procedures have been evaluated by comparing testing results of Long Term Pavement Performance (LTPP) binders with field performance. A total of 25 binders have been tested using LAS and SENB procedures and comparison to field performance have been conducted. Based on the limited experimental results, both LAS and SENB showed promise in capturing the contribution of asphalt binder in the fatigue and thermal cracking performance of asphalt pavements.

Issues Identified During the Previous Year and Their Implications on Deliverables

None

21-Month Extension Work Plan

In Year 6, validation efforts of ARC products using new pavement sections and WCTG/RMAUPG database will be coordinated with WRI. The following subtasks are planned.

Subtask V3e-Yr6-I: Select New Pavement Sections and/or New LTPP Sites to Validate Selected ARC Products

The research team will solicit DOT's participation for field validation sites. Also, if new LTPP sections are approved and become available, materials from these sections will be used for validation efforts. The new pavement sections will aid in the evaluation of the relationship between pavement performance and the testing parameters obtained from the selected ARC products. The main products that will be target for validation are listed in Table V3e.1, which includes technologies/procedures that showed most promise during Years 3-5 of the ARC project. In case of successful validation, the results can be used to develop specification criteria, as described in subtasks V3e-Yr6-III and V3e-Yr6-IV.

Table V3e.1. List of ARC products to be validated with new pavement sections.

Product	**ARC Work Element**
Bitumen Bond Strength Test (BBS)	M1a
Elastic Recovery – DSR (ER-DSR)	F2a
Linear Amplitude Sweep (LAS)	F2e
Rigden Voids for fillers	F2e
Binder Lubricity Test – DSR	E1c
RAP Binder PG True Grade Determination	E2b
Single Edge Notch Bending (SENB)	E2d
Binder Glass Transition Test (Tg)	E2d
Asphalt Mixture Glass Transition Test	E2d
Planar imaging/ Aggregate Structure (iPas)	E1b
Gyratory Pressure Distribution Analyzer (GPDA)	E1c

Subtask V3e-Yr6-II: Population and Improvement of Database for Binder/Mixture/Field Measurements

The research team will continue updating the database as new test results become available. The collection of data for the WCTG/ RMAUPG database established in Year 4 and 5 will continue into Year 6. The research team will follow the guidelines used in LTPP for the WCTG/RMAUPG database. The team will explore the possibility of making the WCTG/RMAUP database compatible with the LTPP database and testing procedures. Also, the research team will continue efforts for unifying and improving PG+ specifications.

Subtask V3e-Yr6-III: Development of Specification Criteria Based on Evaluation of Field Performance

Testing of the WCTG/RMAUPG loose mix samples for dynamic modulus, fatigue, and flow number will continue in Year 6. Mixture testing results in combination with field performance evaluation of WCTG/RMAUPG sections will be used to develop specification criteria for selected ARC products. The research team anticipates having mixture testing data linked to binder test results and eventually to field sections.

Subtask V3e-Yr6-IV: Interviews and surveys for soliciting feedback on ARC products

Feedback from WCTG and RMAUPG members will be collected to evaluate feasibility of ARC products. Interviews with DOT personnel and the WCTG board regarding ARC products will be used to develop specification criteria and to improve products/procedures in Table V3e.1.

Table for Decision Points and Deliverables

Type of Deliverable	Description	Original Delivery Date	Revised Delivery Date	Reason for change
Journal Paper	Paper on validation efforts using selected DOT's pavement sections	07/12	N/A	N/A
Journal Paper	Paper on validation of ARC products using WCTG sections	06/13	N/A	N/A
Presentation	Update on technology/products validation using mix and field performance at ETG	09/12	N/A	N/A
Presentation	Update presentation at annual Rocky Mountain Asphalt User Producer Group and Western Cooperative Testing Group combined meeting	04/13	N/A	N/A
Report	Validation efforts of ARC technology/products	06/13	N/A	N/A

Work Element V3f: Validation of the AASHTO MP-19 Specifications and Improvements of the TP-70 Procedure (UWM)

Major Findings and Status

The MSCR test procedure (AASHTP TP70) and the new binder Specifications (MP19) is currently being considered as a replacement for PG+ and M320 binder specifications. The results collected to date indicate that modified binders vary in their nonrecoverable creep compliance (J_{nr}) and percent recovery (%R) values depending on temperature, stress level and modifier type. In addition, binders vary significantly sensitivity to change in stress level. The sensitivity of all binders to stress changes significantly with temperature and with aging. There are many questions being raised about the requirements for percent recovery and the need for the stress sensitivity in specifications. In addition, some of the round robin results show significant variations in protocols used for calculation of J_{nr} and %Recovery, resulting in wide variation is results. There are also ideas to improve the repeatability by using different range of cycles and by including a check on stability of response during various cycles in the test.

Mixture Flow number (FN) test results have been collected to evaluate the need for the various parameters and limits proposed in the MP19, and correlate them with mixture performance. Initial testing was conducted for both fine and coarse gradations of limestone using four binders with different J_{nr} and % recovery values. The testing was done at stress levels of 344 and 1034 kPa and at a temperature of 46^{o}C. Results show consistently that the fine gradation had a greater FN value than the coarse gradation for each of the binder types and at both stress levels. Also, the FN values show consistent reduction when the stress level was increased. Contrary to what was expected, the mixtures with plastomer modification exhibited higher FN values than those with elastomeric modification for all combinations of stress levels and gradations. These observations are consistent with the behavior of the plastomeric binder measured with the MSCR J_{nr} values at low stress levels, but no correlations were found with other MSCR parameters.

Issues Identified During the Previous Year and Their Implications on Deliverables

Recently the Binder ETG Task force investigated the MSCR tests. The following issues were considered important:

- The relationship between elasticity and binder/mixture performance in terms of rutting and fatigue cracking.
- The relationship between traffic volume/ speed/ climate and the selected parameter (J_{nr}) to quantify rutting resistance.
- The number of cycles required to achieve a steady state response.

21-Month Extension Work Plan

The main objectives in Years 6 are to investigate the relationship between elasticity and stress sensitivity of binders and mixture performance in terms of rutting and fatigue cracking resistance.

These objectives will be addressed by pursuing the following tasks:

Subtask V3f-Yr6-I: Quantify the effect of binder elasticity on mixture performance in terms of rutting and fatigue cracking resistance at selected temperatures and loading rates.

Subtask V3f-Yr6-II: Determination of role of binder stress susceptibility in MSCR and its relationship with mixture performance.

Subtask V3f-Yr6-III: Evaluating the issue of variability and differences in measurements from various rheometers and determination of required number of cycles for binders to reach steady state at each stress level in MSCR.

Subtask V3f-Yr6-IV: Based on the results from subtasks I-III, a final report will be submitted with recommendations to revise limits on elasticity and stress sensitivity that could be incorporated in MP19; as well as revise TP-70, if needed, to improve repeatability of test methods and unify the methods of calculations from various rheometers.

Table for Decision Points and Deliverables

Date	**Deliverable**	**Description**
06/12	Presentation	MSCR modification
08/12	Journal Paper	Journal paper
12/12	Report	Interim report
6/13	Final report	Relationship between elasticity and mixture performance

TABLE FOR DECISION POINTS AND DELIVERABLES FOR THE VALIDATION PROGRAM AREA

Name of Deliverable	**Type of Deliverable**	**Description**	**Original Delivery Date**	**Revised Delivery Date**	**Reason for change**
V1b: Construction and Monitoring of Additional Comparative Pavement Performance Sites (WRI)	Topical report	Topical report on construction and monitoring activities	June 2013		
V3c: Validation of PANDA (TAMU)	Journal Paper	Paper documents the calibration and validation of PANDA based on the ARC laboratory testing	10/12		
	Journal Paper	Paper documents the validation of PANDA against other existing databases.	3/13		
	Final Report	Documentation of PANDA constitutive models, calibration, and Validation	3/13		
	PANDA standalone software	Provide the standalone finite element software	3/13		
	PANDA standalone software user and theory manuals	Detailed manuals that explain the constitutive models in PANDA and how to install and use the finite element program.	3/13		
	PANDA Workshop	Workshop on PANDA models, calibration, validation, and using the PANDA standalone finite element software and the PANDA-UMAT within the commercial finite element software Abaqus.	4/13		

Name of Deliverable	**Type of Deliverable**	**Description**	**Original Delivery Date**	**Revised Delivery Date**	**Reason for change**
V3e: Performance Monitoring Sections and Field Validation of New ARC Products and Uniformity of PG+ Specifications (UWM)	Journal Paper	Paper on validation efforts using selected DOT's pavement sections	07/12	N/A	N/A
	Journal Paper	Paper on validation of ARC products using WCTG sections	06/13	N/A	N/A
	Presentation	Update on technology/products validation using mix and field performance at ETG	09/12	N/A	N/A
	Presentation	Update presentation at annual Rocky Mountain Asphalt User Producer Group and Western Cooperative Testing Group combined meeting	04/13	N/A	N/A
	Report	Validation efforts of ARC technology/products	06/13	N/A	N/A
V3f: Validation of the AASHTO MP-19 Specifications and Improvements of the TP-70 Procedure (UWM)	Presentation	MSCR modification	06/12		
	Journal Paper	Journal paper	08/12		
	Report	Interim report	12/12		
	Final report	Relationship between elasticity and mixture performance	6/13		

PROGRAM AREA: TECHNOLOGY DEVELOPMENT

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

Simplified Continuum Damage Fatigue Analysis for the Asphalt Mixture Performance Tester (AMPT)

Major Findings & Status

In Year 1 of the project an improved method for continuum damage analysis based on reduced cycles was developed, and a spreadsheet for performing the analysis using data collected with the Asphalt Mixture Performance Tester (AMPT) was developed. In Year 2 of the project, a Draft AASHTO Standard Test Method for reduced cycles continuum damage analysis was prepared. The Interlaken AMPT that is owned by the National Cooperative Highway Research Program (NCHRP) was modified to perform the basic testing required by the draft standard method. Initial testing with this device in Year 3 of the project at 10 Hz, the frequency normally used for continuum damage fatigue testing, revealed that there were actuator seal movements that resulted in poor sinusoidal loading when going from tension to compression. Replacement of the AMPT actuator with an improved actuator with less seal movement would add significant cost to the equipment. At 1 Hz, the computer control system could compensate for the seal movement and apply reasonable sinusoidal loading; therefore, a series of tests were conducted at 1 Hz. These tests produced damage curves that were significantly different than previously reported. As a result an extended uniaxial fatigue experiment was undertaken in Work Element E2e to verify that the reduced cycles approach can be used to collapse uniaxial fatigue data gathered over a wide range of temperatures, frequencies and strains. The data from this experiment were analyzed over much of Year 4, leading to the conclusion that the damage relationship for an asphalt mixture depends on the initial stiffness of material. It was concluded that a revision to the testing protocol and data analysis are needed so that damage curves as a function of initial stiffness can be efficiently measured. Further analysis of previously collected data in Year 5 indicated the importance of measuring the damage tolerance of a mixture, that is the point during the fatigue process when micro-cracks and other forms of micro-damage coalesce into a large, propagating crack. A revised test method was developed in Year 5. The revised test uses increasing stresses, rather than a constant stress or strain level, to characterize the development of damage in the specimen. The stresses start an initially low level and several hundred load cycles are applied. The stress is then increased by a factor of 1.5 and several hundred additional load cycles are applied. The test continues, increasing the stress by a factor of 1.5 and applying several hundred load cycles until failure of the sample occurs. An evaluation of the test procedure will be completed in Year 5, and the procedure will be applied to eight different mixtures.

Year Six Work Plan

Finalization of the test protocol for the AMPT is dependent on final outcome of the Continuum Damage Fatigue Experiment included in Work Element E2e. This work is behind schedule;

therefore, completion of the final draft test method has been delayed into Year 6 of the project. The anticipated completion date for the test method is 6/30/2012.

Table for Decision Points and Deliverables

Type of Deliverable	Description	Original Delivery Date	Revised Delivery Date	Reason for change
Test Method	Simplified Continuum Damage Fatigue Analysis for the Asphalt Mixture Performance Tester	9/30/2011	6/30/2012	Testing delays in Work Element E2e

Work Element TD3: Identify Products for Mid-Term and Long-Term Development (AAT, WRI)

Work Element TD4: Develop Mid-Term and Long-Term Products (AAT, WRI)

Major Findings and Status

The ARC research team has identified 44 products for development. Product briefs have been prepared and distributed to the ETG's for review and prioritization. The Product briefs are available on the ARC website www.arc.unr.edu. Development plans have been prepared for many of products and is underway. The ARC team will continue to review the current and past work to identify potential mid-term and long-term development projects.

21-Month Extension Work Plan

Development of the identified products will continue according to the previously developed plans. The ARC researchers will continually review research progress to identify any additional potential products.

PROGRAM AREA: TECHNOLOGY TRANSFER

CATEGORY TT1: OUTREACH AND DATABASES

Work Element TT1a: Development and Maintenance of Consortium Website (UNR)

Major Findings & Status

The Consortium Website has been in operation since 2007. The website will continue to be maintained throughout the extension period of the Consortium project. The final copies of work plans, all the quarterly progress reports, the ARC newsletters, and any other technical reports will continue to be uploaded to the website.

Issues Identified During the Previous Year and Their Implications on Future Work
None

21-Month Extension Work Plan

The Consortium website will continue to be maintained and appropriate documents will be uploaded. The "Outreach" webpage will be updated periodically.

Work element TT1b: Communications (UNR)

Major Findings & Status

Three newsletters were published in year 5 of the Consortium. The newsletters were electronically distributed to the industry and are available on the Consortium website.

Issues Identified During the Previous Year and Their Implications on Future Work

None

21-Month Extension Work Plan

Three ARC newsletters per year will be published.

Work element TT1c: Prepare Presentations and Publications

Major Findings & Status

Several presentations were made to the Expert Task Groups and in professional meetings. Several publications were developed and submitted to TRB, AAPT, and technical reports were uploaded onto the ARC website.

Issues Identified During the Previous Year and Their Implications on Future Work
None

21-Month Extension Work Plan

The ARC team will continue to make presentations to ETGs and submit papers to various journals and conferences.

Work Element TT1d: ARC Materials Database (UNR)

Major Findings and Status

Nearly all of the work from the original software development proposal dated 2008.10.26 has been completed. The database has been implemented to store the ARC materials, properties to be studied, measures of various test results, and the work performed at ARC validation sites, per work element TT1d. In addition, all of the material database files (MDF) have been incorporated into the ARC database.

The role-based authorization and authentication scheme has been completed. The implementation of this subsystem was changed so as to categorize users into organizational users and organizational super users. The role of the administrative user has not changed.

As users began to enter extensive data into the ARC system, some performance issues were identified. To date, these performance issues have been resolved by selecting more limited data sets on pages loaded, and upgrades to the database and Web server.

Issues Identified During the Previous Year and Their Implications on Deliverables

As the database moved from development mode to production mode this year, several changes were suggested by the Work Element Lead and various consortium members. The following list summarizes these changes and their status:

- The initial design of the file upload system allowed supporting files to be uploaded into a flat file system. During training sessions and teleconferences, it was decided that this original system was not adequate so several improvements were made and additional improvements proposed. At this time, the uploaded file structure has been modified such that the file system is hierarchical. A keyword search subsystem was added using a list of predefined keywords. These keywords were reviewed by the ARC consortium and approved by the work element lead. In addition, the concept of a file group was also introduced as a way to further categorize uploaded files. One further change is underway – the ability for multiple files to be selected and uploaded at once. Under discussion, is the addition of supplemental file metadata. The exact structure of this additional metadata has not been finalized at this time. Current design suggestions include associating file extensions with specific applications. Metadata including file and field formats is also being considered.

- The database development team expected data entry for tests performed and the resulting measures be entered by ARC consortium participants directly into the ARC database. However, the development team has found that various institutions have been entering data into different systems. UWM, for example, has been entering data into their own SQL database. UWM desires that all or part of this data be automatically imported into the ARC database to the greatest extent that is feasible. WRI also has another database system in which data is being entered. Development of this data import subsystem is underway using UWM as a prototype case.
- Much of the development effort thus far has focused on entering database data and uploading support files. The initial implementation of the user interface for public users has been completed and was presented during the training sessions and workshop. We expect further development in this area to improve search and presentation capabilities.
- There were several smaller changes resulting from actual database use. In summary, these changes involved how data was displayed to the user, various selection criteria, replicate measures, and the introduction of the concept of a test run. Additional and significant changes were made the Measure Editor so that users could enter multiple measures. In addition, a significant development effort was required to work with multi-dimensional properties.
- The implementation of the validation site subsystem has been complete for some time. To date, two validation sites have been entered. The development team expects that changes might be necessary – especially in the sub system that links validation sites to support data files.

21-Month Extension Work Plan

Based on the preceding findings and issues mentioned above, the following items are suggested to complete the ARC database to satisfy user needs and expectations:

- The end user documentation (help files) requires revision based on the significant changes already made and changes proposed. "How to" task-based tutorials should also be developed.
- Database schema documentation was created based on the initial design and implementation. Based on required changes, the database schema documentation requires modification and enhancement to address several new tables and relationships between them.
- A subsystem needs to be completed allowing users to import data from the databases implemented by various consortium users. UWM will be used as a prototype for this

subsystem. Other consortium members might be able to utilize this subsystem depending on the structure of their data.

- The user interface for general users (users not part of the ARC consortium) to search for test results and supporting documentation (files) needs to be updated to account for new keyword and metadata search features. In addition, the administrative decision needs to be made about which forms will be accessible to public users. The infrastructure is in place for this implementation.
- Several discussions have taken place regarding the ultimate home for the Web-based ARC database. Presently, the database is being hosted at the University of Nevada, Reno. However, ultimately that might not be the case. Thus, documentation needs to be created allowing another site to deploy the ARC database and maintain it. In addition, specifications need to be fully defined for the hosting requirements (Software and software version requirements, performance specifications, network bandwidth requirements, and disk requirements).

Work element TT1e: Development of Research Database (UNR)

Major Findings & Status

The final version of the year 5 work plan and the quarterly progress reports were uploaded onto the appropriate sections of the ARC website.

The original ARC work plan and the year 2 work plan identify the information to be included in the Research Database as follows: problem statement, budget, timeline of activities, results update in forms of reports, white papers or any other type of documents, contact information, and relationship to other studies.

All of the information identified above has been incorporated in the various sections of the ARC website. Specifically; problem statements, timeline of activities, and external coordination are incorporated in the yearly work plans that are published under the Publications section of the ARC website. The results updates are incorporated in the quarterly progress reports that are published under the Publications section of the ARC website. The contact information for the ARC members are listed in the Home and Contact sections of the ARC website.

Technical reports and Journal papers are available in the Publications section of the ARC website and the Materials Database (i.e. TT1d) will include a link to the specific reports that contain the information on the various materials that are being evaluated in the ARC.

Issues Identified During the Previous Year and Their Implications on Future Work
None

21-Month Extension Work Plan

Publish the annual work plan, quarterly progress reports, and any research reports on the ARC Website.

Work element TT1f: Workshops and Training

Major Findings & Status

Teleconference database training sessions were held during year 5 for the ARC "super users" and "sub users" of the materials database. The training sessions provided exposure to the ARC database framework and contained a detailed demonstration of the user interface for the software and best practices for its use.

Issues Identified During the Previous Year and Their Implications on Future Work

None

21-Month Extension Work Plan

A workshop session will be held in year 6 for the materials database in Reno, Nevada. A workshop for PANDA software will be conducted in Year 6.

The ARC researchers will assess the availability and need for other workshops and training activities of the various areas of the ARC. If it is found necessary to conduct workshops and training activities, a request will be made to FHWA for the approval of such activities.

TABLE FOR DECISION POINTS AND DELIVERABLES FOR THE TECHNOLOGY TRANSFER PROGRAM AREA

Name of Deliverable	**Type of Deliverable**	**Description**	**Original Delivery Date**	**Revised Delivery Date**	**Reason for change**
TT1a: Development and Maintenance of Consortium Website	Progress Report	Upload quarterly progress report	07/31/12		
	Progress Report	Upload quarterly progress report	10/31/12		
	Progress Report	Upload quarterly progress report	01/31/13		
	Progress Report	Upload quarterly progress report	04/30/13		
	Progress Report	Upload quarterly progress report	07/31/13		
	Progress Report	Upload quarterly progress report	10/31/13		
TT1b: Communications	Newsletter	Newsletter will be published	07/31/12		
	Newsletter	Newsletter will be published	11/30/12		
	Newsletter	Newsletter will be published	03/31/13		
TT1d: Development of Materials Database (UNR)	Documentation	Revise ARC application help files	2010	08/31/2012	Changes to ARC implementation
	Documentation	Revise database scheme documentation	2010	12/31/2012	Changes to ARC implementation
	Documentation	Deployment and administrative documentation, and List hosting requirements for the ARC database including machine performance specification, database specifications, and cumulative file sizes	2010	08/31/2013	Changes to ARC implementation
	Training	Develop training materials and conduct additional and continuing training sessions for ARC members and public users	2012	01/01/2012 Thru 03/30/2013	

Name of Deliverable	**Type of Deliverable**	**Description**	**Original Delivery Date**	**Revised Delivery Date**	**Reason for change**
TT1d: Development of Materials Database (UNR) (continued)	Development	Finalize file upload subsystem to support multi-file uploads more efficiently.	2011	12/31/2012	Original and revised file upload system was not efficient for users uploading multiple files.
	Development	Finalize end user search system for uploaded files and research results using new keyword implementation and proposed metadata and finalize the metadata scheme for uploaded files	2011	04/30/2012	Original implementation did not include complex keywords and file metadata
	Development	Finalize the design of and implement the system to import data from other sources using UWM as a prototype		06/30/2012	The original implementation did not include such a feature
	Development	Enhance the public user interface for the ARC system	2011	09/30/2013	Addition of new features
	Database population	Populate validation sites and define connections with support files and work tasks. Additional metadata might be needed, and Define associations between materials and other entities such as validation sites and work tasks	2012	09/30/2013	
	Documentation Draft Final Report	ARC Materials Database	06/30/2013		
	Documentation Final Report	ARC Materials Database	12/31/2013		

Name of Deliverable	**Type of Deliverable**	**Description**	**Original Delivery Date**	**Revised Delivery Date**	**Reason for change**
TT1f: Workshops and Training	Workshop	PANDA software training	TBD	N/A	N/A

ARC REPORT OUTLINES

This section provides outlines for the Asphalt Research Consortium (ARC) Reports which are part of the deliverables for the ARC. The reports will be formatted to comply with FHWA Section 508 requirements. These will be comprehensive reports that document findings and protocols. The reports are targeted to both the research and practitioner audiences. However, researchers will require supplemental information found in journal technical papers as well as in Ph.D. dissertations and/or master-of-science theses that are products of this research. All such supplemental materials will be fully referenced in the 508 format reports. Table 1 provides a summary of these reports and the submittal dates.

Table 1. Summary of ARC Reports.

Report Designation	Report Title	Draft Submittal Date	Final Submittal Date
A	Moisture Damage	12/30/11	8/30/12
B	Characterization of Fatigue Damage and Relevant Properties	3/30/12	10/30/12
C	**PANDA:** Pavement Analysis using a Nonlinear Damage Approach	3/30/13	10/30/13
D	Characterization of Asphalt Binders using Atomic Force Microscopy	3/30/13	10/30/13
E	Multiscale Virtual Fabrication and Lattice Modeling	12/30/11	8/30/12
F	Microstructure Cohesive Zone Modeling for Moisture Damage and Fatigue Cracking	12/30/11	8/30/12
G	Design System for HMA Containing a High Percentage of RAP Material	6/30/2013	12/31/2013
H	Critically Designed HMA Mixtures	5/31/2013	11/30/2013
I	Thermal Cracking Resistant Mixes	4/30/2013	10/31/2013
J	Pavement Response Model to Dynamic Loads	3/31/2013	9/30/2013
K	Development of Materials Database	6/30/2013	12/31/2013
L	Development and Validation of the Bitumen Bond Strength Test (BBS)	10/11	4/12
M	Development of Test Procedures for Characterization of Asphalt Binder Fatigue and Healing	10/11	4/12

Table 1 (con't). Summary of ARC Reports

Report Designation	Report Title	Draft Submittal Date	Final Submittal Date
N	Guideline for Selection of Modification Techniques	3/13	10/13
O	Characterization of Binder Damage Resistance to Rutting	3/13	10/13
P	Quantifying the Impacts of Warm Mix Asphalt on Constructability and Performance	3/13	10/13
Q	Improvement of Emulsion Characterization and Mixture Design for Cold Bitumen Applications	3/13	10/13
R	Studies on Tire-Pavement Noise and Skid Response	12/11	7/12

REPORT A
MOISTURE DAMAGE

SCOPE

This report will address five primary objectives spelled under the moisture damage task in the year 2 revised work plan. The objectives are:

i. Identify the mechanisms that contribute to moisture susceptibility of mixtures.
ii. Explain the contribution of material properties such as aging of the asphalt, pH of the water, aggregate structure, and diffusion properties of the binder or mastic, and surface energies of the asphalt and aggregate to the moisture susceptibility of mixes.
iii. Explain the contribution of mixture properties such as internal void structure and diffusivity of the mixture.
iv. Present a model of the moisture damage process that is linked to and compatible with the model of fatigue damage developed by the ARC (work element F3).
v. Exemplify the utility of tests and models to evaluate the moisture susceptibility of mixtures and quantify the effect of moisture on pavement distress.

OUTLINE

Chapter 1: Mechanisms and Properties Related to Moisture Induced Damage

This chapter will present an overview of the moisture damage mechanism and a comprehensive discussion on the various material properties, physical models, and test methods that are employed to assess moisture damage sensitivity of different asphalt mixtures at different length scales. More specifically, this chapter will cover:

- an overview of the physics and mechanisms of moisture induced damage at multiple length scales,
- the material and mixture properties that influence these mechanisms,
- test and analytical methods by which these properties can be measured, and
- test and analytical methods that can be used to quantify the moisture damage resistance at the material or structural length scale.

Details of the aforementioned aspects will be included in subsequent chapters.

Chapter 2: Moisture Transport in Asphalt Binders, Mortars and Mixtures

A precursor to moisture-induced damage is transport of moisture through the asphalt mixture. This chapter will discuss the moisture transport in asphalt mixtures at different length scales. More specifically, this chapter will cover:

- the test and analytical methods to measure the diffusivity of water through asphalt mixtures, mortars, and asphalt binders,
- hysteretic effect of water diffusion through asphalt binders, and
- simple examples demonstrating the significance of diffusivity on moisture damage in asphalt mixtures at different length scales.

Chapter 3: The Use of a DMA to Quantify Moisture Damage in Asphalt Mortars

As moisture travels through an asphalt mixture composite, it softens the mastic and eventually debonds the binder from the aggregate surface. This chapter will present:

- a test method using the DMA to quantify the combined effect of these two mechanisms of failure (cohesive and adhesive),
- analytical methods that are used with the results from the test to evaluate moisture sensitivity,
- guidelines to use a user-friendly software to analyze results from this test method,
- Experiment design for DMA testing that demonstrates the sensitivity to combinations of mixture variables including binder type, aggregate type, level of conditioning (different relative humidities (RHs)), and void content,
- Suction diffusion model including the effect of wind speed that was developed to illustrate the "wetting" within the hot mix asphalt (HMA) layer due to an increase in RH over the service life of the pavement,
- Mechanistic model to determine fracture properties of the fine aggregate matrix based on strain energy equivalence,
- A stress-controlled, repeated direct tension (RDT) method that can be used in place of the DMA to assess mechanical properties of the FAM as well as the impact of moisture damage.

It is envisaged that this test method can be used to evaluate the efficacy of binder additives (e.g. polymers, chemical modifiers and anti-strip agents) or performance of mineral-binder systems that are likely to result in poor moisture damage resistance. Appendix ** will provide details of the testing protocol.

Chapter 4: Water, Mineral Aggregate and Binder Properties that Influence Bond Strengths

As the moisture travels through the asphalt mixture composite, it softens the mastic or mortar and eventually debonds the binder from the aggregate surface. More specifically, this chapter will provide:

- a database of mineral properties that can be used to quantify their propensity to bond with different asphalt binders,
- examples to demonstrate potential applications of this database, and
- findings from a study conducted to evaluate the influence of pH of water on the bond strength between the aggregate and the binder.

It is envisaged that this chapter will provide a database that can be used for forensic analysis of adhesive failures, identification of potentially problematic or beneficial mineral-binder combinations, selection of mineral fillers and fines for asphalt mixtures that may improve moisture damage resistance.

Chapter 5: Computational Modeling of Moisture Damage in Mixtures

Computational models provide a framework to combine and compare the relative affect of several different processes associated with the moisture damage mechanism. This chapter will present an example of a computational model to quantify moisture damage in an asphalt mixture. The computational model will use material properties obtained from Chapters 2 and 3 for a parametric analysis that demonstrates the influence of time of exposure to moisture and distribution of air voids on the moisture damage resistance of an asphalt mixture.

Chapter 6: Modeling Continuum Damage to Fracture of Asphalt Concrete

This chapter presents:

- A review of the viscoelastic continuum damage (VECD) model with some insights into the mechanics of dilute microcrack distribution
- Development of a criterion for the onset of localization
- A material model that extends the VECD model beyond localization to the onset of failure
- A computational procedure that simulates a pavement from its virgin state to failure

Appendix 1: Procedure to measure diffusivity of asphalt binders

Appendix 2: Procedure to measure diffusivity of mortars

Appendix 3: Procedure to measure moisture damage in FAM specimens using DMA

Appendix 4: Testing protocols using DMA and RDT methods (Two DMA protocols and one DRT protocol are included)

REPORT B
CHARACTERIZATION OF FATIGUE DAMAGE AND RELEVANT PROPERTIES

SCOPE

This report will address the following primary objectives spelled under the fatigue task in the year 2 revised work plan.

TENTATIVE OUTLINE

Chapter 1: Mechanisms and Properties Related to Fatigue Damage

This chapter will present an overview of fatigue damage, healing as well as material properties, physical models, and test methods that are employed to characterize fatigue cracking, self-healing at different length scales. More specifically, this chapter will cover:

- an overview of the physics and mechanisms of fatigue damage and self-healing in asphalt mixtures,
- an overview of the physics and mechanisms of oxidative aging in asphalt mixtures that ultimately affect the fatigue cracking resistance and self-healing characteristics of asphalt mixtures,
- inherent fracture resistance of asphalt binders,
- inherent healing characteristic of asphalt binders and influence of aging and temperature,
- influence of state of stress on fracture and healing in asphalt mixtures,
- influence of state of damage and duration of rest period on healing in asphalt mixtures,
- influence of oxidative aging gradients on properties of asphalt mixtures as a function of depth of pavement, and
- influence of state of stress on the properties of asphalt binder and composites.

This chapter will also discuss on the potential applications and scenarios in which the aforementioned factors must be considered (and concomitant test methods be employed) during materials selection, mixture design and pavements design. Details will be included in subsequent chapters.

Chapter 2: Inherent Fracture Resistance of Asphalt Binders – Ideal and Practical Work of Fracture

The fracture resistance of asphalt mixtures is dictated by the inherent cohesive fracture energy of asphalt binders or asphalt binder - aggregate interfaces. The ideal work of fracture of an asphalt binder can provide a measure of its inherent fracture resistance. This chapter will present:

- a detailed review of the ideal work of fracture and practical work of fracture,
- measurement and comparison of the ideal and practical work of fracture for different asphalt binders, the test and analytical methods to measure the diffusivity of water through asphalt mixtures, mortars, and asphalt binders, and

- a test method to measure the practical work of fracture of asphalt binders or binder-aggregate interfaces in wet and dry conditions.

Chapter 3: Inherent Healing Characteristics of Asphalt Binders

Micro damage in asphalt binders can reverse and heal at temperatures above its glass transition temperature. The healing capacity of an asphalt mixture is largely dictated by the healing capacity of the asphalt binder, temperature of the mix or binder, state of stress experienced by the binder within a mixture (Chapter 5), and level of damage (Chapter 6). This chapter will present findings related to the inherent healing capacity of asphalt binders and influence of temperature and aging on this healing capacity. More specifically this chapter will present:

- a mechanism that describes micro-damage healing at a micrometer length scale,
- a test method to measure the healing capacity of asphalt binders, and
- data obtained using this test method that demonstrates the influence of time, temperature and aging on the intrinsic healing in asphalt binders.

Chapter 4: Thermal and Oxygen Transport and Oxidation Kinetics to Characterize Oxidative Aging in Asphalt Binders and Mixtures

Oxidative aging of asphalt binder is a major factor in fatigue and other deterioration mechanisms of asphalt pavements. As binders oxidize, they harden and become brittle and thereby susceptible to cracking. Predicting the rate at which binders oxidize in pavements is essential to predicting changes to mixture properties over time. This chapter will describe recent developments in a thermal and oxygen transport model to estimate binder oxidation in pavements as a function of time and depth. This chapter will present:

- details of the transport model
- the role of fast-rate and constant-rate reaction kinetics in the model
- the role of air voids in the transport model and methods for quantifying their impact
- pavement validation of the model

Chapter 5: Influence of State of Stress and Permanent Deformation Fracture and Healing in Asphalt Mixtures

Fracture and permanent deformation always coexist in asphalt pavements and in asphalt test specimens. Current characterization method only measure and model one of these two distress types and ignore the other. Healing at the macro scale, in asphalt pavements, is strongly impacted by the driving force provided by the material itself. In the recovery process, this is due to the internal force or internal stress. A commonly used technique is described to measure the internal stress during a creep experiment and this is the so-called strain transient dip test. The principle of measurement is that when the applied stress is equal to the internal stress, the effective stress is zero and the creep strain rate is zero.

This chapter describes a method of evaluating fatigue damage and macro scale or pavement/mixture healing. This chapter highlights:

- use of a controlled-stress repeated direct tension (RDT) fatigue test conducted in the controlled-strain mode because in this mode plastic deformation from yielding in the bulk is small and localized plastic deformation around cracks is significant, and it is this localized plastic deformation that impacts the fracture process,
- a sequence of a non-destructive RDT performed to determine the critical undamaged state (boundary of undamaged state and damaged state) of the specimen followed by destructive fatigue testing (RDT),
- methodology for determining the internal stress, which is the driving force of healing at the macro level, ands overview of the method of using creep and step-loading recovery testing in the mechanical analysis of the healing process, and
- effect of air voids, asphalt binder, and aging on the processes of fatigue and healing based on the testing methodologies described in detail in Appendix 4.

Chapter 6: Influence of State of Damage and Duration of Rest Period on Healing in Asphalt Mixtures

Healing in an asphalt mixture is dictated by the magnitude of micro damage within the mix immediately preceding the rest period as well as the duration of the rest period. This is addition to external factors such as temperature and state of stress (discussed in Chapter 5). This chapter will present a method to quantify percentage healing as a function of the level of damage prior to the rest period and the duration of the rest period. More specifically, this chapter will present:

- a test method to determine the healing characteristics of asphalt mixtures as a function of the level of damage prior to the rest period and the duration of the rest period,
- an analytical method to quantify healing from the above test method using the viscoelastic continuum damage approach,
- validation of the test and analytical methods using laboratory tests with randomized loading and rest periods, and
- typical results for selected asphalt mixtures.

Chapter 7: Influence of Oxidative Aging Gradients on Properties of Asphalt Mixtures

This chapter describes how field aging imparts a gradient on the complex modulus of the asphalt pavement layer. This stiffness gradient due to aging impacts the response of the pavement and the damage that occurs due to permanent deformation and the fatigue and healing process. This chapter also provides an overview of how field cores can be tested to determine fracture and healing properties that reflect the impact of the stiffness gradient and gradient of fracture and healing properties caused by oxidative aging. Appendix 5 provides a detailed testing methodology. Specific point addressed in Chapter 7 include:

- how undamaged properties of field-aged asphalt samples are determined using direct tensile tests,

- how the stiffness gradient in field-aged samples are determined using direct tensile testing and verified by finite element analysis,
- a micromechanical constitutive model used to develop a correlation between stiffness gradient and binder aging, and
- a method to measure and predict fatigue and healing properties of asphalt field-aged mixtures using the overlay tester.

Chapter 8: Influence of State of Damage and Duration of Rest Period on Healing in Asphalt Mixtures

Asphalt binders and mixtures demonstrate nonlinear viscoelastic response due to the interaction of stresses (e.g. shear combined with compression). Asphalt mixtures experience such complex stress states in a pavement structure. This Chapter will present a constitutive model to characterize such non linear response. More specifically this chapter will present:

- a review of models that can be used to characterize nonlinear viscoelastic response,
- a constitutive model for nonlinear response of asphaltic materials that accounts of interaction effects between shear and tension or compression,
- a method to obtain the parameters for this constitutive model, and
- data and numerical examples that demonstrate the significance of accounting for these interaction effects in characterizing asphalt materials.

Appendix 1: Procedure to measure intrinsic healing in asphalt binders using a DSR

Appendix 2: Procedure to measure overall healing in asphalt mixtures based on viscoelastic continuum damage theory

Appendix 3: Procedure to quantify and model interaction effects in asphalt binders and composites

Appendix 4: Controlled Strain Repeated Direct Tensile Testing (RDT) to measure fatigue cracking potential and creep and step loading recovery testing to characterize healing

Appendix 5: Viscoelastic and fracture properties with respect to time and depth in field-aged and laboratory asphalt specimens

REPORT C
PANDA: Pavement Analysis using a Nonlinear Damage Approach

Preliminary Draft of Table of Contents

REPORT D
CHARACTERIZATION OF ASPHALT BINDERS USING ATOMIC FORCE MICROSCOPY

SCOPE

This report will present seven primary objectives of the AFM asphalt binder characterization method under the Fundamental Properties contract. The objectives are:

i. Identify the phase microstructural and micromechanical properties of three different SHRP asphalt binders using Atomic Force Microscopy (AFM) imaging and nano-indentation.
ii. Evaluate the effects of aging on asphalt binder micro-rheology.
iii. Determine composite viscoelastic properties and investigate differences between AFM composite properties and macro-scale elastic and viscoelastic properties.
iv. Link physical properties of AFM phases to chemical properties and determine how the relationship is influenced by aging.
v. Present the application of AFM imaging, nanoindentation, and chemical mapping of asphalt binder as a potential method to understand and modify weaknesses amongst phase interfaces while improving the fatigue and fatigue healing characteristics of asphalt binders.
vi. Calibrate closed form solutions data using the finite element method (FEM) to calculate indentation response. Explain what assumptions the closed form solutions are based on and how the finite element model is used to make corrections.
vii. Simulate AFM indentation using various constitutive models such as elasticity, plasticity, viscoelasticity, and viscoplasticity and compare the results to experimental AFM data. Explain which constitutive model is the most accurate at describing actual mechanical response of the asphalt binder.

OUTLINE

Chapter 1: Asphalt Binder Phase Micro-rheology and the Effects of Aging

This chapter describes the characterization of micromechanical properties of various structural components in asphalt binder using AFM and describes the observed changes in microstructure and micromechanical behavior due to oxidative aging of the asphalt binders. More specifically, this chapter will cover:

- The distinctive phase distribution of each asphalt microstructure
- The material behavior of the different phases under constant load
- Age-induced microstructural changes related to phase structure, phase distribution, and physical properties
- Test methods by which these properties can be measured

Chapter 2: The use of AFM Nanoindentation to Determine Composite Viscoelastic Properties

A unique combination of AFM imaging and nanoindentation is used to determine the viscoelastic Young's moduli of bi-modal and tri-modal distributions of asphalt microphases in order to assess differences between macro-scale and composite nano-scale viscoelastic behavior. More specifically, this chapter will cover:

- The geometry and contact mechanics of an AFM indentation test.
- Elastic and viscoelastic Young's modulus of individual asphalt phases.
- Comparison of composite elastic and viscoelastic Young's modulus to values at larger length scales.
- The analytical methods to determine composite viscoelastic properties from AFM creep data of asphalt binder microphases.

Chapter 3: Associations between Asphalt Chemical Composition and Asphalt Micromechanical Properties

The focus of future work will be to link physical properties of AFM phases to chemical properties and determine how the relationship is influenced by aging. This chapter will present:

- Findings of chemical mapping of asphalt binders using soft x-ray beamline testing and testing with functionalized AFM tips
- Relationships amongst the measured physical properties of asphalt phases and the chemical composition
- The overall effect that these links have on the ability to modify and improve asphalt fatigue life and durability

Chapter 4: Nano-modification of Asphalt Binder using AFM

The application of AFM imaging, nanoindentation, and chemical mapping of asphalt binder will be presented as a potential method to understand and modify weaknesses amongst phase interfaces while improving the fatigue and fatigue healing characteristics of asphalt binders. This chapter will present:

- Results of fabrication and testing of synthetic asphalt binders and individually extracted asphalt components
- Links between asphalt phase microstructure and physical properties before and after modification/extraction
- Overall effectiveness of binder modification in reducing weak zones/interfaces that theoretically exist at the nano-scale

Chapter 5: Finite Element Analysis of Indentation and Comparison to Closed Form Solutions

This chapter will present various closed form solutions that are available in the literature. It will describe the assumptions that were made in order to formulate them and explain how they fail to accurate calculate indentation response in certain situations.

Furthermore, finite element analyses are also presented to show the mechanical response of the binder during an indentation test. Comparisons are then made between the closed form solutions and the finite element data. A specific list includes:

- A detailed list of all closed form solutions to analyze indentation depth based on given material property and force applied and how they were formulated.
- Various finite element simulations performed with varying tip geometry ranging from realistic geometry obtained from scanning electron microscopy images to simplified spherical and conical tip geometry.
- Explanation of sensitivity analysis performed using the finite element method to calculate a calibration factor for the closed form solutions. Modified closed form solutions are also proposed.

Chapter 6: The Effect of Different Constitutive Behavior on the Indentation Response

In this chapter finite element simulations will be presented to study the effects of various constitutive models. AFM indentation will be simulated and the response under the mentioned constitutive models will be shown and compared to measured experimental data. This chapter will cover:

- Finite element simulation of AFM indentation using different constitutive models.
- These simulated constitutive models are compared to experimental data.
- AFM images of aged samples are converted to finite element model geometry. The binder is then modeled as a composite material corresponding to the separate phases found during testing. The composite response will then be compared to that of a uniform single phased binder. Both elastic and viscoelastic composite effects are presented and are both compared to single phased constitutive response.

Appendix 1: Statistical Analysis of AFM Creep Data

Appendix 2: Procedure to measure AFM Creep of Asphalt Binders

Appendix 3: Finite element model input files and calibration factor determination procedure.

REPORT E
MULTISCALE VIRTUAL FABRICATION AND LATTICE MODELING

SCOPE

This report provides details that underlie the integrated multiscale virtual fabrication and lattice modeling (MS-VFLM) software that is aimed at linking the mastic and aggregate material properties to the fatigue properties of the mix with the help of micromechanical lattice modeling at various length scales.

OUTLINE

Chapter 1: Introduction

This chapter presents an overview of the entire multiscale virtual fabrication and lattice modeling procedures, and explains ways that the various components are brought together.

Chapter 2: Lattice Modeling

This chapter presents an overview of lattice modeling as it applies to asphalt concrete, and includes the following:

- The lattice meshing procedure via Delaunay triangulation
- Verification of the robustness of the lattice modeling procedure for homogeneous media
- Extension of the lattice modeling procedure to heterogeneous elastic media
- Incorporation of viscoelastic deformation
- The modeling of rate-dependent viscoelastic damage and fracture
- Accelerated modeling of cyclic loads via extrapolation

Chapter 3: Virtual Fabrication Procedure

This chapter presents details regarding the virtual fabrication procedure, including:

- The random generation of virtual aggregate structure using inverse stereology and geometric transformations (AIMS may be used here)
- The generation of air voids that have shapes determined by the local aggregate structure
- Verification of the robustness of the virtual fabrication procedure by comparing the properties of the virtual structures with the properties of actual microstructures

Chapter 4: Multiscale Modeling

To facilitate tractable computational modeling, the virtual fabrication and lattice modeling procedures are incorporated into a hierarchical multiscale modeling framework. This chapter discusses this multiscale modeling and includes:

- A practical scale separation methodology to reduce the computational costs while retaining engineering accuracy
- A procedure to scale up the fracture and damage parameters
- Incorporation of changing time dependency based on experimental observations
- Verification of the robustness of the scale separation algorithms

Chapter 5: Integrated Software and Validation

This chapter contains the user guide for the integrated multiscale virtual fabrication and lattice modeling (MS-VFLM) software, along with some illustrative and validation examples.

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

SCOPE

This report will address five primary objectives for the moisture damage and fatigue cracking tasks. The objectives are:

- To develop an integrated framework combining experimental testing and microstructure computational modeling for the characterization and simulation of moisture damage and cracking in asphalt mixtures;
- To develop appropriate testing protocols for determining material properties and model parameters that are used as microstructure model inputs;
- To develop cohesive zone models which are appropriate to address damage behavior related to fatigue cracking and/or moisture damage in asphalt mixtures;
- To conduct laboratory tests for model validation and calibration; and
- To examine material-specific characteristics of moisture damage and cracking, damage mechanisms and damage resistance potential of asphalt mixtures through parametric analyses of the model developed.

OUTLINE

Chapter 1: Introduction

This chapter will present:

- Problem statements to the issues of moisture damage and fatigue cracking in asphaltic pavements as primary failure modes.
- An overview of the traditional approaches and research attempts made to address the moisture damage and fatigue cracking.
- The pressing needs of new and advanced models to better understand the damage mechanisms and to better predict performance behavior of asphalt mixtures and pavement structures.

Chapter 2: Background (Literature Review)

This chapter will present:

- A comprehensive literature review on several approaches attempting to characterize the mechanical behavior related to moisture damage and fatigue cracking of asphalt mixtures, as well as advantages, limitations, and shortcomings of these approaches.
- Conventional and recent experimental testing protocols available in the literature to characterize material properties and fracture characteristics of asphalt mixtures.
- Constitutive modeling efforts by researchers to address damage and fracture behavior of bituminous mixtures and asphaltic pavements.

Chapter 3: Model Development and Formulation

This chapter will present a description of the initial boundary value problem (IBVP) for a general elastic-viscoelastic asphalt microstructure containing cracks. Then, a discussion on the formulation of the computational cohesive zone model developed for the fracture simulations due to moisture and loading is provided. Verification of the model is also presented in this chapter.

Chapter 4: Materials and Laboratory Tests

This chapter will present:

- Materials used in this research for laboratory tests.
- An experimental testing program developed through this research to identify material properties of the different mixture phases (e.g., fine aggregate matrix and aggregates).
- Laboratory test results of mixture components and their further analyses to identify material properties and fracture characteristics that are used as model inputs.
- Mixture test results that are used for model validation and calibration.

Chapter 5: Model Simulation and Discussion

This chapter will present:

- Geometric representation of mixture microstructures through image treatment.
- Model simulations of the mixture microstructures incorporated with moisture damage and fracture. The simulations are conducted with material properties obtained from laboratory tests (Chapter 4).
- Model validation, calibration, and application. Various simulations will be conducted and presented to validate and calibrate the microstructure cohesive zone model when asphalt mixtures are induced by moisture damage and fatigue fracture.

Chapter 6: Parametric Study of the Model

This chapter will present parametric analyses of microstructure modeling through model applications to various cases: different asphalt mixture microstructures subjected to different loading conditions and with varying mixture component properties. This effort will demonstrate the model capability to account for the effects of important variables (materials and/or geometric) on the overall mechanical behavior of mixtures and structures. Outcomes from this chapter will highlight the benefits of the modeling as an efficient tool for better selection of mixture components, more optimized mixture design, and clearer understanding of the role of mixture variables to the structural behavior, etc.

Chapter 7: Conclusions

In this chapter, significant outcomes and conclusions resulting from this research will be presented. Future work recommended to improve the model will also be presented.

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

Proposed Final Report Outline

1. **Introduction**
    1.1 Problem Statement
    1.2 Objectives
    1.3 Research Report Outline

2. **Literature Review**
    2.1 Current State of Practice
    2.2 Current State of Research Studies

3. **Evaluation Process of RAP Materials for Mix Design Purposes**
    3.1 Evaluation of RAP Aggregate Properties
    3.1.1 Experimental Plan
    3.1.2 Mix Design Summaries
    3.1.3 Extracted Asphalt Binder Contents
    3.1.4 Extracted Aggregate Properties
    3.1.5 Mechanical Breakdown Experiment
    3.1.6 Effect of RAP Aggregate Properties on Voids in Mineral Aggregates
    3.1.7 Findings and Conclusions
    3.2 Evaluation of RAP Binder Properties
    3.2.1 Description of Proposed Approach To Evaluate RAP Binder
    3.2.2 Experimental Plan
    3.2.3 Test Results
    3.2.4 Findings and Conclusions

4. **Compatibility of RAP and Virgin Binders**
    4.1 Background
    4.2 Description of the Proposed Method to Determine Compatibility
    4.3 Experimental Plan
    4.4 Test Results
    4.5 Findings and Conclusions

5. **Laboratory Mixing Process for HMA Mixtures Containing High RAP Materials**
    5.1 Background
    5.2 Experimental Plan
    5.3 Materials and Mix Designs
    5.4 QC/QA and Project Specific Information
    5.5 Discussion of Laboratory Processes and Testing
    5.6 Laboratory Evaluation
    5.7 Findings and Conclusions

6. **Field Trials of HMA Mixtures Containing High RAP Materials**
    - 6.1 Description of Projects
    - 6.2 Experimental Plan
    - 6.3 Pavement Sections Construction
    - 6.4 Mix Designs
    - 6.5 Laboratory Evaluation
    - 6.6 Field Performance
    - 6.7 Findings and Conclusions

7. **Impact of RAP Fractionation**
    - 7.1 State of the Practice
    - 7.2 Advantages and Disadvantages of RAP Fractionation
    - 7.3 Findings and Recommendations

8. **Mix Design System**
    - 8.1 Binder Selections
    - 8.2 Aggregate Properties
    - 8.3 Laboratory Mixing Procedure
    - 8.4 Laboratory Compaction Procedure
    - 8.5 Volumetric Mix Design Criteria
    - 8.6 Selection of Design Binder Content
    - 8.7 Evaluation of Moisture Sensitivity
    - 8.8 Evaluation of Performance Characteristics
    - 8.9 Overall Mix Design Process

9. **References**

REPORT H
CRITICALLY DESIGNED HMA MIXTURES

REPORT I
THERMAL CRACKING RESISTANT MIXES

1. **Introduction**
   - 1.1 Background
   - 1.2 Research Objective
   - 1.3 Research Report Outline

2. **Literature Review:**
   - 2.1 Test Methods for Low Temperature Characterization of Binders
   - 2.2 Test Methods for Low Temperature Characterization of Mixtures
   - 2.3 Effect of Environmental Conditions on Thermal Cracking
   - 2.4 Modeling and Prediction of Thermal Cracking

3. **Research Approach**
   - 3.1 Test Methods for Evaluating Material Properties
     - 3.1.1 Binder
       - 3.1.1.1 Single Edge Notch Beam (SENB)
       - 3.1.1.2 Glass Transition (T_g)
       - 3.1.1.3 Asphalt Binder Cracking Device (ABCD)
       - 3.1.1.4 Bending Beam Rheometer (BBR)
       - 3.1.1.5 Fourier Transform Infrared Spectroscopy (FTIR)
       - 3.1.1.6 Dynamic Shear Rheometer (DSR)
     - 3.1.2 Mastic
       - 3.1.2.1 Single Edge Notch Beam (SENB)
       - 3.1.2.2 Glass Transition (T_g)
     - 3.1.3 Mixture
       - 3.1.3.1 Glass Transition (T_g)
       - 3.1.3.2 Thermal Stress Restrained Specimen (TSRST)
       - 3.1.3.3 Dynamic Modulus
   - 3.2 Environmental Conditions
     - 3.2.1 Pavement Temperature Profiles
       - 3.2.1.1 Cooling and Warming Rates
     - 3.2.2 Aging
       - 3.2.2.1 Description of Model
       - 3.2.2.2 Input Parameters
   - 3.3 Pavement Modeling
   - 3.4 Experimental Design

4. **Pavement Temperature Rates in Hot Mix Asphalt Layers**
   - 4.1 Introduction
   - 4.2 Section Properties
   - 4.3 Analysis of Temperature Data
   - 4.4 Investigation of Cooling Rate Behavior
   - 4.5 Conclusions and Recommendations

5. **Analysis and Interpretation of Experimental Results**
    - 5.1 Effects of Oxidative Aging
        - 5.1.1 Asphalt binders Kinetics
        - 5.1.2 Impact of Mixture Characteristics on Aging
    - 5.2 Material Properties
        - 5.2.1 Binders and Mixtures Glass Transition
        - 5.2.2 Binders and Mixtures Fracture Properties
    - 5.3 Summary of Findings

6. **Pavement Modeling Approach**
    - 6.1 Assumptions
    - 6.2 Factors Considered
    - 6.3 Modeling Development
    - 6.4 Findings and Conclusions

7. **Validation of Proposed Approach**
    - 7.1 Validation sites
    - 7.2 Experimental Plan
    - 7.3 Testing and Results
    - 7.4 Pavement Modeling
    - 7.5 Validation

8. **Proposed System to Evaluate and test HMA mixture resistance to thermal cracking**
    - 8.1 Binder Properties
    - 8.2 Mixture Properties
    - 8.3 Pavement Modeling

9. **Recommendations for Implementation Efforts**

10. **References**

11. **Appendix: Standard Testing Procedures for Low Temperature Characterization of Binders and Mixtures**
    - 11.1 Single Edged Notched Bending test of Binders
    - 11.2 Measurement of Tg of binders
    - 11.3 Measurement of Tg of Mixture
    - 11.4 TSRST testing of Mixtures
    - 11.5 Standard Procedure for using prediction model

REPORT J
PAVEMENT RESPONSE MODEL TO DYNAMIC LOADS

REPORT K
DEVELOPMENT OF MATERIALS DATABASE

    - 5.4.4. Test runs
  - 5.5. Uploading support files
    - 5.5.1. Core support file data
    - 5.5.2. Support file meta data
    - 5.5.3. Links to materials and property groups
  - 5.6. Public user interface application process and approval
- **6. Public User interface**
  - 6.1. Material selection
  - 6.2. Measure browser
  - 6.3. File downloader
  - 6.4. Material tests
  - 6.5. Validation sites
- **7. Help System**
  - 7.1. Functional documentation
  - 7.2. Database documentation
  - 7.3. Administrative and support documentation
- **8. Deployment plan**
  - 8.1. Hardware requirements to run the database and ARC application
    - 8.1.1. Server configuration
    - 8.1.2. Database configuration
    - 8.1.3. IIS configuration
    - 8.1.4. ARC configuration settings
  - 8.2. Administrative processes to host the ARC application and database
    - 8.2.1. Backup and restore procedures
- **9. Proposed improvements**
  - 9.1. Graphical view of validation sites
  - 9.2. Generalized data import facility
  - 9.3. Usage tracking
    - 9.3.1. Public user downloads
    - 9.3.2. Public user queries
    - 9.3.3. Save user queries
    - 9.3.4. Generalized data import facility
    - 9.3.5. Maintenance and general improvements

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

1. **Introduction** (*From JM and RM theses*)
2. **Background** *(From JM and RM theses)*
    - 2.1. Adhesion
    - 2.2. Asphalt-Aggregate Adhesion Mechanisms
    - 2.3. Factors Influencing Adhesive Bond Between Asphalt and Aggregate
3. **Development of the Bitumen Bond Strength Test (BBS)** (From JM and RM theses)
    - 3.1. Materials
    - 3.2. Experimental Design
    - 3.3. Sample Preparation
    - 3.4. Aggregate Plate Preparation
    - 3.5. Asphalt Sample Preparation
    - 3.6. Testing Procedure
4. **Analysis of BBS Experimental Results**
    - 4.1. Effect of Conditioning Time (From JM and RM Theses)
    - 4.2. Effect of Asphalt Modification (From JM and RM Theses)
    - 4.3. Effect of Aggregate Type (From JM and RM Theses)
    - 4.4. Effect of Conditioning Media (From JM Thesis)
    - 4.5. Effect of Testing Temperature and Rate of Loading (From JM Thesis)
    - 4.6. Statistical Analysis of Results (From JM and RM Theses)
    - 4.7. Reproducibility of the BBS Test (From TRB 2011 BBS paper)
5. **Validation Efforts for the Bitumen Bond Strength (BBS) Test**
    - 5.1. Comparison between Modified Dynamic Shear Rheometer (DSR) and BBS test for Moisture Damage Characterization (From TRB 2011 BBS paper)
    - 5.2. Comparison between BBS Results and Contact Angle (From RM thesis)
    - 5.3. Comparison between BBS Results and Surface Energy Measurements (From BBS AAPT 2012 paper and RM thesis)
        - i. BBS vs. Work of Cohesion
        - ii. BBS vs. Work of Debonding
    - 5.4. Comparison between Moisture Damage Mixture Testing (TSR) and BBS Test (From RM thesis)
6. **Conclusions and Recommendations**
    - 6.1. Summary (From JM and RM thesis and TRB 2011 and AAPT 2012 BBS papers)
    - 6.2. Conclusions and Recommendations (From JM and RM thesis and TRB 2011 and AAPT 2012 BBS papers)
7. **Appendix**
    - 7.1 Bitumen Bond Strength (BBS) AASHTO Standard

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

1. **Introduction** (*From CJ thesis, LAS TRB and AAPT 2011 papers and Healing TRB 2012 paper*)
2. **Background** *(From CJ Thesis and Healing TRB 2012 paper)*
    - 2.1. Damage in Viscoelastic Materials
        - i. Molecular Structure and Effect on Mechanical Response
        - ii. Definition of Damage and Design Considerations
    - 2.2. Asphalt Pavement Fatigue
    - 2.3. Use of Viscoelastic Continuum Damage Theory for Asphalt Fatigue Characterization
    - 2.4. Current Research & Practice for Asphalt Binder Fatigue Characterization
        - i. Current Performance-Based Specification for Asphalt Binder Fatigue
        - ii. National Cooperative Highway Research Program Project 9-10
    - 2.5. Current Research & Practice for Asphalt Binder Healing Characterization Using Cyclic Loading with Rest Periods
3. **Development of the Binder Yield Energy Test (BYET) for Binder Fatigue Characterization** (From AAPT 2009 paper and CJ thesis)
    - 3.1. Test Development
    - 3.2. Analysis Methods
    - 3.3. Materials
    - 3.4. Analysis of Results
4. **Development of the Linear Amplitude Sweep Test (LAS) for Binder Fatigue Characterization** (From CJ thesis and LAS 2011 TRB paper)
    - 4.1. Test Procedure
        - i. Amplitude Sweep
        - ii. Frequency Sweep
        - iii. Stress Relaxation Test
    - 4.2. Experimental Plan
    - 4.3. Results and Analysis
        - i. Linear Amplitude Sweep Results
        - ii. Stress Relaxation Test Results
        - iii. Damage Analysis
        - iv. A simplified Method to Determine Alpha
        - v. Sensitivity of Fatigue Life to Alpha
        - vi. Repeatability of the Linear Amplitude Sweep
        - vii. Investigation of a Stress-Controlled Linear Amplitude Sweep Test
    - 4.4. Simplified Method for Calculation of VECD Damage Curve Coefficients (From LAS 2011 TRB paper)
    - 4.5. Modification of Amplitude Sweep Loading (From LAS 2011 TRB paper)
    - 4.6. Effect of Normal Stresses (From MARC Memo to AB)

5. **Validation Efforts for the Linear Amplitude Sweep Test**
    - 5.1. Comparison of Binder LAS results with Transportation Pooled Fund Study 5(146) (From CJ thesis)
    - 5.2. Comparison of Linear Amplitude Sweep Results with Accelerated Pavement Testing (From CJ thesis)
    - 5.3. Comparison of Binder LAS Results with Long Term Pavement Performance (LTPP) Program Cracking Data (From LTPP-LAS paper TRB 2012)
    - 5.4. Comparison of LAS results with NCHRP 9-45
6. **Binder Fatigue Studies Using the Linear Amplitude Sweep**
    - 6.1. Effect of Modification (From CC thesis)
    - 6.2. Effect of Aging (From LAS AAPT 2011 paper)
    - 6.3. Effect of Filler (From 2011 ICPT paper)
7. **Characterization of Asphalt Binder Healing Using the Dynamic Shear Rheometer (DSR)** (From Healing 2012 TRB paper and AS thesis)
    - 7.1. Development of the Test Procedure
        - i. Strain-Controlled Time Sweep with Short Loading Times and many Rest Periods
        - ii. Modified Time Sweep with Short Loading and many Rest Periods
        - iii. Time Sweep with a Single Rest Period
    - 7.2. Experimental Plan
    - 7.3. Results and Analysis
        - i. Typical Results
        - ii. Effect of Oxidative Aging on Healing
        - iii. Effect of Damage Level Prior to Rest Period and Rest Period Duration on Healing
        - iv. Effect of Healing on the Relationship Between Strain and Fatigue Life
        - v. Effect of a Single 30 minute Rest Period on Fatigue Life
        - vi. Effect of Rest Period Duration on Fatigue Law
        - vii. Effect of Number of Rest Periods on Fatigue Law
8. **Conclusions and Recommendations**
    - 8.1. Summary (From CJ and AS Theses and TRB and AAPT 2011 papers on LAS)
    - 8.2. Conclusions and Recommendations (From CJ and AS Theses and TRB and AAPT 2011 papers on LAS)
9. **Appendix**
    - 9.1. Binder Yield Energy Test (BYET) Draft AASHTO Standard
    - 9.2. Linear Amplitude Sweep Test (LAS) Draft AASHTO Standard

REPORT N
GUIDELINE FOR SELECTION OF MODIFICATION TECHNIQUES
(The final report will be written in the form of a guideline.)

1. **Literature review (CC TRB 2012, HT AAPT 2011, CH AAPT 2011)**
   a. Types of modification used for asphalt
   b. Testing Methods for Characterization of Modified Binders: DSR, SENB, BBR
   c. Challenges and issues of binder modification: Compatibility, cost, storage, etc.
2. **Scope of Guideline (CC TRB 2012, HT AAPT 2011, CH AAPT 2011)**
   a. Materials Covered (polymer, acid, synthetic, bio-binders, extenders, etc.)
   b. Experimental methods: DSR, SENB, BBR, BYET, MSCR, LAS, Tg, Frequency sweep
   c. Mixture validation tests: FENIX (Low temperature), EBADE (amplitude sweep) (From Spanish report)
   d. Economic Analysis
3. **Effect of Modification Techniques on Pavement Performance (CC TRB 2012, HT AAPT 2011, CH AAPT 2011)**
   a. Analysis of effect of modification on high temperature performance
   b. Analysis of effect of modification on Intermediate temperature performance
   c. Analysis of effect of modification on low temperature performance
   d. Analysis of effect of modification on binder adhesion and moisture susceptibility
   e. Analysis of effect of modification on mixing, compaction and construction through workability and storage stability
4. **Modifier Classification and Ranking Model**
   a. Modifier Classification system
   b. Modifier Performance Ranking System
   c. Modification economic index
5. **Asphalt Modification Selection**
   a. Guidelines for selection of modifier type and level of modification
   b. Guideline for mix design and production procedures adjustments through use of modifiers
   c. Guideline for analysis of economics of binder modification
6. **Conclusions and Recommendations**
   a. Summary
   b. Conclusions
   c. Recommendations and Implementation efforts

REPORT O
CHARACTERIZATION OF BINDER DAMAGE RESISTANCE TO RUTTING

1. **Introduction** (*From AG and AC thesis*)
2. **Literature review**
   2.1. Rutting of modified asphalts: differences between elastomeric and plastomeric modification (*From AG Thesis*)
   2.2. Modeling Rutting of Asphalt Binders, Mastics, and Mixtures (*From RD and AG Theses*)
   2.3. Testing Methods for Rutting Resistance Characterization of Binders and Mastics: MSCR, RCR, Indentation (*From AM and AG Theses*)
   2.4. Testing Methods for Rutting Resistance Characterization of Mixtures: Flow Number and aggregate structure characterization (*From AC and NR Theses, NR AAPT 2012 paper*)
   2.5. Characterization of internal aggregate structure by means of Digital Imaging Analysis and it relation to rutting performance (*From AC Thesis and NR AAPT 2012 paper*)
3. **Research Methodology and Experimental Matrix**
   3.1. Materials: Binders, Mastics, and Mixtures (*From AG, AC , AM, and NR Theses*)
   3.2. Experimental design
      i. Binder: MSCR, RCR, Indentation (*From AM and AG Theses*)
      ii. Mastic: MSCR and RCR (*From AG Thesis*)
      iii. Mixture: Flow Number and Image Analysis (*From AC and NR Thesis*)
4. **Analysis and Interpretation of Experimental Results**
   4.1. Relationship between permanent deformation in Binders, Mastics, and Mixtures (*From AG Thesis*)
   4.2. Comparison of permanent deformation in binders modified with elastomers and plastomers (*From AG Thesis*)
   4.3. Effect of elastomeric and plastomeric modification on rutting performance of mixtures (*From AG Thesis*)
   4.4. Using indentation as simple method for rutting characterization of asphalt binders (*From AM Thesis*)
   4.5. The influence of the internal structure of asphalt mixtures to rutting performance (*From AC and NR Theses*)
5. **Standard Testing Procedure for Rutting Characterization of Binders**
   5.1. Effect of Jnr and %R of asphalt binder on mixture performance. (*From AG Thesis*)
   5.2. Effect of stress level and temperature on rutting of binders and mixtures (*From AG Thesis*)
   5.3. Inter-laboratory variability analysis of Jnr and %R based on WCTG database (From CTAA 2012 paper and WCTG presentations)
6. **Conclusions and Recommendations**
   6.1. Summary (*From AG, AC, NR, and AM Theses*)
   6.2. Conclusions and Recommendations (*From AG, AC, NR, and AM Theses*)

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

1. **Introduction** *(Sources: AH PhD thesis; AH TRB 2011; AH AAPT 2011; AH TRB 2010)*
    - 1.1. Identify the potential benefits of WMA in terms of energy and environmental savings.
    - 1.2. Establish the use of WMA and how it has grown in the past five years.
    - 1.3. Introduce challenges associated with development of specifications for WMA.
    - 1.4. Define research objectives and experimental framework.
    - 1.5. Research Methodology
2. **Literature Review** *(Sources: AH PhD thesis; UNR input)*
    - 2.1. WMA additive types, range of concentrations, and manufacturer recommended production temperatures.
    - 2.2. Effects of WMA on workability:
        - i. Asphalt Binder: Viscosity, Lubricity, DSR- Phase Angle
        - ii. Asphalt Mixture:
            1. Methods of measurement:
                - a. Tests on Loose Mix – Nynas workability tester, asphalt workability device.
                - b. Compaction Tests – SGC, Marshall, Slab Compaction.
            2. Summary of mix properties that influence workability and establishing sensitivity to compaction temperature observed for HMA and WMA.
    - 2.3. Effects of WMA on performance:
        - i. Asphalt Binder
            1. Establish effects of WMA additive type and concentration, and aging temperature.
            2. Previous methods used to integrate aging susceptibility into evaluation of binder properties.
        - ii. Asphalt Mixture
            1. Define critical properties and published effects of WMA type, WMA concentration, and aging temperature.
    - 2.4. Potential Impact of WMA on Reduction of Energy Consumption and Emissions
3. **Experimental Design** (Sources: AH PhD thesis; PT M.S. thesis; UNR input)
    - 3.1. Materials Selection: Aggregates, gradations, WMA additives, asphalt binders.
    - 3.2. Experimental Matrix and Summary of Test Methods and Conditions:
        - i. Asphalt Binder and Mixture Workability
        - ii. Asphalt Binder and Mixture Performance

4. **Results and Analysis** *(Sources: AH PhD thesis; PT M.S. thesis)*
    - 4.1. Construction Properties – Workability and Coating
        - i. Development of the Asphalt Lubricity Test
        - ii. Definition of Production Temperature Ranges for WMA Additives
        - iii. Modeling of mixture workability - Identification of Factors that Influence Mixture Workability and their relative significance.
    - 4.2. Performance Properties
        - i. Development of a Thin Film aging method to simulate mix oxidation.
        - ii. Impact of reduced asphalt binder aging and WMA additives on performance properties and relationship to mix properties.
            1. MSCR and FN
            2. LAS Test and Mix IDT
            3. SENB and TSRST
        - iii. Impact of WMA moisture susceptibility
            4. Effect of reduced temperatures on development of adhesion – BBS Test
            5. Mixture Performance
                - a. Effect of reduced temperatures: TSR and E*Ratio
                - b. Effect of internal aggregate moisture: E* Ratio
5. **Development of Procedures and Specifications** (Sources: AH PhD thesis; PT M.S. thesis; AH AAPT 2012; PT TRB 2012; AH TRB 2011; AH AAPT 2011)
    - 5.1. Guideline for Determination of Acceptable WMA Production Temperatures
    - 5.2. Evaluation of WMA Mix Design Guideline
    - 5.3. Development of WMA Performance Tests for Design Specification
    - 5.4. Development of WMA Mix Design Adjustment Methods
6. **Recommendations** (Sources: AH PhD thesis; PT M.S. thesis; UNR input)
    - 6.1. Constructability
        - i. Mix Design. Definition of critical mix and binder properties to ensure workability.
    - 6.2. Performance
        - i. Relative impacts of reduced production temperatures on rutting resistance and durability.
        - ii. Proposed procedure for identification of when adjustment of PG grade is necessary to ensure performance.
    - 6.3. Practical Applications
        - i. Benefits: Reduced emissions/energy, increased workability, increased durability, reduced asphalt content.
        - ii. Costs: Additive costs, short-term performance, equipment modifications, increased moisture damage.

REPORT Q

IMPROVEMENT OF EMULSION CHARACTERIZATION AND MIXTURE DESIGN FOR COLD BITUMEN APPLICATIONS

1. **Introduction and Research *Objectives*** *(Sources: PJ M.S. thesis, PJ AAPT 2012, TM TRB 2010, AH TRB 2010)*
    - 1.1. Review of emulsion characterization related to spray application
    - 1.2. Construction properties
    - 1.3. Residue recovery methods
    - 1.4. Residue performance properties
    - 1.5. Chip seal performance characteristics (Sweep Test)
    - 1.6. Review of emulsion characterization related to mix application
    - 1.7. Cold in place recycling (CIR)
    - 1.8. Cold mix asphalt (CMA); design & performance evaluation

2. **Literature and Standards Review** *(Sources: PJ M.S. thesis, PJ AAPT 2012, TM TRB 2010, AH TRB 2010, UNR input)*
    - 2.1. Current Emulsion Specification & Test Methods
    - 2.2. Spray Applications of Emulsions
    - 2.3. Mixture Applications of Emulsions

3. **Development and Identification of Associated Test Methods & Experimental Plan** *(Sources: PJ M.S. thesis, TM M.S. thesis, PJ AAPT 2012, TM TRB 2010, AH TRB 2010a-b, UNR input)*
    - 3.1. Tests on asphalt emulsions
        - i. Tests on Constructability Parameters
            1. Bitumen Bond Strength (BBS)
            2. Sweep Test (ASTM D 7000)
            3. Rotational Viscometer
        - ii. Tests on Emulsion Residues
            1. Low, Intermediate, and High Temperature Properties
    - 3.2. Test Methods for Asphalt Emulsion Mixes
        - i. CMA
            1. Aggregate Gradation and Emulsion Selection Guidelines
            2. Procedure for Evaluating Aggregate Coating
            3. Procedure for CMA Sample Preparation and Compaction
            4. Test Method to Evaluate Workability
            5. Evaluation of CMA Curing Properties
            6. Mechanical Testing of CMA Mixtures & Optimum Emulsion

- ii. CIR
  - 1. Selection of emulsion for CIR (Cold In-place Recycling)based on coating
  - 2. Selection of emulsion for CIR based on workability
- 3.3.Research Plan
  - i. Materials and Methods

4. **Analysis and Validation of Experimental Plan** *(Sources: PJ M.S. thesis, TM M.S. thesis, PJ AAPT 2012, TM TRB 2010, AH TRB 2010a-b, UNR input)*
   - 4.1.Test Methods for Asphalt Emulsions and Spray Applications of Asphalt Emulsions
     - i. Emulsion Residue Recovery Methods
     - ii. Tests on Fresh Emulsion Properties
       - 4. BBS Test Results
       - 5. Sweep Test Results
       - 6. Rotational Viscometer
     - iii. Tests on Emulsion Residue Properties
     - iv. Development of guideline for Emulsion performance grading
   - 4.2.Test Methods for CMA Mixes
     - i. Review and Proposal of Mix Design Methods
     - ii. Development and Validation of CMA Performance Guidelines
   - 4.3.Test Methods for CIR Mixes
     - i. Mixing/coating
     - ii. Compaction/air-voids
     - iii. Early raveling
     - iv. Early stability
     - v. Moisture sensitivity
     - vi. Fatigue cracking – (long-term property)
     - vii. Thermal cracking – (long-term property)
5. **Conclusions and Recommendations**
   - 5.1.Asphalt Emulsions and Spray Applications of Asphalt Emulsions
   - 5.2.Applications of Asphalt Emulsions for CMA
   - 5.3.Applications of Asphalt Emulsions for CIR
6. **Appendices**
   - 6.1.AASHTO BBS Standard
   - 6.2.ASTM Sweep Test Standard
   - 6.3.Emulsion Performance Grading Specification
   - 6.4.CMA Mix Design Criteria
   - 6.5.CIR Mix Design Criteria

REPORT R

STUDIES ON TIRE-PAVEMENT NOISE AND SKID RESPONSE

1. **Introduction** (From TM Thesis)
    - 1.1. Establish significance of the research: why we are concerned with friction and noise.
    - 1.2. Description of complexities of tire-pavement interaction.
    - 1.3. Implications of having pavement with good frictional characteristics.
    - 1.4. Implications of having pavements with good noise characteristics.

2. **Literature review** (From NCHRP Report 01-43: "Guide for Pavement Friction" and TM thesis)
    - 2.1. Friction and noise characteristics and guidelines
        - i. Friction background: description of texture spectrum, with a focus on micro-texture and macro-texture.
        - ii. Noise background: mechanisms for noise generation and how mix design influences noise.
    - 2.2. Discussion of existing test methods, protocols, etc. for evaluating pavement friction.
        - i. Field methods: DFT, CTM, BPT, SLP, skid trailers, sand patch
        - ii. Lab methods: SLP, BPT, others.
    - 2.3. Discussion of existing test methods, protocols, etc. for evaluating pavement noise.
        - i. Field methods: close proximity method (CPX), others
        - ii. Lab methods: Kundt tube

3. **Testing Methods** (From TM thesis and ISO 13473 Parts 3, 4 and 5)
    - 3.1. Theoretical background of pavement profile analysis
        - i. Introduction to profile acquisition and signal processing
    - 3.2. Development of SLP analysis method and texture indicators
        - i. UW procedure for SLP analysis
        - ii. Description of Fourier transform outputs and related texture indicators
    - 3.3. Description of sample set and design of experiment
        - i. Field: WHRP samples, local field test sections
        - ii. Lab: WHRP samples, V3a samples, ARC samples, contractor loose mix samples
    - 3.4. Application of texture parameters to friction
        - i. Appropriate texture indicator for friction analysis
    - 3.5. Application of texture parameters to noise
        - i. Appropriate texture indicator for noise analysis

4. **Results and Analysis**
    - 4.1. Macro-texture analysis (From TM thesis and TRB 2012 paper)

        i. Comparison of sand patch, circular track meter to stationary laser profilometer macro-texture indicators.
        ii. Applicability of texture indicators to friction.
    4.2. Micro-texture analysis (From TM thesis and TRB 2012 paper)
        i. Comparison of British Pendulum, dynamic friction tester to stationary laser profilometer micro-texture indicators.
        ii. Applicability of texture indicators to noise.
    4.3. Noise analysis (From TM thesis and TRB 2012 paper)
    4.4. Mix design guidelines (From TM thesis and TRB 2012 paper)
        i. Significant factors affecting friction and noise based on statistical analyses.
        ii. Appropriate mix design models.
        iii. Implications for specifications.

5. **Conclusions and Recommendations**
    5.1. Combination of SLP and BPT provides a means to evaluate friction and noise in a laboratory setting.
    5.2. Method will allow for prediction of field characteristics based on laboratory evaluation of mix design.
    5.3. SLP can replace CTM
    5.4. SLP/BPT can replace DFT

6. **Appendix**
    6.1. SLP Draft Procedure
    6.2. Statistical Analyses