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Asphalt Research Consortium

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RESEARCH PLAN FOR YEAR 5 OF FEDERAL HIGHWAY ADMINISTRATION CONTRACT DTFH61-07-H-00009 "ASPHALT RESEARCH CONSORTIUM"

INTRODUCTION

This document is the proposed Research Plan for Year 5 of the Federal Highway Administration (FHWA) Contract DTFH61-07-H-00009, the Asphalt Research Consortium (ARC). The Consortium is coordinated by Western Research Institute with partners Texas A&M University, the University of Wisconsin-Madison, the University of Nevada Reno, and Advanced Asphalt Technologies.

The Year 5 Work Plans continue the research that was extensively detailed in the Year 2 and Year 3 Work Plans and are grouped into seven areas, Moisture Damage, Fatigue, Engineered Paving Materials, Vehicle-Pavement Interaction, Validation, Technology Development, and Technology Transfer.

A considerable amount of the background information for the Year 5 Work Plan is contained in the Work Plans from Years 2, 3, 4, and Quarterly Reports, and associated documents on the website, www.ARC.unr.edu. The Year 5 Work Plan is strongly focused on delivering the products that have been identified through the research effort thus far. There is also continuing work in some areas that we believe still hold promise for research products.

PROGRAM AREA: MOISTURE DAMAGE

CATEGORY M1: ADHESION

Work Element M1a: Affinity of Asphalt to Aggregate (UWM)

Major Findings and Status

In Year 4, the Bitumen Bond Strength Test (BBS) used to evaluate bonding between emulsions and aggregate was also utilized to study the moisture susceptibility of asphalt-aggregate systems for hot binders. A test matrix, which included different binders, modifications and aggregate types, to account for different chemical and physical conditions in the aggregate-asphalt interface was completed. The research team obtained promising results regarding characterization of asphalt-aggregate interface by means of a simple-to-perform BBS test. The conditioning of specimens in water has caused a significant reduction in the bond strength and has also changed the failure mode (i.e., cohesive to adhesive) regardless of the selected asphalt binder or aggregate type. It was observed that the bond strength between asphalt and aggregate under wet conditions is highly dependent on modification type and conditioning time. Polymers are found to improve the adhesion between the asphalt and aggregate as well as the cohesion within the binder. Also, limestone aggregate shown to have higher adhesive bond to asphalts than granite and, thus, more resistance to adhesive failure.

The reproducibility (i.e., operator variability) of the BBS test was evaluated. Statistical analyses indicated that, generally, the BBS test is not sensitive to the operator performing the test. It was observed that the test is repeatable and applicable to quantify the bonding between asphalt and aggregate under moist conditions. The research team conducted a validation/verification effort by conducting limited Dynamic Shear Rheometer (DSR) strain sweep tests on aggregate disks. The comparison between the BBS test results and the modified DSR strain sweep test showed that the BBS test can rank asphalt-aggregate systems with respect to moisture damage similarly to the more sophisticated, and time consuming, DSR test. A draft of AASHTO standard for the Bitumen Bond Strength (BBS) test that covers the moisture damage was submitted for final approval by AASHTO.

In an effort to understand the mechanisms of adhesion between asphalt and aggregate based on surface energy measurements. The team explored the use of the Sessile Drop Method to measure contact angle of asphalt binders and aggregates. Measurements of the contact angle at the surface of the binders and aggregates with three different liquids with known surface energy can be used to estimate surface energy. Furthermore, contact angle is an indication of the potential wettability of a liquid (i.e., drop) in a surface (e.g., binder or aggregate). The lower the contact angle, the better the wettability of the liquid of that surface. Sessile Drop measurements with distilled water indicated that neat binders have a significantly different contact angle compared to modified asphalts. Furthermore, it was observed that the addition of Polyphosphoric Acid (PPA) increased the potential for wettability of the binders. Contact angle measurements for the aggregate indicated their hydrophilic (e.g., limestone) and hydrophobic (e.g., granite) nature.

In Year 4, the research team decided to combine the work elements M1a, Affinity of Asphalt to Aggregate, and M2c (Measuring Thin Film Cohesion and Adhesion Using the PATTI Test and the DSR) due to their similarities and overlapping objectives. All the research activities in work element M2c are included in the work plan and results will be part of reports for M1a.

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

Significant time was spent using the AFM (Atomic Force Microscopy) to estimate surface energy. The complications of the AFM and the cost of using it were so high that a different approach was investigated. The sessile drop measurements are found to be simple and practical enough to conduct. To reflect actual progress of this work element the Year 5 and 5-year Gantt charts have been updated to indicate extended work planned for subtasks M1a-3, M1a-4, and M1a-6.

Year Five Work Plan

Subtask M1a-1: Select materials

The work for this subtask was completed in Year 2.

Subtask M1a-2: Conduct PATTI and modified DSR tests

The work for this subtask was completed in Year 4.

Subtask M1a-3: Evaluate the moisture damage of asphalt mixtures

The asphalt binders tested in M1a-2 will be used to prepare mixture specimens for moisture susceptibility testing using the Tensile Strength Ratio (TSR) procedure. Table M1a.1 shows the materials for mixture testing. The results obtained with the TSR procedure will be compared to the BBS asphalt binder results.

Table M1a.1. Moisture damage testing of asphalt mixtures.

Testing technique	Tensile Strength Ratio (TSR)
Aggregates	Granite and limestone
Binders	FH 64-22, FH 64-22 + Styrene-Butadiene-Styrene (SBS), FH 64-22 + PPA, FH 64-22+Elvaloy

Subtask M1a-4: Correlate moisture damage between PATTI, DSR and mix tests

The research team will correlate moisture susceptibility performance obtained from the BBS test with those from mixture testing using the TSR. Also, efforts will focus on the estimation of surface energy for both binders and aggregates indirectly with the contact angle measurements (table M1a.2). Four different liquids with known surface energy will be used to estimate free surface energy. These measurements will be then compared with experimental results from the BBS test to determine if the BBS procedure can be used as a surrogate test for surface energy measurements and if it can be a good predictor of TSR values.

Table M1a.2. Test matrix for contact angle measurements using Sessile Drop.

Liquids with known surface energy	Water, glycerol, formamide, ethylene glycol
Mineral Surfaces	Granite, limestone, and diabase
Asphalt Binders	CRM 58-28, CRM 58-28 + 2% SBS, CRM 58-28 + 1% PPA, FH 64-22, FH 64-22 + ELVALOY, FH 64-22 + 1% PPA

Subtask M1a-5: Propose a novel testing protocol

The work for this subtask was completed in Year 4.

Subtask M1a-6: Standard testing procedure and recommendation for specifications

An AASHTO standard for the Bitumen Bond Strength Test was submitted for review in Year 4. In Year 5, transportation agencies and consulting laboratories will be contacted to collect feedback about the BBS test and its merits for standardization. Presentations at the Binder ETGs and TRB will be prepared to collect feedback from experts. Based on the database of BBS results collected in Year 4 and validation efforts in Year 5, guidelines for the specification acceptance criteria based on BBS results to ensure proper resistance to moisture damage will be proposed.

Table for Decision Points and Deliverables

Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
Draft Report		03/31/11	N/A	N/A
Final Report		06/30/11	N/A	N/A

Work Element M1b: Work of Adhesion Based on Surface Energy

Subtask M1b-1: Surface Free Energy and Micro-Calorimeter Based Measurements for Work of Adhesion (TAMU)

Major Findings & Status

The main goal of this subtask is to provide material property inputs required in other work elements. The data obtained from this subtask is being compiled in the materials property database.

Year Five Work Plan

The plan for year five is to utilize the available test methods to measure surface properties of materials that have been included in the test plan. The information generated from this sub-task will serve as an input for other subtasks on materials characterization and modeling.

Table for Decision Points and Deliverables

Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
Journal paper	A method to use the micro calorimeter to measure total adhesion including the influence of chemical interactions and specific surface area.	9/30/09	Complete	N/A

Subtask M1b-2: Work of Adhesion at Nano-Scale using AFM (WRI)

Major Findings & Status

The detailed work plan for this subtask is presented in the Year 3 ARC Work Plan.

Year Five Work Plan (*Continuation*)

Sub-Subtask M1b-2.1: Selection of neat asphalt samples which vary based on compatibility and wax content (SHRP asphalt, validation site asphalts, Accelerated Loading Facility Site asphalts, etc.). Preparation of aged asphalt samples employing RTFO-PAV methodologies.

Sub-Subtask M1b-2.2: Preparation of neat and aged asphalt thin-films that vary as a function of film thickness which range in thickness between 100-nm to 1000-nm prepared as solvent spin coated samples.

Sub-Subtask M1b-2.3: Conduct contact mechanic measurements as a function of load, rate of contact and sample temperature on asphalt thin films.

Sub-Subtask M1b-2.4: Conduct surface roughness and frictional imaging analyses of selected course and fine aggregate materials

Table for Decision Points and Deliverables

Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
Test Method	A method to determine surface roughness of aggregate and fines based on AFM	12/30/11		N/A

Subtask M1b-3: Identify Mechanisms of Competition between Water and Organic Molecules for Aggregate Surface (TAMU)

Major Findings and Status

Physical and chemical properties of aggregates at the macro and molecular scale influence the performance of asphalt mixes. These properties control the nature and durability of the bond between aggregates and asphalt in wet and dry conditions and its resistance to moisture induced damage and fatigue cracking. Recent research by Little and colleagues have shown that surface energy of the aggregate-asphalt interface is a reliable predictor of engineering properties of the asphalt mixture. Current understanding of the aggregate and bitumen properties that control and shape surface energy is limited, limiting our ability to *a priori* predict surface energy of any given aggregate-asphalt combination.

Surface energy of natural substances can be divided into two major components: van der Waals and polar forces. Van der Waals forces are present in all molecules to varying degrees. Polar forces are found where electron donor/electron acceptor interactions take place. The ability to predict the magnitude of these components (and subcomponents) is valuable in understanding species behaviour. Surface energy is controlled by three master variables: surface chemistry, surface morphology, and surface coatings. Each of these has been studied on natural minerals and aggregates; however there has not yet been a comprehensive study of the surface energies of a variety of the most common minerals and aggregates. In addition there has not yet been a study of the effect of these three master variables on surface energies of natural minerals and rocks.

Our research measured the surface energy of 22 common minerals and 7 aggregates. The surface energies were broken down into van der Waals, Lewis Acid, and Lewis Base components. The samples' bulk and surface chemistries were characterized with wavelength and energy dispersive spectra (WDS & EDS) analyses on an electron microprobe and x-ray photoelectron spectroscopy (XPS). The XPS was also used to quantify the organic and inorganic coatings on the mineral and aggregates surfaces. The surface morphology was analyzed for roughness with processing software on SEM images. These data were used to predict the surface energies of aggregates based on their mineralogical content. The analyses highlighted the importance of all three variables in the type and magnitude of surface energy of natural minerals and rocks in the environment.

Year Five Work Plan

Reference year 2 and 3 work plans (M3a-1) were focused on characterizing the surface energy of a suite of minerals and aggregates. This work is completed and will be used to support the next phase of research on aggregate surfaces. In year five, we plan on using a flow- through calorimeter to characterize the influence of surface chemistry on organic-water-aggregate interactions as a function of the surface energy of the aggregate.

We have completed the design and construction of a dual-mode flow adsorption calorimeter (figure M1b-3.1). Differences in molar heats of reaction of different absorbates with the same absorbent are indicative of differences in the bonding strength of each adsorbate with the adsorbent of interest. Larger molar heats of reaction, in this case molar heat of adsorption, are usually indicative of stronger bond formation. The calorimeter will be used to determine the molar heats of reaction occurring at the mineral-solution interface using pure mineral phases (commonly found in aggregates) as adsorbents and model organic compounds (containing functional groups commonly found in asphalt binders) as adsorbates.

The dual-mode flow adsorption calorimeter is capable of operating in both injection and/or flow-through modes and is currently being tested and optimized. The sensing unit of the calorimeter is thermistor based and consists of: (i) a reference thermistor (Thermistor 1), which senses the temperature of the incoming adsorbate; (ii) a calibrating resistor, for calibrating calorimetric response to known heat input; (iii) a column, containing the adsorbent of interest; and (iv) a column thermistor (Thermistor 2), which senses the temperature of the adsorbate after interacting with the adsorbent. The difference in temperature between Thermistor 1 and 2 is amplified and recorded as a voltage output over time, with a return to baseline (or zero difference) considered to be the end of the reaction. The output is attributed to adsorbent-adsorbate interaction and can be used along with calibration data and the difference between initial adsorbate and effluent concentrations to directly determine molar heats of reaction.

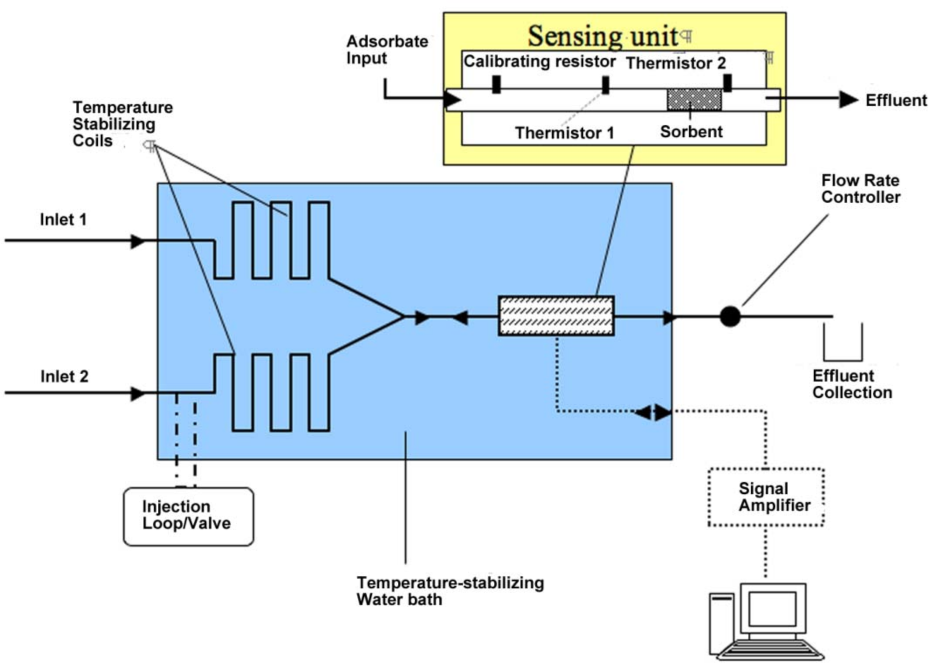

Figure M1b-3.1. Schematic of dual mode flow adsorption calorimeter.

The planned activity for year five is to develop a synthesis of mechanisms of interaction between organic functional groups commonly found in asphalt and mineral surfaces. In addition this synthesis will also identify: i) minerals that can be used to represent aggregate surfaces, as well as aggregate standards, ii) model organic compounds that can be used to represent the most common functional groups in asphalt binders, based on asphalt binder and aggregate analysis data from the Strategic Highway Research Program's (SHRP) Materials reference library, and (iii) treated aggregates with lime and binders.

For multi-mineral investigations, different pure phase minerals will be mixed in ratios typical of what is found in aggregates. Interactions between these mineral mixes and single functional groups will be investigated to determine the effect of mixed mineralogy on interaction mechanism. Interactions between the mineral mixes and solutions containing multiple organic functional groups will also be investigated. Multiple organic functional group solutions will be configured consistent with ratios commonly found in different asphalt binders. Results from these multiple-functional groups experiments will be used to determine the effect of mixed solution chemistry on organic-mineral interactions.

Experiments characterizing the molecular interactions of water, rather than organic functional groups, will also be conducted with single- as well as multi-mineral mixes. Results from these experiments will be compared to those obtained from experiments with organic functional groups in order to get a first comparative look at possible mechanisms involved in asphalt water damage.

We plan on initiating flow through experiments to measure the molar heat of reaction of the adhesion of model organic compounds that represent asphalt to minerals and aggregates, as well as the molar heats of reactions of water adsorption to organic-coated minerals and aggregates. Adhesion will be modeled in the flow-through calorimeter by organic sorption from nonaqueous phase solvents. Experimental variables include the chemistry of the model organic, single versus mixtures of model organics, ionic salt content of the nonaqueous phase solvent, and the surface chemistry of the mineral or aggregate. Competition of water and the model organics for the mineral or aggregate surfaces will be characterized through flow-through experiments that introduce small amounts of water to the systems created during the adhesion studies above.

Table for Decision Points and Deliverables

Type of Deliverable	**Description of Deliverable**	**Original Delivery Date**	**Revised Delivery Date**	**Reason for changes in delivery date**
Final Report	Final report documenting the testing protocol and findings of experiments on asphalt-aggregate interactions	10/31/10	10/31/11	Program activity delayed in order to redirect critical manpower to PANDA development
Journal paper	Journal paper on organic-aggregate interactions tying together the results of subtasks M1b-3 and M3a			

Work Element M1c: Quantifying Moisture Damage Using DMA (TAMU)

Major Findings and Status

A new method for preparing Fine Aggregate Matrix (FAM) specimens for the DMA testing was developed. Software for the analysis of DMA results and calculating the crack growth index was developed and used in the analysis of various FAM materials. The new method and results are documented in the research paper by Sousa et al. (2011).

Year Five Work Plan

Two draft methods written in AASHTO format will be transferred to Advanced Asphalt Technologies for further refinement. These methods are for preparation of DMA specimens and for the method of testing.

Cited References

Sousa, P., E. Kassem, E. Masad, and D. Little, 2010, New Design Method of Fine Aggregates Mixtures and Automated Method for Analysis of Dynamic Mechanical Characterization Data. *Paper number 11-3210, Transportation Research Board,* Washington DC.

Table for Decision Points and Deliverables

Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
AASHTO procedure and journal papers	AASHTO procedure for preparing Fine Aggregate Matrix (FAM) specimens for the DMA testing	9/31/10	Complete	N/A

CATEGORY M2: COHESION

Work Element M2a: Work of Cohesion Based on Surface Energy

Subtask M2a-1: Methods to Determine Surface Free Energy of Saturated Asphalt Binders (TAMU)

Major Findings & Status

The objective of this subtask was to determine the work of cohesion (based on surface free energy) for asphalt binders that were saturated with moisture. Although the task was planned for year 5 start, researchers believe that other products and deliverables (e.g., development of PANDA) will benefit by redirecting resources from this subtask. In addition, the required material properties such as the work of cohesion will be obtained through mechanical tests in other tasks such as Work Element F1a.

Year Five Work Plan

The objectives of this subtask will be accomplished through other subtasks and methods.

Subtask M2a-2: Work of Cohesion at Nano-Scale using AFM (WRI)

Major Findings & Status

The detailed work plan for this subtask is presented in the Year 3 ARC Work Plan.

A custom designed nano-contact mechanics scanning probe microscope (AFM) has been assembled and tested, figure M2a-2.1. This system allows for independent stress/strain control and detection of both a nano-actuated sample stage and AFM probe. This device will be used to conduct nano-rheological measurements as discussed in FP-III Subtask 2-3, and ductile/brittle contact mechanics measurements.

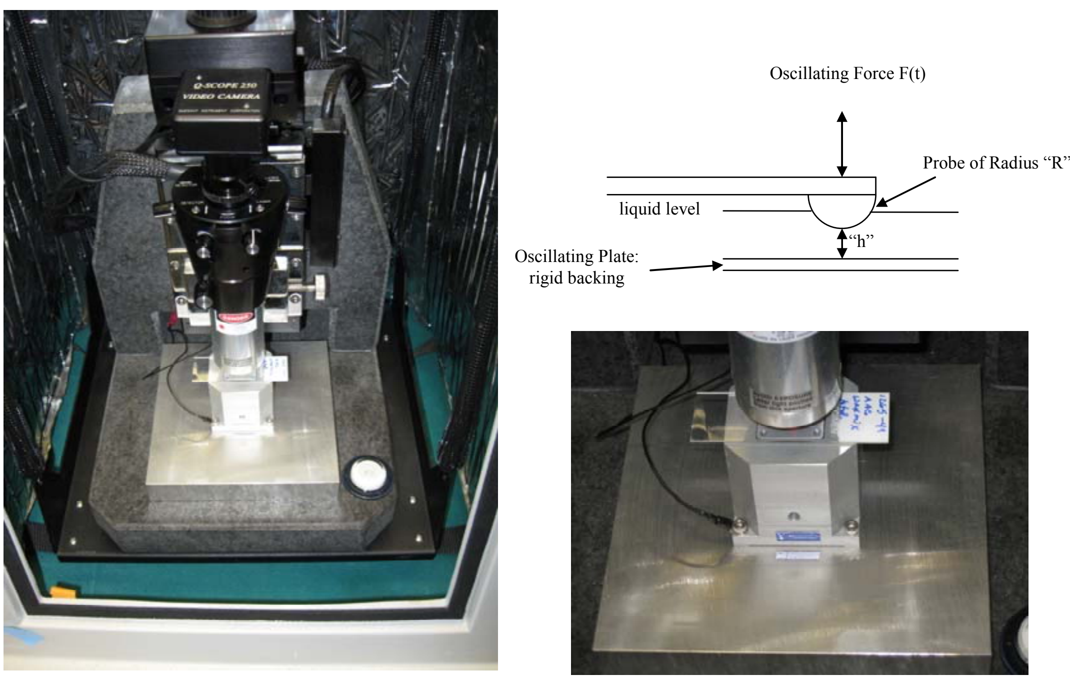

Figure M2a-2.1. Nano-mechanical AFM.

Year Five Work Plan (*Continuation*)

Sub-Subtask M2a-2.1: Selection of eight asphalts and four aggregate materials to prepare samples. Measure surface tension as a function of temperature of asphalts and asphalt fractions over temperature ranges experienced in the pavement. Determine phase transition temperatures from surface tension vs. temperature data and correlate data with physical and performance data, including dynamic viscosity and fracture temperature.

Sub-Subtask M2a-2.2: Prepare and conduct temperature varied water soaking experiments for four sets of mastics comprised of four aggregates prepared with four different asphalts. Determine asphalt stripping temperatures of asphalt mastic materials in temperature varied water soaking experiments.

Sub-Subtask M2a-2.3: Conduct AFM pull-off force "nano-contact mechanics" measurements on asphalt thin-film and aggregate surfaces employing chemically functionalized cantilever tips. Determine polarity components of surface energy of both asphalt thin-films and aggregate fine particles and relate these properties to the tendency of these materials to promote emulsification. Asphalt films, 1-5 micrometers in thickness, will be prepared on glass substrates via solvent spin casting followed by thermal annealing in an inert gas atmosphere. Samples will then be tested by conducting rate and temperature dependent nano-indentations, followed directly by a pull-off action to record penetration depth, from which hardness and adhesion-capillarity interactions with the film are calculated. Indentation cantilevers will be selected based on reported stiffness's of asphalts at very cold temperatures increasing to near ambient conditions. Tests will be run by starting at a low temperature and increasing the temperature of the film until a transition is observed. The change in stiffness transitioning to "stickiness" will be evaluated to determine the temperature (range) at which these transitions take place as a function of crude source. Additionally, tests will be performed at different locations on the surface of the film where notable differences in the surface morphology are subsequently observed. In this sense, a stiffness map of the surface of the film will be obtained. Correlations will be sought to compare between the data gathered from these tests and rheological and mechanical test data related to stiffness (relaxation), fracture temperature and healing rates generated at other scales, most particularly at macroscopic scale based on conventional asphalt rheology.

Cited References

ASTM D6703-07, 2008 Standard Method for Automated Heithaus Titrimetry. *Annual Book of ASTM Standards, Road and Paving Materials; Vehicle-Pavement Systems*, Section 4, vol. 04.03. ASTM International, West Conshohocken, PA. 808-816.

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Schapery, R.A., 1988, Theory of Mechanical Behavior of Elastic Media with Growth Damage and Other Changes in Structure. Report No. MA4 5 762-88-1, Texas A& M University.

Tayebali, A. A., J. A. Deacon, J, S. Coplantz, F. N. Finn, and C. L. Monismith, 1994, *SHRP-A-404, Fatigue Response of Asphalt-Aggregate Mixes, Part II. Extended Test Program*. Strategic Highway Research Program, National Research Council, Washington, DC.

Traxler, R. N., 1960, Relation Between Hardening and Composition of Asphalt. *Preprints, Div. Petrol. Chem., Am. Chem. Soc*., 5: A71-A77.

Work Element M2b: Impact of Moisture Diffusion in Asphalt Mixtures

Subtasks M2b-1: Measurements of Diffusion in Asphalt Binders and Mixtures (TAMU)
M2b-2: Kinetics of Debonding at the Binder-Aggregate Interface (TAMU)

Major Findings & Status

The main objectives and findings / status of this task are as follows.

1. *Diffusivity of water at the binder and mortar length scales (Complete)*: **This is an essential material property that describes moisture transport at these length scales** and it is also a necessary input for micromechanical modeling of moisture damage. The diffusivity of water through the bulk of several different asphalt binders and mortars was determined using spectroscopic and gravimetric method. Results indicate that the rate of moisture transport at different length scales (binder vs. mortar) can differ by an order of magnitude. Results also indicate that the heterogeneity within the asphalt binder results in dual mode diffusion of water.

2. *Methods to determine diffusivity at the binder and mortar length scales (Complete)*: **A method based on the use of FTIR spectroscopy was developed** to determine the diffusivity of water through the bulk of the binder. This method was based on an earlier method developed by NIST but unlike the NIST method it does not measure water concentration at the binder-mineral interface. Instead this method measures the rate of moisture diffusion through the bulk of the binder. **A simple gravimetric method was also developed** to measure water transport through mortars.

3. *Hysteretic effect on moisture induced damage (Complete):* The objective was to **investigate whether or not diffusivity and damage are influenced by the wet and dry**

cycles. Results demonstrate that diffusivity of water through asphalt binder is significantly influenced by its history of exposure to moisture. Dry films of asphalt binder that were previously exposed to moisture demonstrated significant changes in their physical microstructure as revealed by AFM images.

4. *Rate of moisture diffusion through binder-aggregate interface (See notes below)*: The objective of this task was to investigate the rate of moisture transport through the binder-aggregate interfaces.

In addition, we have developed an experimental protocol for measuring the moisture diffusion in asphalt mixtures (Kassem et al. 2009; Arambula et al. 2010a). We have also collaborated with the National Institute for Standards and Technology in comparing numerical simulations of moisture diffusion with the experimental measurements (Arambula et al. 2010b). The main outcome of this work that we have obtained results for the moisture diffusion coefficient that is being used in the numerical simulations of moisture damage.

Year Five Work Plan

Most of the objectives of this work element are now complete and reported in a Ph.D. dissertation. The dissertation will be used as a basis to modify and present the final report following the 508 format. The subtask M2b-2 was planned for years 4 and 5. However, researchers believe that other products and deliverables (e.g. development of PANDA) will benefit by redirecting resources from this subtask. In addition, based on available literature the rank order for the rate of moisture diffusion at the interface can be estimated from the rank order of interfacial work of adhesion.

Cited References

Arambula, E., S. Caro, and E. Masad, 2010a, Experimental Measurement and Numerical Simulation of Water Vapor Diffusion through Asphalt Pavement Materials. *Journal of Materials in Civil Engineering*, ASCE, 22 (6), 588-598.

Arambula, E., E. Garboczi, E. Masad, and E. Kassem, 2010b, Numerical Analysis of Moisture Vapor in Asphalt Mixtures Using Digital Images. *Materials and Structures*, 43 (7), 897-911.

Kassem, E., E. Masad, R. Bulut, and R. Lytton, 2009, Measurements of the Moisture Diffusion Coefficient of Asphalt Mixtures and its Relationship to Mixture Composition. *International Journal of Pavement Engineering*, 10 (6), 389-399.

Table for Decision Points and Deliverables

Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
Two journal papers	Mechanism and model for the diffusion of moisture through films of asphalt binder, methods to measure diffusivity in binders and mortars, and the influence of wet-dry cycles on the cumulative moisture induced damage.	12/21/09	Complete	N/A
Test Method	A method to determine ductile-brittle properties via AFM measurements	12/30/11		N/A

Work Element M2c: Measuring Thin Film Cohesion and Adhesion Using the PATTI Test and the DSR (UWM)

Standard procedure has been developed. Recommendations for specifications will be completed as part of work element M1a.

CATEGORY M3: AGGREGATE SURFACE

Work Element M3a: Aggregate Surface Characterization (TAMU)

Major Findings & Status

The main tasks in this work element included: (1) characterization of the chemical composition of the surfaces of reference minerals and aggregates using electron beam spectroscopes, (2) characterization of the surface energies of reference minerals and aggregates using the universal sorption device and microcalorimetry, (3) quantification of surface atomic species and chemical state, and (4) surface topography characterization using the scanning electron microscope.

A research report was completed and submitted for faculty review. The revised master of science thesis is a full and complete report on the characterization of approximately 22 mineral surfaces and seven aggregate surfaces. We believe that this contains the most extensive set of data in the world on the surface energy characteristics of pure minerals. The study also identified the impact of certain organic coatings and certain oxides contained as impurities in the minerals or rock surfaces on the surface energy properties. The report also evaluated the impact of aging on the surface energy properties.

Due to FHWA’s request to focus on the development of PANDA, manpower that would have focused on minor efforts within this task has been redirected toward the development of PANDA and to the characterization of material and engineering properties as input to PANDA. Furthermore, we believe that the efforts within this work element have been highly successful and will benefit our understanding of the impact of surface energy properties of aggregates on the bond strength of asphalt and aggregate. The development of this work element is considered complete and successful.

Year 5 Work Plan

Work during year 5 will consist of focusing directly on the properties of the aggregates used in validatin testing of PANDA and other ARC products. These aggregates will at a minimum be those aggregates used in the laboratory validation of products produced by Texas A&M. These include a Texas Limestone, a Wyoming siliceous aggregate, a Nevada andesite, and a Wisconsin limestone.

Table for Decision Points and Deliverables

Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
Research report	Report on methods and experimental findings and utility of methodology and findings	6/30/10	Complete	
Research report	Describes implementation of findings into PANDA and expands experiments to characterization for four aggregates used for validation experiments	6/30/11		

CATEGORY M4: MODELING

Work Element M4a: Micromechanics Model (TAMU)

The micromechanics model is being developed at two different length scales that compliment each other. In addition, the modeling is carried out using finite elements as well as the lattice model; each approach has its advantages in terms of modeling the processes and computational efficiency. The work accomplished and planned is described below.

Major Findings and Status

(i) Finite element modeling of micro crack growth using cohesive zone model (TAMU)

We have formulated and applied a numerical micromechanical model of moisture-induced damage in asphalt mixtures. The model focuses on coupling the effects of moisture diffusion with the mechanical performance of the microstructure. Specifically, the model aims to account for the effect of moisture diffusion on the degradation of the viscoelastic bulk matrix of the mixture (i.e., cohesive degradation) and on the gradual deterioration of the adhesive bonds between the aggregates and the asphalt matrix (i.e., adhesive degradation).

The micromechanical model was applied to study the role of some physical and mechanical properties of the constitutive phases of the mixtures on the susceptibility of the mixture to moisture damage. The results from this analysis suggest that the diffusion coefficients of the asphalt matrix and aggregates, as well as the bond strength of the aggregate-matrix interface, have the most influence on the moisture susceptibility of the mixtures.

The micromechanical model was further used to investigate the influence of the void phase of asphalt mixtures on the generation of moisture-related deterioration processes. Two different probabilistic-based approaches were used to accomplish this objective. In the first approach, a volumetric distribution of air void sizes measured using X-Ray Computed Tomography in a dense-graded asphalt mixture was used to generate probable void structures in a microstructure of an asphalt mixture. In the second approach, a stochastic modeling technique based on random field theory was used to generate probable air void distributions of the mixture. In this second approach, the influence of the air void was accounted for by making the physical and mechanical properties of the asphalt matrix dependent on probable void distributions. Although both approaches take into consideration the characteristics of the air void phase on the mechanical response of the mixtures subjected to moist environments, the former explicitly introduces the air phase within the microstructure while the latter indirectly includes its effects by modifying the material properties of the bulk matrix. The results from these simulations demonstrated that the amount, variability and location of air voids are decisive in determining the moisture-dependent performance of asphalt mixtures. The results of this work are documented in the research papers Caro et al. (2010a-d).

The results from this task provide new information on the kinetics of moisture damage mechanisms in asphalt mixtures. In particular, the results obtained from applying the micromechanical model permitted identification of the relative influence of the characteristics of the constitutive phases of a mixture on its moisture-related mechanical performance. This information can be used as part of design methodologies of asphalt mixtures, and/or as an input in life-cycle analysis models and maintenance programs of road infrastructure.

(ii) Finite element modeling of macro crack growth using cohesive zone model for SCB specimen (UNL)

A modeling approach for predicting and characterizing fracture damage of asphalt mixtures subjected to moisture damage has been developed based on the cohesive zone concept. The modeling is an integrated experimental-numerical approach to estimate the progressive moisture damage characteristics of asphalt mixtures. To this end, a gravimetric technique together with Fickian model was utilized to determine mixture's diffusion coefficient, which is a key material property to simulate a moisture transport causing moisture damage in asphalt mixtures. Then, semi-circular bend (SCB) fracture tests were carried out to obtain fracture properties at different levels of moisture conditioning. The moisture diffusion process and the SCB fracture testing were sequentially coupled using finite element method so as to model the progressive damage behavior due to the moisture infiltration followed by the mechanical loading. To simulate the fracture process as a gradual separation, a cohesive zone model was incorporated into the finite element method. The integrated approach resulted in a degradation function that can characterize the progressive damage due to moisture uptake with two degradation parameters. With the two degradation model parameters, moisture damage mechanisms and damage resistance potential, both of which are material specific, could be estimated.

Using the moisture-dependent degradation characteristics of the mixture, model validation was conducted with SCB test results at an arbitrary level of moisture saturation and SCB mechanical loading. The diffusion coefficient of the mixture and the two degradation model parameters of individual material properties (stiffness, cohesive strength, and cohesive zone fracture energy) were applied to the validation. As presented in quarterly reports, model simulation showed a good agreement with experimental data, which implies that the proposed sequentially coupled modeling approach incorporated with the degradation function can successfully predict the progressive damage behavior of asphalt mixtures when moisture damage is involved.

(iii) Lattice modeling of moisture damage (NCSU)

The plan for Year 4 included: (a) incorporation of damage and fracture under cyclic tests; (b) incorporation of air voids; (c) Experimental work related to change in the time dependence during scale-up; (d) incorporation of this changing time-dependence in the lattice modeling framework. Item (a) is complete and cyclic damage modeling can be done efficiently using the lattice modeling software. With respect to (b), a simplified implementation of inclusion of elliptic air voids is complete, but incorporation of more complicated shapes is realized to be important and is currently underway. As for (c), experimental work related to changing time-dependence is turning out to be much more challenging yet illuminating – incorporation of these effects in lattice modeling (item d) is postponed to year 5 after the experimental work is complete.

With respect to linking continuum damage to fracture, while a framework has been investigated into incorporation of nonlocal effects into damage model, it has been realized that experimental investigation is needed before a model can be finalized. Given this, it has been decided that a general computational framework will be developed for nonlocal viscoelastic continuum damage (VECD) model. This year's effort focused on incorporating general nonlocal damage framework into a finite element code, setting the stage for the development of computational model for nonlocal VECD model.

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

Work on lattice modeling is delayed because both changing time-dependency and air void generation turned out to be much more complicated than expected. Similarly, work on continuum damage to fracture has been delayed due to required experimental work, which will be completed this year.

<u>Year Five Work Plan</u>

(i) Finite element modeling of micro crack growth using cohesive zone model (TAMU)

This task is complete and there is no work planned for Year 5.

(ii) Finite element modeling of macro crack growth using cohesive zone model for SCB specimen (UNL)

For this task, in Year 5, we will work on the following remaining activities:

- Microstructure modeling of asphalt mixtures with moisture damage through the sequentially coupled approach.
- Parametric analyses of the microstructure model incorporated with moisture damage characteristics.
- A final report that comprehensively describes all activities performed for this project: model development, testing protocols, test results and analyses, integration of test results into the model, model simulations, model calibration/validation, and model applications.
- Presentations of findings and results at several significant places: conferences, meetings, and workshops, etc.

(iii) Lattice modeling of moisture damage (NCSU)

Experimental work related to change in the time dependence during scale-up will be concluded, followed by the development and incorporation of the model into the lattice modeling framework. The important effect of varying shapes of air voids will be included in the lattice model. Finally, the integrated multiscale virtual fabrication, lattice modeling framework (MSVF-LM) will be finalized to include viscoelastic damage of realistic microstructure under large number of loading cycles. The resulting framework will then be utilized to simulate realistic mixtures and compared with experimental results.

Continuum Damage to Fracture: The computational framework for nonlocal VECD will be completed. The parameters of the nonlocal model will be obtained with the help of experimentation based on digital image correlation (DIC). The resulting model along with the finite element code will be extensively tested and compared with experimental observations.

Cited References

Caro, S., E. Masad, D. Little, and M. Sanchez-Silva, 2010a, Stochastic Micromechanical Modeling of Asphalt Mixtures Subjected to Moisture Diffusion Processes. *International Journal for Numerical and Analytical Methods in Geomechanics*, (Accepted for Publication).

Caro, S., E. Masad, A. Bhasin, and D. Little, 2010b, Micromechanical Modeling of the Influence of Material Properties on Moisture-Induced Damage in Asphalt Mixtures. *Construction and Building Materials*, 24 (7), 1184-1192.

Caro, S., E. Masad, A. Bhasin, D. Little, and M. Sanchez-Silva, 2010c, Probabilistic Modeling of the Effect of Air Voids on the Mechanical Performance of Asphalt Mixtures Subjected to Moisture Diffusion. *Journal of the Association of Asphalt Paving Technologists,* Vol. 79.

Caro, S., E. Masad, A. Bhasin, and D. Little, 2010d, Coupled Micromechanical Model of Moisture-Induced Damage in Asphalt Mixtures. *Journal of Materials in Civil Engineering*, ASCE, 22 (4), 380-388.

Table for Decision Points & Deliverables

Related to finite element model

Date	Deliverable	Description
June, 2011	Draft Report	Draft report that describes model development, testing protocols, test results and analyses, integration of test results into the model, model simulations, and model calibration/validation
July, 2011	Journal Paper(s)	Papers presenting significant findings from the project
September, 2011	Decision Point	Time to make a decision on parallel paths as to which is more promising to follow
December, 2011	Final Report	Final report that comprehensively describes all activities performed for this project: model development, testing protocols, test results and analyses, integration of test results into the model, model simulations, model calibration/validation, and model applications
January, 2012	Presentation(s)	Presentations of any significant findings resulting from the project

Related to lattice model

Date	Deliverable	Description
05/31/11	Decision Point	Complete the experimental investigation into the change in time dependence during the up-scaling process.
05/31/11	Decision Point	Incorporate air voids and cyclic loading into the lattice modeling.
07/31/11	Journal Paper	Write the journal paper on multiscale lattice modeling.
07/31/11	Decision Point	Incorporate the model for change in the time dependence into the lattice modeling framework.
11/30/11	Decision Point	Finalize and validate MSVFLM framework
12/31/11	Journal Paper	Write a journal paper on the validation of MSVFLM
05/01/11	Decision Point	Finalize the computational implementation of nonlocal VECD model
07/01/11	Decision Point	Quantitative characterization of model parameters through DIC
10/01/11	Decision Point	Validation of nonlocal VECD-FEM framework with experimental data
12/31/11	Journal Paper	Write the journal paper on continuum damage to fracture process, including validation with experimental data.

Work Element M4b: Analytical Fatigue Model for Mixture Design (TAMU)

The analytical fatigue model for specimens subjected to moisture damage will be the same as the model being developed under work element F2b. Major findings and Year 4 work plan are described jointly with work element F2b.

Work Element M4c: Unified Continuum Model (TAMU)

Major Findings & Status

The moisture-induced damage model has been modified to accurately capture the degradation in the mechanical properties due to moisture diffusion. The proposed evolution laws for degradation of the adhesive and cohesive moisture-induced damage variables that are modeled independently allows one to introduce fundamental mechanical properties for each process. Also, the proposed moisture damage evolution laws take into consideration the irreversibility process of moisture damage, describe damage process as a function of moisture history and current moisture state, and predict crack propagation both in the matrix and at the interface. The modified moisture-induced adhesive and cohesive damage evolution laws are fully implemented in PANDA.

One major application of PANDA with the formulated moisture-induced damage evolution laws is the ability to conduct micromechanical simulations of asphalt mixtures with various microstructures that are subjected to different moisture conditioning times and levels. Therefore, this will allow one to conduct multiscale computational modeling of moisture-damage in asphalt mixtures in order to identify the key microstructural features and properties that mitigate moisture-induced damage.

Until now, the moisture-damage model has 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.

Year Five Work Plan

The main focus of the fifth year work plan is on the experimental validation of the moisture damage model using the materials from the ARC 2x2 matrix validation plan. Please refer to task V3c for the validation plan.

Table for Decision Points and Deliverables

Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
Journal paper	Paper on formulating the moisture-damage model based on laws of thermodynamics	6/11	N/A	N/A
Journal paper	Validation of the moisture-damage model against experiments on asphalt mixtures	10/11	N/A	N/A
Journal paper	Effect of moisture damage on rutting and fatigue damage	01/12	N/A	N/A
Draft Report	Draft Report on the moisture-damage modeling	03/12	N/A	N/A

CATEGORY M5: MOISTURE DAMAGE PREDICTION SYSTEM (All, TAMU lead)

Major Findings and Status

This work element is being performed in close coordination with other agencies in the Technology Development work area of this consortium. Accordingly, some part of the budget for this work element has been allocated in the Technology Development work area.

This task is being directed toward the development of a moisture damage prediction system that will consist of the following components:

i) A method for the selection of materials with good resistance to moisture damage. This method is based on the components of surface energy of asphalt binders and aggregates.
ii) An experimental method that accounts for the resistance of asphalt mastic and fine portion of the mixture to moisture damage. This will be done primarily using the dynamic mechanical analyzer.
iii) An experimental method for measuring the resistance of the full mixture to moisture damage.
iv) Models that account for the material, microstructure, and loading factors that affect moisture damage.

Year 5 Work Plan

The background work for the five components listed above has been essentially completed. In year 5 some validation testing is planned, especially for items iii) and iv). However most of the work related to item iii) was successfully completed in year 4.

The final deliverable for M5 will be a protocol or system by which to assess overall moisture susceptibility that contains all of the components listed above in an appropriate manner for a specific task where a question exists as to the potential for moisture damage, e.g., component selection, impact of a specific filler, impact of a specific binder, impact of moisture diffusion, overall mixture damage sensitivity. This protocol will be separate from PANDA with the thought that the sophisticated continuum and micromechanical approached offered by PANDA may not always be the most appropriate approach.

<u>Table of Deliverables</u>

Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
Protocol	Protocol for implementation of component selection	6/30/11		
Experimental method	Experimental method for measuring moisture damage resistance of full mixture	9/30/11		
Research report	Report in 508 format that describes a comprehensive and integrated approach to assessing moisture damage on three scales; binder and aggregate components, fine aggregate matrix with DMA and in the full mix – Alternative to more sophisticated PANDA approach	12/31/11		

Table of Decision Points and Deliverables for the Moisture Damage Program Area

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
M1a: Affinity of Asphalt to Aggregate (UWM)	Draft Report		03/31/11	N/A	N/A
	Final Report		06/30/11	N/A	N/A
M1b-1: Use of micro calorimeter to measure the total energy of adhesion	Journal paper	A method to use the micro calorimeter to measure total adhesion including the influence of chemical interactions and specific surface area.	9/30/09	Complete	N/A
M1b-2: Work of Adhesion at Nano-Scale using AFM	Test Method	A method to determine surface roughness of aggregate and fines based on AFM	12/30/11		N/A
M1b-3: Identify mechanisms of competition between water and organic molecules for aggregate surface	Final Report	Final report documenting the testing protocol and findings of experiments on asphalt-aggregate interactions	10/31/10	10/31/11	Program activity delayed in order to redirect critical manpower to PANDA development
	Journal paper	Journal paper on organic-aggregate interactions tying together the results of subtasks M1b-3 and M3a			
M1c: Quantifying Moisture Damage Using DMA	AASHTO procedure and journal papers	AASHTO procedure for preparing Fine Aggregate Matrix (FAM) specimens for the DMA testing	9/31/10	Complete	N/A
M2b-1: Measurement of diffusion of water through thin films of asphalt binders and FAM	Two journal papers	Mechanism and model for the diffusion of moisture through films of asphalt binder, methods to measure diffusivity in binders and mortars, and the influence of wet-dry cycles on the cumulative moisture induced damage.	12/21/09	Complete	N/A
M2b-2: Work of Cohesion at Nano-Scale using AFM	Test Method	A method to determine ductile-brittle properties via AFM measurements	12/30/11		N/A
M3a: Aggregate Surface Characteristics	Research report	Report on methods and experimental findings and utility of methodology and findings	6/30/10	Complete	
	Research report	Describes implementation of findings into PANDA and expands experiments to characterization for four aggregates used for validation experiments	6/30/11		
M4a: Micro-mechanics Model (TAMU)	Journal papers	Numerical micromechanical model of moisture-induced damage in asphalt mixtures	9/30/10	Complete	N/A

Table of Decision Points and Deliverables for the Moisture Damage Program Area (cont.)

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
M4a: Micromechanics Model Development (Moisture Damage) (UNL)	Two journal papers	Cohesive zone modeling with moisture damage of asphalt mixtures considering mixture microstructure: modeling methodology, constitutive theory, testing protocols, test data, model simulation/calibration/validation, and user-friendly manuals.	10/30/10 03/31/12	Complete No change	N/A
	Models and Algorithm		3/31/11	No change	N/A
	Draft report		06/30/11		
	Final report		12/31/11		
M4a: Lattice Micromechanics Model (NCSU)	Two journal papers	One paper on a method to include air voids in the virtual microstructure and the second paper on the description and verification of Multiscale Virtual Microstructure Lattice Model.	7/31/11 9/30/11	7/31/11 12/31/11	The experimental work is slightly delayed due to equipment issues.
	Draft Final Report		2/14/12	2/14/12	N/A
M4a: Model to Bridge Continuum Damage and Fracture (NCSU)	Two journal papers	One paper on the experimental characterization of the fracture process zone using Digital Image Correlation and the second paper on the continuum damage to fracture process including validation with experimental data.	9/30/11 9/30/11	12/31/11 12/31/11	The experimental work is delayed due to the acquisition of the new equipment for the DIC.
	Draft Final Report		2/14/12	2/14/12	N/A
M4c: Unified Continuum Model (TAMU)	Journal paper	Paper on formulating the moisture-damage model based on laws of thermodynamics	6/11	N/A	N/A
	Journal paper	Validation of the moisture-damage model against experiments on asphalt mixtures	10/11	N/A	N/A
	Journal paper	Effect of moisture damage on rutting and fatigue damage	01/12	N/A	N/A
	Draft Report	Draft Report on the moisture-damage modeling	03/12	N/A	N/A

Table of Decision Points and Deliverables for the Moisture Damage Program Area (cont.)

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
M5: Moisture Damage Prediction System	Protocol	Protocol for implementation of component selection	6/30/11		
	Experimental method	Experimental method for measuring moisture damage resistance of full mixture	9/30/11		
	Research report	Report in 508 format that describes a comprehensive and integrated approach to assessing moisture damage on three scales; binder and aggregate components, fine aggregate matrix with DMA and in the full mix – Alternative to more sophisticated PANDA approach	12/31/11		

	Moisture Damage Year 5	Year 5 (4/11-3/12)												Team
		4	5	6	7	8	9	10	11	12	1	2	3	
Adhesion														
M1a	**Affinity of Asphalt to Aggregate - Mechanical Tests**													
M1a-1	Select Materials													**UWM**
M1a-2	Conduct modified DSR tests													
M1a-3	Evaluate the moisture damage of asphalt mixtures													
M1a-4	Correlate moisture damage between DSR and mix tests													
M1a-5	Propose a Novel Testing Protocol													
M1a-6	Standard Testing Procedure and Recommendation for Specifications													
M1b	**Work of Adhesion**													
M1b-1	Adhesion using Micro calorimeter and SFE													**TAMU**
M1b-2	Evaluating adhesion at nano scale using AFM													**WRI**
M1b-3	Mechanisms of water-organic molecule competition													**TAMU**
M1c	**Quantifying Moisture Damage Using DMA**													**TAMU**
Cohesion														
M2a	**Work of Cohesion Based on Surface Energy**													
M2a-1	Methods to determine SFE of saturated binders						JP							**TAMU**
M2a-2	Evaluating cohesion at nano scale using AFM													**WRI**
M2b	**Impact of Moisture Diffusion in Asphalt**													
M2b-1	Diffusion of moisture through asphalt/mastic films						F							**TAMU**
M2b-2	Kinetics of debonding at binder-aggregate interface													
M2c	**Thin Film Rheology and Cohesion**													
M2c-1	Evaluate load and deflection measurements using the modified PATTI test													**UWM**
M2c-2	Evaluate effectiveness of the modified PATTI test for Detecting Modification													
M2c-3	Conduct Testing													
M2c-4	Analysis & Interpretation													
M2c-5	Standard Testing Procedure and Recommendation for Specifications	see Subtask M1a-6												
Aggregate Surface														
M3a	**Impact of Surface Structure of Aggregate**													
M3a-1	Aggregate surface characterization													**TAMU**
Modeling														
M4a	**Micromechanics model development**			D			DP			F,SW			JP	**TAMU**
M4b	**Analytical fatigue model for use during mixture design**									M&A, D			F	**TAMU**
M4c	**Unified continuum model**			D			DP			F,SW				**TAMU**
M5	**Moisture Damage Prediction System**													**ALL**

LEGEND

Deliverable codes	Deliverable Description
D: Draft Report	Report delivered to FHWA for 3 week review period.
F: Final Report	Final report delivered in compliance with FHWA publication standards
M&A: Model and algorithm	Mathematical model and sample code
SW: Software	Executable software, code and user manual
JP: Journal paper	Paper submitted to conference or journal
P: Presentation	Presentation for symposium, conference or other
DP: Decision Point	Time to make a decision on two parallel paths as to which is most promising to follow through
[x]	Indicates completion of deliverable x

Work planned

Work completed

Parallel topic

Moisture Damage Year 2 - 5

		Year 2 (4/08-3/09)				Year 3 (4/09-3/10)				Year 4 (04/10-03/11)				Year 5 (04/11-03/12)				Team
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	
Adhesion																		
M1a	**Affinity of Asphalt to Aggregate - Mechanical Tests**																	
M1a-1	Select Materials		DP															**UWM**
M1a-2	Conduct modified DSR tests		P		P													
M1a-3	Evaluate the moisture damage of asphalt mixtures				DP		P			P	JP		P					
M1a-4	Correlate moisture damage between DSR and mix tests						P		P									
M1a-5	Propose a Novel Testing Protocol				P				P, D				JP, F					
M1a-6	Standard Testing Procedure and Recommendation for Specifications										P							
M1b	**Work of Adhesion**																	
M1b-1	Adhesion using Micro calorimeter and SFE						JP											**TAMU**
M1b-2	Evaluating adhesion at nano scale using AFM							JP									JP, F	**WRI**
M1b-3	Mechanisms of water-organic molecule competition				JP													**TAMU**
M1c	**Quantifying Moisture Damage Using DMA**										JP	D	F					**TAMU**
Cohesion																		
M2a	**Work of Cohesion Based on Surface Energy**																	
M2a-1	Methods to determine SFE of saturated binders														JP			**TAMU**
M2a-2	Evaluating cohesion at nano scale using AFM							JP									JP, F	**WRI**
M2b	**Impact of Moisture Diffusion in Asphalt**																	
M2b-1	Diffusion of moisture through asphalt/mastic films						JP	D	F	D	F				F			**TAMU**
M2b-2	Kinetics of debonding at binder-aggregate interface																	
M2c	**Thin Film Rheology and Cohesion**																	
M2c-1	Evaluate load and deflection measurements using the modified PATTI test	DP	JP	D	F													**UWM**
M2c-2	Evaluate effectiveness of the modified PATTI test for Detecting Modification			D	DP,F													
M2c-3	Conduct Testing						JP											
M2c-4	Analysis & Interpretation				P				D									
M2c-5	Standard Testing Procedure and Recommendation for Specifications					D					**see Subtask M1a-6**							
Aggregate Surface																		
M3a	**Impact of Surface Structure of Aggregate**																	
M3a-1	Aggregate surface characterization									JP		P						**TAMU**
Models																		
M4a	**Micromechanics model development**				JP				JP				M&A	D	DP	F, SW	JP	**TAMU**
M4b	**Analytical fatigue model for use during mixture design**															M&A,D	F	**TAMU**
M4c	**Unified continuum model**								JP				M&A	D	DP	F, SW		**TAMU**
M5	**Moisture Damage Prediction System**																	**ALL**

LEGEND

Deliverable codes	**Deliverable Description**
D: Draft Report	Report delivered to FHWA for 3 week review period.
F: Final Report	Final report delivered in compliance with FHWA publication standards
M&A: Model and algorithm	Mathematical model and sample code
SW: Software	Executable software, code and user manual
JP: Journal paper	Paper submitted to conference or journal
P: Presentation	Presentation for symposium, conference or other
DP: Decision Point	Time to make a decision on two parallel paths as to which is most promising to follow througjh
[x]	Indicates completion of deliverable x

Work planned
Work completed
Parallel topic

PROGRAM AREA: FATIGUE

CATEGORY F1: MATERIAL AND MIXTURE PROPERTIES

Work Element F1a: Cohesive and Adhesive Properties (TAMU)

Subtasks F1a-1: Critical review of the literature
F1a-2: Development of test method
F1a-3: Thermodynamic work of adhesion and cohesion
F1a-4: Mechanical work of adhesion and cohesion
F1a-5: Evaluate acid base scales for surface energy calculations

Major Findings & Status

We have completed a comprehensive search on the relationship between the ideal work of fracture and practical work of fracture (Masad et al. 2010). The literature review covered fundamental and practical studies in polymers and adhesives. The knowledge gained from this literature review was very valuable to explain the relationship between the adhesive and cohesive bond energy of asphalt mixtures and the measured fracture energy. The literature review is documented by Masad et al. (2010).

We have completed the subtask in which we measured the thermodynamic work of adhesion (F1a-3) and the mechanical work of adhesion (F1a-4). These experiments involved the use of steel plates as well substrates made of the ARC aggregate materials tested along with the ARC binders. The work on measuring the fracture energy with steel substrates is documented by Masad et al. (2010). We are currently preparing a paper with the results of using the ARC aggregates and binders.

The evaluation of the acid base scales for surface energy calculation was accomplished using a large number of asphalt binder and the results are documented by Howson et al. (2011).

Year Four Work Plan

This task is completed and there is no work planned for Year 5.

Cited References

Howson, J., E. Masad, A. Bhasin, D. Little, and R. Lytton, 2011, Comprehensive Analysis of Surface Free Energy of Asphalts and Aggregates and the Effects of Changes in pH. *Construction and Building Materials*, 25 (5), 2554-2564.

Masad, E., J. Howson, A. Bhasin, S. Caro, and D. Little, 2010, Relationship between Ideal and Practical Work of Fracture: Background and Experimental Results. *Journal of the Association of Asphalt Paving Technologists*, Vol. 79.

Table for Decision Points and Deliverables

Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
Journal Paper	Paper on relationship between ideal and practical work of fracture for aggregate-asphalt systems	6/11	N/A	N/A
Draft Report	Draft Report on Cohesive and Adhesive Properties	11/11	N/A	N/A

Work Element F1b: Viscoelastic Properties

Subtask F1b-1: Viscoelastic properties under cyclic loading **(TAMU)**

Major Findings & Status

The main objective of this subtask was to determine a constitutive model that accurately characterizes the nonlinear 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.** In addition, nonlinear viscoelastic response can be erroneously interpreted as damage when energy dissipation methods are employed. The following is a summary of the aspects that were or will be addressed in this subtask.

1. *Investigating the types of nonlinear response (Complete):* An understanding of the nature of the material response must precede the development of a constitutive model. A systematic investigation using experimental and analytical tools was carried out to **investigate the nature of nonlinear response in asphalt binders subjected to shear stresses**. Results indicate that asphalt binders subjected to shear stresses (similar to those experienced in asphalt mixtures) tend to deform axially due to Poynting effect and dilatation. In addition, the combination of shear and normal stresses experienced by the binder specimen results in what is referred to as "interaction nonlinearity". This form of nonlinearity results in a reduction of the shear modulus due to the presence of axial stresses.

2. *Model for the nonlinear response and obtaining model parameters (Nearing completion):* **A constitutive model based on the Schapery's model for nonlinear viscoelastic response was developed**. The constitutive relationship takes into account the three-dimensional stress-state experienced by the asphalt binder. A method was also developed to obtain the model parameters and validation of this model is in progress.

3. *Poisson's ratio (In progress):* Another important element for an accurate constitutive model is the Poisson's ratio of asphalt binder. Work is in progress under this subtask to determine the E* and G* of thin films of asphalt binder, the time dependency (or

independency) of **Poisson's ratio, as well as the influence of confining stresses on the viscoelastic response** of asphalt binders.

<u>Year Five Work Plan</u>

Results available up to date from this subtask are also summarized in journal publications or manuscripts that are in review. Remaining tests will be completed and comprehensive results, constitutive model and methods to obtain the model parameters for this subtask will be summarized in a Ph.D. dissertation around December 2011. The final report following the 508 format based on this dissertation will be prepared during this year.

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

Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
Four journal papers		12/30/08 3/31/10 9/30/10 12/31/11	Complete Complete 3/31/11 No change	Development of the protocols required slightly more time than anticipated. A draft of the third paper is almost complete.
Models and Algorithm	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.	3/31/09 6/30/10 12/31/11	3/31/12	It is more efficient and informative if the three different final reports, models and algorithms are consolidated into a single final report. The work at UT Austin that will make up the final report is 60% complete.
Draft report		12/31/08 12/31/11		
Final report		6/30/08 3/31/12		

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

<u>Major Findings & Status</u>

A method was developed to separate the recoverable and irrecoverable responses using creep recovery experimental measurements at various temperatures and stress levels. This method is now implemented in the analysis of the viscoelastic and viscoplastic response of asphalt mixtures which is needed to determine the parameters of the PANDA constitutive model. This method is documented in the paper by Huang et al. (2011a, 2011b) and Darabi et al. (2011).

Year Five Work Plan

We will implement this method in the analysis of the experimental measurements of the ARC mixtures. Consequently, the analysis will yield the PANDA parameters that are used in the finite element simulations of asphalt pavement performance.

Cited References

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

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.

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

Table for Decision Points and Deliverables

Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
Draft Report	Documentation of PANDA Models and Validation Including the Method for Analysis of Viscoelastic Properties	11/11	N/A	N/A
Final Report	Documentation of PANDA Models and Validation Including the Method for Analysis of Viscoelastic Properties	3/12	N/A	N/A

Work Element F1c: Aging (TAMU)

Major Findings & Status

Year four produced significant improvements in our ability to calculate binder aging in pavements over time in a way that includes measurements of air void pore size distribution and number. Also, a preliminary validation of this model was made by comparing oxidative aging model calculations to measurements of oxidation in pavements.

Additionally, work proceeded on developing a fast-rate, constant-rate kinetics model of binder oxidation, with emphasis on reaction mechanisms and possible links between the two parallel steps of the kinetic model. A key question that is being investigated is the role of species such as free radical intermediates in the reactions.

An important element of this work plan is to obtain an improved understanding of the effect of binder oxidation on mixture fatigue resistance. This work continues in year 5.

Two papers partially supported by this work are in press and a third is currently under review. Additionally, presentations were made in July and September 2010. The publications and presentations were shown in the January 2011 Quarterly Report.

<u>Year Five Work Plan</u>

Subtask F1c-1: Critical Review of Binder Oxidative Aging and Its Impact on Mixtures

This work element is ongoing. New information obtained in year 5 on binder oxidation rates in pavements and the impact of binder oxidation on mixture properties will be evaluated from the perspective of existing and new literature. Of particular current interest is a review of literature articles on oxidation reactions as they might explain the fast-rate oxidation kinetics that are being determined in the laboratory.

Subtask F1c-2: Develop Experimental Design

A 63 page experimental plan was previously completed and submitted. The Year 5 effort will continue to carry out this plan.

Subtask F1c-3: Develop a Transport Model of Binder Oxidation in Pavements

Model Validation. A transport model has been developed and preliminary evaluation with available pavement cores has shown very positive results. The model now is ready for a more complete validation. This effort will continue in Year 5 with field cores from the WRI test pavements in Arizona, Kansas, Nevada, Minnesota, and Wyoming, and the binder, recovered from several depths. Because of previous delays in improvements to the mixture testing equipment and protocols and in receiving test pavement cores, the work of this subtask lags behind the year four plan.

It should be noted that the transport model calculations are based entirely upon *independent* measurements (using independent experimental methods that provide measurements of fundamental properties) of pertinent properties and characteristics:

- properties for the specific asphalts used in the pavements including
    - oxygen diffusivity in asphalt, mastics, and nitrogen
    - oxidation kinetics parameters (activation energy, pre-exponential frequency factor for constant-rate oxidation kinetics parameters)
    - rheological characteristics plus FTIR hardening susceptibility
    - Henry’s constants for oxygen absorption from the literature

- mixture air voids including
  - pore size distribution from X-ray CT imaging
  - total air voids from CoreLok measurements
- properties used to model pavement temperature as a function of depth for each specific pavement site including
  - solar radiation
  - daily high and low temperatures
  - wind speed
  - pavement emissivity and absorptivity
  - thermal diffusivity

That is, there are no adjustable parameters in the model so that if the fundamental physics are properly described (not a trivial goal), then the model should be quite accurate and robust with no calibration. The preliminary validation, shown in figure F1c-3.1, was quite encouraging in the agreement between measured and modeled values.

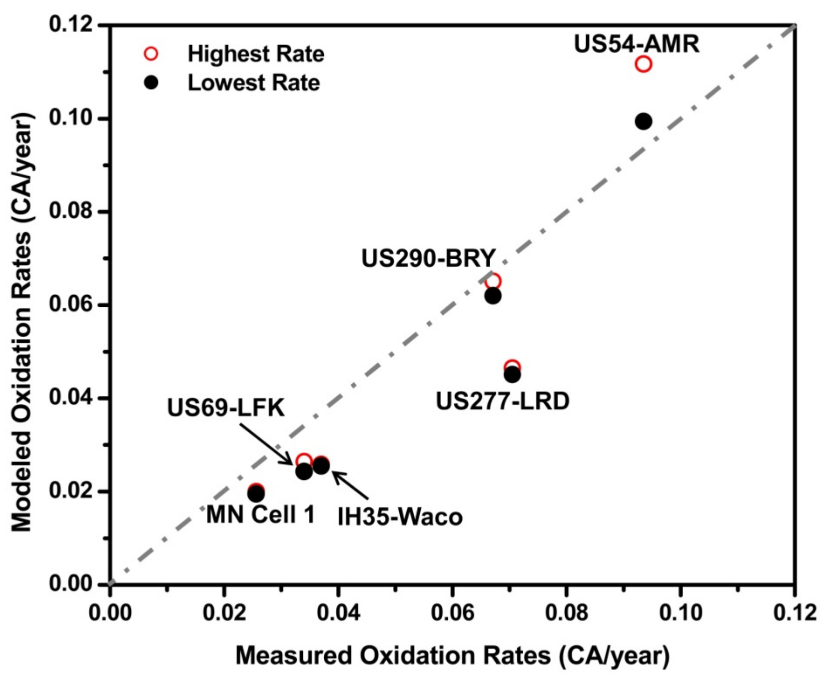

Figure F1c-3.1. Comparison of Measured and Modeled Field Oxidation Rates

The planned work on the WRI field test site cores will add important and essential validation in a variety of climates throughout the mid-west. Field core characterization will include physical property measurements (see work element F1c-4) followed by X-ray CT imaging and air voids determination (as a function of depth below the surface), binder extraction, recovery (as a function of depth) and measurements of carbonyl, rheology, and constant-rate oxidation kinetics. Additionally, historical meteorological data will be obtained for the pavement site. With these results, model calculations will be made to compare to pavement oxidation measurements over time.

Fast-rate, constant-rate reaction mechanisms using antioxidants. The model does not yet include fast-rate reaction kinetics parameters, important in the early part of a pavement's life (perhaps important in the first third of its life in warm climates and throughout the entire pavement life in colder climates). The effort outlined in this section will continue work begun in year four to improve our fundamental understanding of the fast-rate reaction mechanism. The ultimate objective would be to discover a relationship between the fast-rate and constant-rate mechanisms that would allow a more direct measurement of the reaction kinetics needed for model calculations. For example, if a sufficient connection is discovered, then measurement of constant-rate kinetics parameters will be sufficient to deduce fast-rate kinetics as well. This approach will significant time at the least, and provide very important but otherwise unobtainable data at best (in the case of determining kinetics parameters from field cores, e.g.). The work plan follows.

Objectives

1. To examine two possible reaction pathways of binder oxidation: free radical chain reaction (FRCR) and electron transfer initiated oxidation (ETIO).
2. To develop a new protocol to evaluate antioxidant effectiveness based on two asphalt oxidation properties: oxidation rates and hardening susceptibility.

Experimental Design

An initial design is described, below. The results of these experiments will provide direction for further tests throughout the year.

Materials

Three binders and two antioxidants have been selected. The three binders are NuStar PG 67-22 and PG 76-22 (from Atlanta), and Valero PG 64-16 (from Benicia). The two antioxidants are Irganox 1010 (from Sigma-Aldrich) and Carbon Black (Raven 790, from Columbia Chemicals Company).

The antioxidants are to be blended with binders at different percentages by weight of binder. NuStar PG 67-22 is designated as A, NuStar PG 76-22 as B, and Valero PG 64-16 as C. For example, the treatment plan for NuStar PG 67-22 is shown in table F1c-3.1.

Table F1c-3.1. Treatment plan for NuStar PG 67-22.

Notation	Binder	Antioxidant (by Weight of Binder)
A	NuStar PG 67-22	-
AX1	NuStar PG 67-22	1.5% Irganox 1010
AX3	NuStar PG 67-22	3.0% Irganox 1010
AC1	NuStar PG 67-22	1.5% Carbon Black
AC3	NuStar PG 67-22	3.0% Carbon Black
AS	NuStar PG 67-22	1.5% Irganox 1010 and 1.5% Carbon Black

Aging Protocol

An aging protocol in two phases has been designed. Phase I screens for the most effective treatment method. Phase II will test the screened treatment method for its effect on binder oxidation during both the fast-rate and constant-rate aging periods. In both phases, control and treated binders will be aged in the pressure oxygen vessel (POV) at one elevated temperature (175˚F). Two replicate samples will be collected each time according to table F1c-3.2.

Table F1c-3.2. Sampling plan for Phase I and Phase II experiment.

Phase	Time (Days)
I	0, 3, 7, 10, 20
II	0, 2, 4, 6, 10, 20, 30, 40

Material Characterization

Two analytical techniques will be used to characterize the binder samples. Fourier-Transform Infrared Spectroscopy (FTIR) will be used to measure the carbonyl area (integrated peak area of 1820~1650 cm^{-1}) and a Carri-Med CSL 500 controlled stress rheometer will be used to measure both the low shear rate limiting viscosity and the DSR function (combines both viscous and elastic properties in a way that relates quantitatively to binder ductility). The low shear rate limiting viscosity is obtained from a frequency sweep at 60 °C from 0.1 rad/s to 100 rad/s. The DSR function is measured at 44.7 °C and 10 rad/s then time-temperature shifted to 15 °C, 0.005 rad/s (Ruan et al. 2003).

Parallel to comparisons of model calculations with field aging will be collaborative efforts with the several mixture modeling efforts of the ARC. The objective will be to provide links between the transport oxidation model and the mixture modeling that can be used to enhance pavement performance prediction as it is affected by binder oxidative hardening. A key element of this linkage will be to develop the connections between binder physical properties and their changes due to oxidative hardening and mixture properties that reflect durability performance. This connection likely will depend upon an improved fundamental understanding of the relationships between binder properties and mixture performance, especially the non-linear properties of cracking and fatigue. These collaborative efforts between the aging modeling effort and other members of the ARC continue.

Subtask F1c-4: The Effects of Binder Aging on Mixture Viscoelastic, Fracture, and Permanent Deformation Properties

This subtask will continue in year 5. Details were given in the experimental plan. This effort is providing essential information on the effect of binder oxidation on mixture properties, especially fatigue. The mixtures of interest are both lab mix, lab compacted (LMLC) mixtures (which have been prepared and aged prior to mixture testing) and pavement field cores, specifically cores obtained from the WRI test sites.

Subtask F1c-5: Polymer Modified Asphalt Materials

Polymer modification of asphalt binders provides enhancement of binder properties by providing an elastic polymer network interacting with asphalt. The interaction of the polymer modifier and the base asphalt binder appear to be critical in establishing the beneficial effects and these interactions need to be better understood. This interaction has been shown to be reduced by oxidative aging of polymer-modified binder (polymer network damage due to polymer oxidative degradation or a reduction in interactions with the asphalt binder), to the point that the modified binder eventually behaves like the aged unmodified binder. Understanding the changes of this interaction with oxidation is an important issue that impacts the evaluation and selection of polymer modifiers. Work continues, based on the year four work plan.

Table for Decision Points & Deliverables

Date	Deliverable	Description
07/11	Presentation	Present early results on improvements to modeling binder oxidation in pavements with field validation (F1c-4)
01/12	Presentation, Journal Paper	Present extended validation of oxidation model (F1c-3, F1c-3). Submit for publication 8/10.
01/12	Presentation, Journal Paper	Results on binder oxidation and mixture fatigue (F1c-4). Submit for publication 8/10.

Work Element F1c: Aging (*Unified Continuum Model for Aging)*

Major Findings & Status

Years three and four produced significant advances in the development of the continuum-based aging model for asphalt mixtures. At this point, 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 that include single creep, creep-recovery, repeated creep-recovery, monotonic tension, monotonic compression, cyclic tension, cyclic compression, relaxation, cyclic relaxation, and rutting performance. Furthermore, how aging affects the viscoelastic, viscoplastic, damage, and healing properties has been investigated thoroughly. It is 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.

Year Five Work Plan

The main focus of the fifth year work plan is on further validation of the aging model against available experimental data from the literature and from laboratory and field core tests that are currently collected and conducted by the research team at Texas A&M University. Please refer to task V3c for the validation plan.

Table for Decision Points and Deliverables

Date	**Deliverable**	**Description**
4/11	Journal Paper	Document the aging model development and validation
11/11	Journal Paper	Further validation of the aging model
03/12	Draft Report	Draft Report on the aging modeling

Work Element F1d: Healing (TAMU)

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

Major Findings & Status

The main objectives and findings / status of this task are as follows.

1. *Synthesis of self-healing properties and mechanisms (Complete):* A detailed literature review of self-healing mechanisms at the microscopic length scale was conducted. The findings from this review were synthesized in previous quarterly reports and a book chapter. **The findings were used to develop a hypothesis for self-healing mechanism at the microscopic length scale** and a concomitant mathematical model to represent this mechanism.

2. *Mathematical model for self-healing (Complete):* Based on the hypothesized mechanism for self-healing in asphalt binders **a two-step mechanism for self-healing and a mathematical model that represents this mechanism** was developed. The first step includes wetting of crack interfaces. The rate of this process is dependent on the inherent physio-chemical properties of the asphalt binder including surface free energy. These second step includes strength gain across the wetted interface. The rate of this process is dependent on the physio-chemical properties of the asphalt binder as well as the viscoelastic properties of the asphalt binder. The model and hypothesis was partially validated by comparing the intrinsic healing characteristics of selected asphalt binders to their surface-free energies as well by using computational techniques such as molecular dynamics.

3. *Method to measure rate of intrinsic self-healing (Complete)*: **A test method** using the DSR was developed **to determine the intrinsic healing characteristics of asphalt binders**. The test method can also be used to compare the inherent ability of different asphalt binders to self-heal as well as the influence of aging and temperature on the rate of intrinsic healing.

4. *Methodology to measure overall rate of self-healing (In Progress)*: **A test method to determine the overall rate of healing as a function of rest period and damage level preceding the rest period** was developed. Healing characteristics for different core materials is currently being collected (on FAM specimens). A validation procedure will also be used to ensure the efficacy of this procedure. Results from the overall healing will also be used to further validate the hypothesized healing mechanism.

5. *Implementing mathematical form of healing model at continuum scale (In Progress)*: **The form for the healing model was also implemented in the continuum scale model (PANDA) with different model constants**. More details on this implementation can be found in the subtask on the development of the continuum model.

Year Five Work Plan

Results available up to date from this work element summarized in journal publications or manuscripts that are in review. Remaining tests will be completed and comprehensive results, constitutive model and methods to obtain the model parameters for this subtask are included in two different theses, one of which is complete while the other will be completed by July 2011. A comprehensive final report following the 508 format based on these theses will be prepared during this year.

Subtask F1d-5b: Thermodynamic model for healing in asphalt binders

Major Findings & Status

This subtask was introduced in year four. The micromechanical model of healing described in F1d-5 addresses the healing of microcracks. As one would glean from a close analysis of the Schapery closure speed model, most of the healing is expected to occur in the β process zone.

The size range of these cracks is not exactly defined but one would expect them to range from the nano scale to a few millimeters. Work by Kringos, Schmets, Pauli and Scarpas (2009) has relied upon Atomic Form Microscope (AFM) surface topography of asphalt binders that show the evidence of phase separation within the bitumen. They postulate that if the mechanical properties, specifically stiffnesses, of the phases are significantly different then the interfaces between the phases serve as natural stress inducers. They used their finite element model CAPA 3-D to demonstrate this. The result of the TU Delft study was to demonstrate the presence of crazing that occurs among the phases at the interfaces. Kringos et al. (2009) described thermodynamic considerations and a constitutive formulation that could explain how a reversal of the crazing process could occur with the input of thermal energy and/or mechanical energy back into the system. This results in healing at a smaller length scale than the model presented in this section. The ARC team applauds the excellent work and approach being developed by the TU Delft team.

In fact, as described in the Year 2 and Year 3 work plans, ARC has designed AFM experiments aimed at investigating the properties of different phases of the bitumen at TAMU. In year four, this work demonstrated differences in the mechanical properties of the phases, and this work will be continued to refine the mechanical properties into viscoelastic properties that can be used to model the performance of asphalt binders in micromechanical models. These models will consider the properties of unaged and aged binders.

Year Five Work Plan

Two Ph.D. level students with expertise in mechanics and trained under the supervision of Professors Rajagopol in the Mechanical Engineering Department of TAMU and Dallas Little will work with a third Ph.D. student who has developed the methodology to measure the mechanical properties of the various phases defined in the AFM analysis. In year five these students will work together to define the viscoelastic properties of the phases of the asphalt binder and work toward the development of micromechanical model of the response of the asphalt binder from this length scale that includes the impact of the phases as defined by the AFM and their influence on fracture, plastic deformation and healing. We believe we can synergistically work with our colleagues at TU Delft who have made significant development in modeling healing at this length scale, and we plan to seek their advice and collaboration in each step of this approach in order to properly recognize their excellent work and optimize the results. In fact Professors Scarpas and Little are working together on synchrotron experiments with Dr. Alexander Schmets, who has already taken steps using Spin Echo Small Angle Neutron Scattering (SESANS) to investigate whether the phase appearance at the surface of the binder identified through AFM is in fact a surface phenomenon or a bulk phenomenon.

References

Kringos, N., A. Schmets, T. Pauli, and T. Scarpas, 2009, “A Finite Element Based Chemo-Mechanical Model to Simulate Healing in Bituminous Materials,” Chemo-Mechanics Workshop, TU Delft, June 2009.

Table for Decision Points and Deliverables

Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
Six journal papers	A mathematical model for self-healing 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 No change No change	
Models and Algorithm		06/30/11	3/31/12	It is more efficient and informative if the different final reports, models and algorithms are consolidated into a single final report. The final report is based on two theses: the thesis from Texas A&M University is complete and work for the thesis from UT Austin is 70% complete.
Draft report		06/30/10 06/30/11 12/31/11		

Subtask F1d-6: Evaluate Relationship Between Healing and Endurance Limit of Asphalt Binders (UWM)

Major Findings and Status

In Year 4 the research team identified limitations of the Dynamic Shear Rheometer (DSR) for running strain-controlled time sweeps with intermittent rest periods. The team found that the DSR is unable to reach the target strain amplitude within an acceptable time after a rest period. This limitation can significantly affect the healing analysis because many of the loading cycles applied to the sample after a rest period have lower target strain in comparison to the no-rest procedure. In an attempt to solve this issue, the team used strain-controlled time sweeps using longer loading times and longer rest periods. For longer loading times, the number of cycles after rest periods that do not reach the target strain level is negligible and therefore the healing analysis is not significantly affected. However, for many of the binders tested, this procedure of longer loading times and longer rest periods was not able to show differences in their healing characteristics.

Based on these findings, the team applied a modification of the time sweep test with rest periods in which an oscillatory linear ramp to the target strain amplitude was used. This was followed by applying a cyclic loading at this strain amplitude followed by a rest period. The loading ramp is used to accommodate the limitations of the DSR in terms of making instantaneous changes in loading. However, it was observed that this modified time sweep with ramp and intermittent loading procedure induced damage during the ramping step for aged binders. This observation complicated healing analysis.Thus, a different approach was investigated in which a single long rest period was adapted. With the use of only one rest period, the number of cycles with strain amplitude below the target became insignificant compared to the total number of loading cycles. Preliminary experimental results showed that the single long rest period procedure is able to capture the difference in healing potential of different binders at different aging levels. Moreover, the test results obtained were more repeatable. It was observed that irrespective of the age level, polymer modified binders exhibit greater healing effect than neat binders.

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

The successful implementation of a procedure for healing characterization by means of cyclic loading with rest periods caused delays due to limitations of the DSR. The research team identified at least three possible procedures to account for these limitations and decided to adapt the time sweep with a single long rest period as the procedure that minimizes the issues observed. The research team plans to double the efforts in completing the experimental matrix with the proposed single long rest period procedure during the first two quarters of Year 5.
To reflect actual progress of this work element, the 5-year Gantt chart has been updated to indicate that a journal paper is available for Q4 of Year 4.

Year 5 Work Plan

The research group plans to characterize healing of binders using a time sweep with a single long rest period. The experimental plan for Year 5 is presented in table F1d-6.1. Three aging levels and six LTPP binders coming from field sections with different cracking performance will be tested.

Table F1d-6.1. Healing tests of LTPP binders.

Variables	Factors	Description
Binders	6	Six LTPP binders with broad range of field performance, SHRP ID: 370901, 90960, 350903, 370964, 310903, and 04B903.
Aging Level	3	Unaged, RTFO, and PAV
Replicates	2	To assess repeatability
Total	**36**	

Also, efforts during Year 5 will focus on writing and editing the draft and final report summarizing major findings of this work element.

Table for Decision Points and Deliverables

Date	Deliverable	Description
8/11	Journal Paper	Healing characterization of binders by means of mechanical testing with rest periods.
12/11	Draft Report	Report summarizing major findings for evaluation of healing of binders by means of cyclic testing with rest periods
1/12	Final Report	Final report on healing characterization of binders and its relation to fatigue performance

Subtask F1d-7: Coordinate with Atomic Force Microscopic (AFM) Analysis (WRI)

Major Findings and Status

In this subtask the preliminary job will be to conduct data analysis of a backlog of experimental results to determine physico-chemical properties of the systems discussed including chemical potentials phase separation phenomena to be fed back into the asphalt microstructure model discussed in Work Element F3a. The data generated from these analyses will then be incorporated into the chemo-mechanical models of asphalt and asphalt mastic structures.

In the later stages of fatigue cracking, the failing sections of pavement are often observed to form distinct crack patterns (i.e., alligator crack pattern) usually localized in the traffic wheel path, and often occurring later in the life of the pavement. By comparison, in investigations relating to metal fatigue, pattern forming cracking has been successfully correlated to the microstructure which develops in these materials during casting (Cappelli et al. 2008; Bian and Taheri 2008) corresponding to grain boundaries at the meso, micron and nanometer scale. Occurrence of grain boundaries may be a result of the heterogeneous nature of a material (Cappelli et al. 2008; Bian and Taheri 2008). Thus, this same idea (i.e., grain boundary formation) can be applied to paving materials if such pattern forming phenomena were to be observed (Robertson et al. 2005, 2006).

Year Five Work Plan (*Continuation*)

Subtask *F1d-7i:* has been completed. The Year 5 plan is to continue with *F1d-7ii*.

F1d-7i: Conduct image analyses of pre-existing results (AFM imaging data of thermally cycled thin films, Spinodal-Blend Films, and asphalt fraction materials representing the eight SHRP core asphalts).

F1d-7ii: Determine asphalt compositional properties from image analysis data and preparation of a database of results.

Cited References

Bian, L., and F. Taheri, 2008, Fatigue Fracture Criteria and Microstructures of Magnesium Alloy Plates. *Materials Science and Engineering A,* 48774–85.

Cappelli, M. D., R. L. Carlson, and G. A. Kardomateas, 2008, The Transition Between Small and Long Fatigue Crack Behavior and its Relation to Microstructure. *International Journal of Fatigue*, 30: 1473–1478.

Robertson, R. E., K. P. Thomas, P. M. Harnsberger, F. P. Miknis, T. F. Turner, J. F. Branthaver, S-C. Huang, A. T. Pauli, D. A. Netzel, T. M. Bomstad, M. J. Farrar, J. F. McKay, and M. McCann. "Fundamental Properties of Asphalts and Modified Asphalts II, Final Report, Volume I: Interpretive Report," Federal Highway Administration, Contract No. DTFH61-99C-00022, Chapters 1-4 submitted for publication, November 2005.

Robertson, R. E., K. P. Thomas, P. M. Harnsberger, F. P. Miknis, T. F. Turner, J. F. Branthaver, S-C. Huang, A. T. Pauli, D. A. Netzel, T. M. Bomstad, M. J. Farrar, D. Sanchez, J. F. McKay, and M. McCann. "Fundamental Properties of Asphalts and Modified Asphalts II, Final Report, Volume I: Interpretive Report," Federal Highway Administration, Contract No. DTFH61-99C-00022, Chapters 5-7 submitted for publication, March 2006.

Table for Decision Points and Deliverables

Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
Journal paper	Paper describing the phase-segregation nature of asphalt at the micro-nano scale		Complete	N/A

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 in PANDA. The healing model has been validated against uniaxial compression and tension fatigue data from the Nottingham database on asphalt mixtures at various temperatures.

Year Five Work Plan

The main focus of the fifth year work plan is on further validation of the micro-damage healing model against: (1) ALF experimental data, (2) other existing data on another asphalt mixture in the Nottingham database, and (3) the ARC 2x2 matrix validation plan. 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

Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
Journal Paper	Formulating the micro-damage healing model based on micromechanics arguments within the framework of continuum damage mechanics	4/11		
Journal Paper	Further validation of the micro-damage healing model	10/11		
Draft Report	Draft Report on the self-healing modeling	03/12		

CATEGORY F2: TEST METHOD DEVELOPMENT

Work Element F2a: Binder Tests and Effect of Composition (UWM)

Major Findings and Status

A simplified method for testing the elastic recovery in the Dynamic Shear Rheometer (DSR) was developed. A 97% correlation between the elastic recovery measured in the DSR (ER-DSR) and the elastic recovery measured in the ductility bath was obtained. The elastic recovery measured in the DSR is on average equal to 70% of the elastic recovery values measured in the ductility bath. The current specifications require 60 minutes relaxation time. The results showed that good correlation can also be achieved after 30 min of relaxation. Therefore, it is recommended to reduce the time required for the relaxation to 30 minutes.

Using the developed protocol, neat and modified binders were tested, and the results were compared with elastic percent recovery from the Multiple Stress Creep and Recovery test (%R-MSCR), and fatigue resistance properties collected from time sweep, binder yield energy test (BYET) and linear amplitude sweep (LAS). The BYET results were analyzed with the aid of three parameters: the energy at the maximum stress divided by the initial stiffness (BYEpeak/G*), the energy calculated at γ=2000% (BYE20) and the energy at γ=2000% divided by the initial stiffness (BYE20/G*).

The results indicate that the ER-DSR correlated well with the %R-MSCR at 3.2 kPa but not at 0.1 kPa. Some correlation was observed between the ER-DSR and BYET results. Better correlations were obtained by selecting specific parameters from the BYET such as the BYEpeak/G* and BYE20/G*. However, there is a wide scatter in the results leading to concerns regarding using the ER values to rank binders or to accept/reject materials based on a specific limit.

The correlation between ER-DSR and number of cycles to failure from the time sweep at 10 kPa and 30 kPa was found to be moderate. Poor correlation was observed between ER-DSR and the number of cycles from the linear amplitude sweep test at 2.5% strain and 5%. Also, it was observed that the data are widely scattered. These poor correlations could be attributed to the different temperatures at which the LAS and ER-DSR were conducted.

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

To reflect actual progress of this work element, the Year 5 and 5-year Gantt charts have been updated to indicate extended work planned for subtask F2a-4.

Year Five Work Plan

Subtask F2a-1: Analyze existing fatigue data on PMA

This subtask was completed during Year 2.

Subtask F2a-2: Select virgin binders and modifiers and prepare modified binder

This subtask was completed during Year 2.

Subtask F2a-3: Laboratory aging procedures

This subtask was completed during Year 3.

Subtask F2a-4: Collect fatigue test data

The research team will continue collecting fatigue data following the testing matrix described in Year 4 and subsequent quarterly reports.

Subtask F2a-5: Analyze data and propose mechanisms

The objective of this subtask will be to analyze the collected data from subtask F2a-4. The team will propose mechanisms by which modifiers control fatigue under various conditions. These mechanisms will be used to develop guidelines for selecting modifiers intended to improve fatigue life. The data analysis will focus on two main areas: rheological properties and damage resistance characterization. Note that damage resistance of different modifiers and/or modification techniques is obtained by means of the BYET, LAS and Time Sweep tests.

Table for Decision Points and Deliverables

Date	**Deliverable**	**Description**
7/11	Presentation	Presentation on the data analysis performed to date.
10/11	Draft Report	Report summarizing major findings for the effect of modification on asphalt binder performance at high and intermediate temperatures
01/12	Final Report	Final report on the effect of modification on binders properties in terms of fatigue cracking and rutting

Work Element F2b: FAM Testing Protocol (TAMU)

The reader is referred to work element M1c where a new procedure for preparing FAM specimens were presented and a new software was developed to analyze DMA data

Year Five Work Plan

The reader is referred to the software development that was presented in work element M1c.

Work Element F2c: Mixture Testing Protocol (TAMU)

The reader is referred to Work Element E1a where mixture testing status and plans are presented.

Work Element F2d: Structural Characterization of Micromechanical Properties in Bitumen using Atomic Force Microscopy (TAMU)

Major Findings and Status

The purpose of this work element is to characterize the micromechanical properties of various structural components in asphalt using Atomic Force Microscopy (AFM) and to observe the change in microstructure and micromechanical behavior due to oxidative aging of the asphalt. The focus of the study is based on nano-indentation experiments performed within a micro-grid of asphalt phases in order to determine micromechanical properties such as stiffness, adhesion and elastic/plastic behavior. The materials used in this study included asphalts AAB, AAD and ABD from the Materials Reference Library (MRL) of the Strategic Highway Research Program (SHRP), chosen due to variations in crude source, chemical composition and elemental analysis for each asphalt type.

Analysis of nano-indentation creep measurements corresponding to phase-separated regions ultimately revealed heterogeneous domains in asphalt with different mechanical properties, and oxidative aging was found to induce substantial microstructural change within these domains, including variations in phase structure, phase properties and phase distribution. The form and extent of these changes, however, were different for each asphalt studied. Data analysis and information collected during this study were used for comparisons to existing models and asphalt data, which validated results and established correlations to earlier, related studies. From these comparisons, it was found that data followed expected trends; furthermore, analogous interpretations and distinctions were made between results from this study and the micellar and microstructural models of asphalt. This study of micromechanical properties that govern asphalt behavior has yielded information essential to the advancement of hot mix asphalt (HMA) performance, including a new “weak zone” hypothesis and a foundation of data for implementation into new and existing asphalt models.

Figures F2d.1 and F2d.2 show topographical maps of two phases (figure F2d.1) for unaged asphalt AAD and three phases (figure F2d.2) for aged asphalt AAD. It is important to note that substantial difference in deflection (creep) between the aged and unaged asphalts.

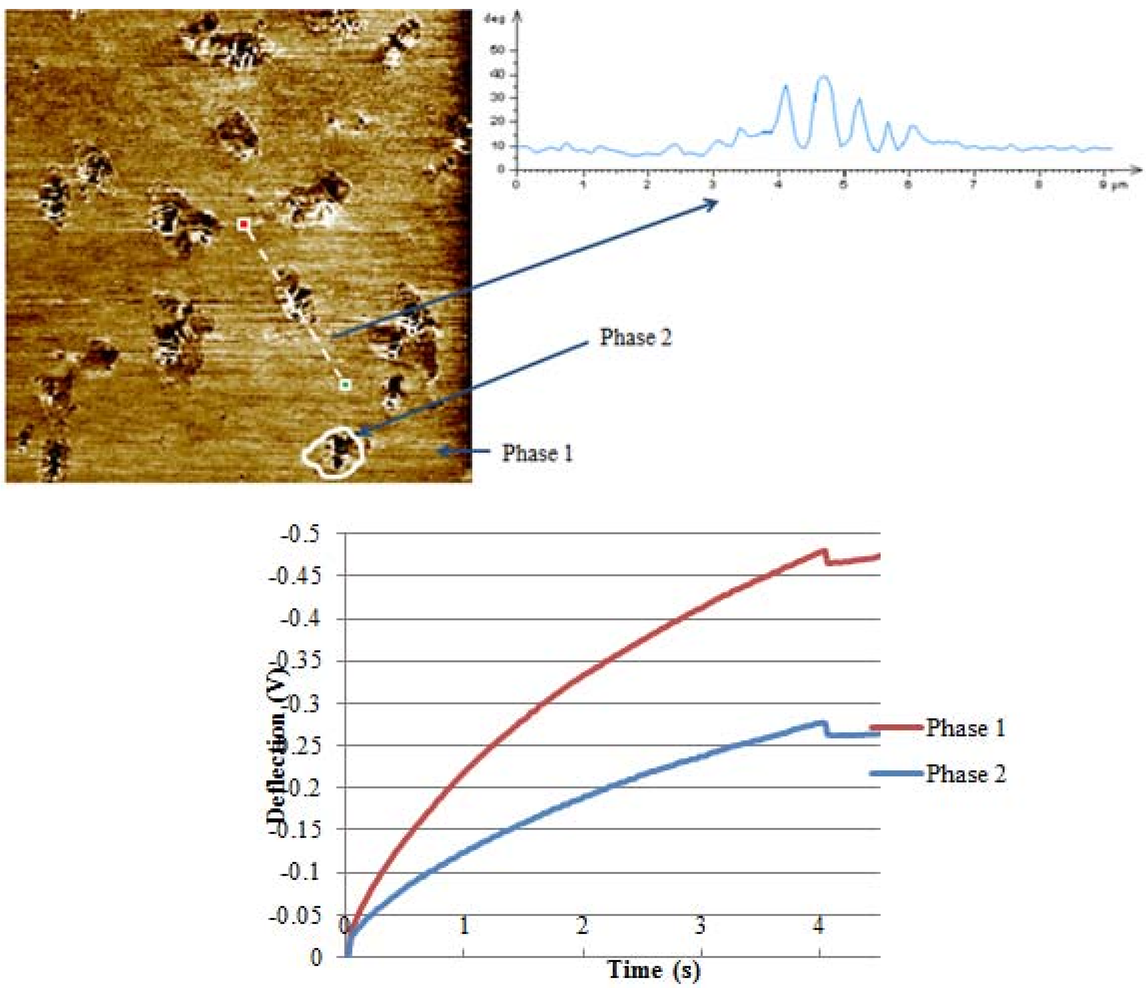

Figure F2d.1. Phase image, profile extraction and creep measurements for asphalt AAD.

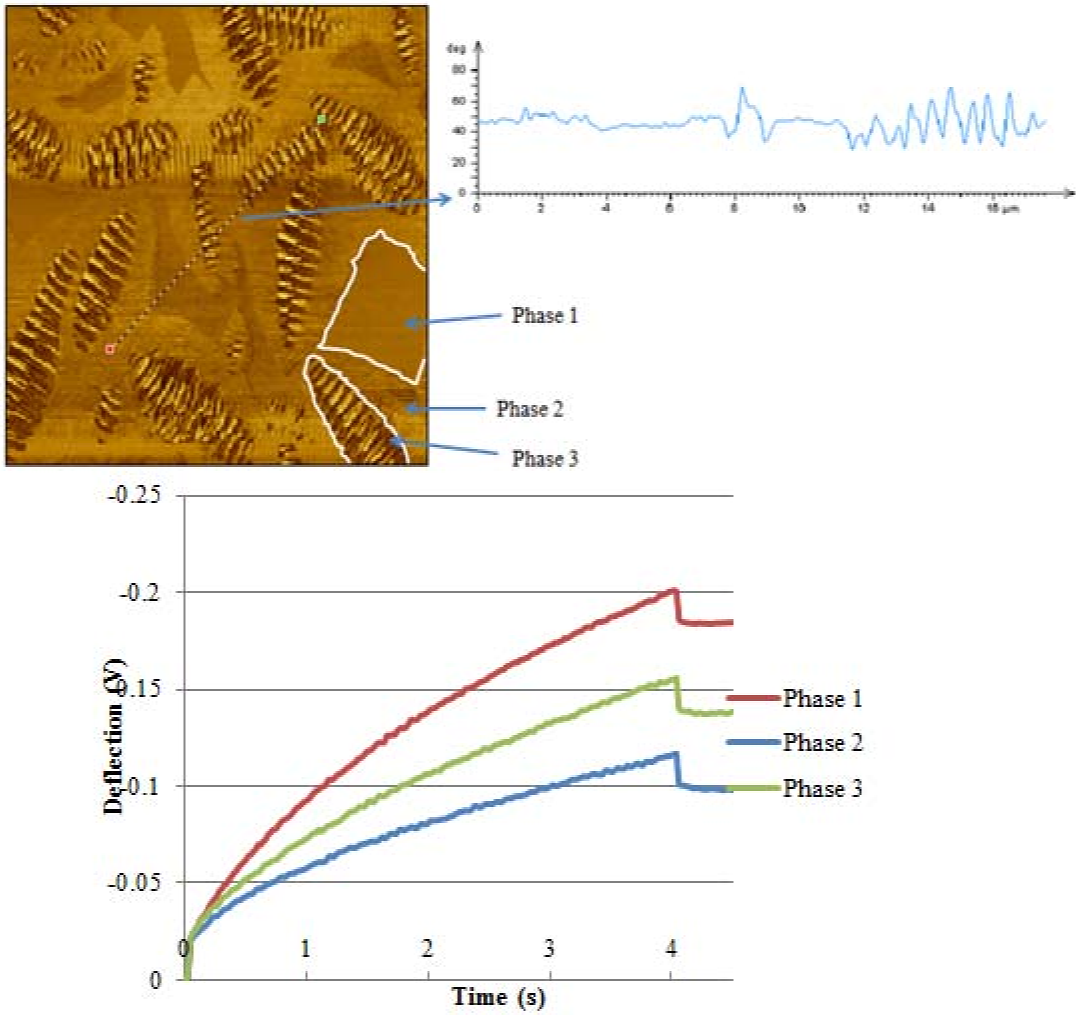

Figure F2d.2. Phase image, profile extraction and creep measurements for aged asphalt AAD.

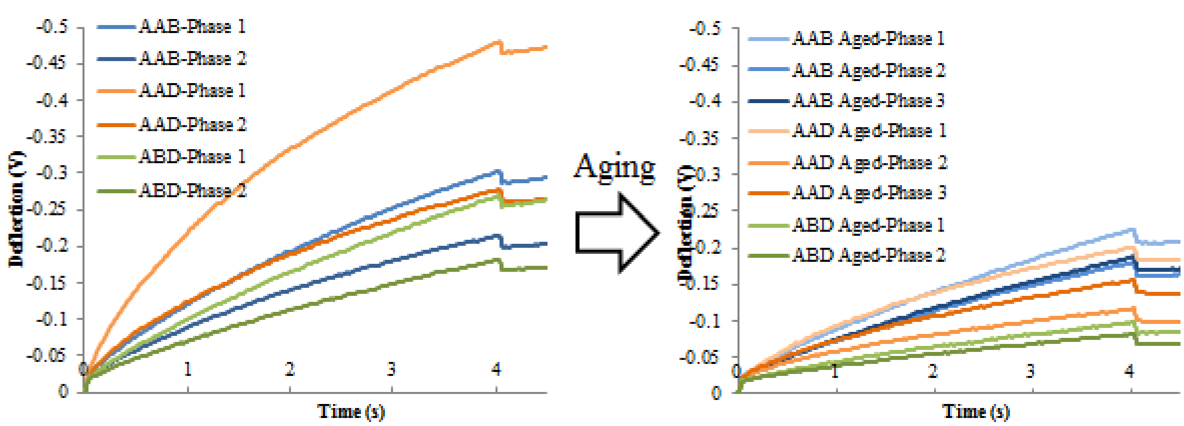

Figure F2d.3. Creep measurement comparison of aged and unaged asphalts AAB, AAD and ABD.

Based on the results obtained from the study, two conclusive observations are readily apparent: all PDM-identified microstructures observed in this experiment demonstrate different material behavior under constant load, and the effects of long-term aging profoundly impact not only the material behavior of these microstructures but also the shape, size and distribution of each asphalt microstructure. The primary findings in this study include:

- Prior to aging, asphalts AAB, AAD and ABD each consisted of two distinctive PDM-identified phases. After aging, asphalt ABD consisted of two phases; whereas, asphalts AAB and AAD each consisted of three phases.
- Long-term aging clearly induces microstructural change in asphalt. The form and extent of these changes, however, were different for each asphalt studied. The three types of microstructural changes observed during this study were: dispersion of phase, clustering of phase and materialization of phase. Dispersion of phase was observed in Phase 2 of asphalts AAB and AAD. Clustering of phase was observed in Phase 2 of asphalt ABD, and materialization of phase was observed within Phase 2 of asphalts AAB and AAD by the appearance of a new sub-phase within Phase 2, which was identified as Phase 3 or “bee” structure.
- Long-term aging not only induces changes in phase structure and distribution, but also in the distinct properties of each phase. In other words, age-induced stiffness increase is not exclusively due to the presence of greater percentages of higher stiffness components after aging. Although results indicate that this is partially the case, distinctive changes in the properties of each phase also occur and contribute greatly to the higher stiffness, which strongly indicates polar interactions within each PDM-identified phase.
- Aging resulted in a stable reduction in percentage of Phase 1 and subsequent steady increase in percentage of Phase 2. Furthermore, Phase 1 exhibited the lowest stiffness, and Phase 2 showed the highest stiffness for each asphalt before and after aging.
- Prior to aging, apparent dispersed phases exhibited stiffness’s ranging from 42 to 50 percent greater than the apparent dispersing phase; after aging, more variability was observed amongst the values as dispersed phase stiffness’s varied from 22 to 67 percent greater than the dispersing phases. Phase 3, which was only observed directly within Phase 2 after aging, exhibited an intermediary stiffness ranging from 6 to 45 percent less than the encircling Phase 2.
- Creep measurements taken from each PDM-identified phase indicated heterogeneous domains in asphalt with clearly different mechanical properties. The combined data collected from these measurements indicated the same overall trend as the viscoelastic material properties determined by SHRP and documented by the SHRP MRL in 1993, which provides validity and reliability to the data collected during this study.

As indicated by the results and analysis previously detailed, Phase 2 consistently exhibited the highest stiffness before and after aging, and Phase 1 consistently displayed the lowest stiffness. This trend specifies the presence of more highly polar molecules in Phase 2 than Phase 1, based on the microstructural model of asphalt. According to phase images, Phase 1 only exhibited minor change during the aging process, but an obvious stiffness increase indicates significant change in chemical composition caused by molecular associations within the phase. Although

Phase 2 appears to disperse during aging, which would contradict the notion of clustering or molecular associations of highly polar molecules within the phase, the resulting Phase 2 structure is likely the product of molecular organizations into a more stable, although dispersed, arrangement within the phase. Based on the force measurements and associated patterns of abruptly shifting high and low elevations that are characteristic of Phase 3, there is a strong indication that these regions are "weak zones" somehow formed during the molecular bonding and organization within Phase 2. The Phase 3 regions are thought to be regions that are highly susceptible to permanent strain or perhaps regions that have already endured permanent strain. This hypothesis indicates that while asphalt becomes more stable during aging through molecular organizations, unavoidable weak zones are also formed that are highly susceptible to permanent strain and, thus, induce pavement distress. This hypothesis furthermore offers a possible visual explanation to the findings of the SHRP researchers in which higher percentages of SEC I resulted in increased brittleness and cracking.

By using PDM to isolate different asphalt microstructures and SM to collect relative creep measurements from each of these locations, data were collected which corroborated expected micromechanical differences of each asphalt phase. Furthermore, the collected data provided the foundation for valuable comparisons to existing models and documented asphalt data. The fact that microstructural and material behavior fluctuations occur as asphalt ages is not a new idea, but the extent to which these changes occur is still widely misunderstood. This research has offered new perspective into the impact of aging on the microstructural behavior of asphalt. Further study of the magnitude of aging effects on the micro-properties of asphalt should be pursued. Additional research is also clearly needed to validate the "weak zone" hypothesis, but continued investigation in this area could lead to a focused effort to minimize or reduce the formation of these "weak zones" and successively result in longer-lasting HMA pavements.

This study to date has identified significant variations in mechanical properties measureable within different aged and unaged micro-phases in asphalt. The findings from this study should ultimately be implemented into a new or existing model to improve its accuracy in predicting HMA performance by reducing some of the assumptions required to build such a model.

<u>Year Five Work Plan</u>

During year five a concerted effort will be made to refine our ability to measure and document the full range of viscoelastic properties of the various phases of the asphalt binder so that these properties can be used in micromechanical models as asphalt behavior and to better understand:

1. The impact of aging on fracture and permanent deformation.
2. The impact of moisture on fracture and permanent deformation.
3. The impact of phase properties on microdamage and nanodamage healing.
4. The use of AFM as a means to "finger print" asphalt materials in order to refine our understanding of viscoelastic behavior of virgin binder and binder impacted by oxidative aging and moisture conditioning.

Table for Decision Points and Deliverables

Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
Protocol for Measuring Viscoelastic Properties Using AFM	Protocol for preparing samples and taking measurements in AASHTO format – Protocol development complete, AASHTO format planned for 5/30/11	7/31/10	N/A	N/A
Journal Paper	Submit ASCE Journal paper describing results of measurement of viscoelastic properties of various phases of three SHRP binders	3/31/11	N/A	N/A
Evaluation of Impact of Aging and Moisture Conditioning	Complete	12/15/10	N/A	N/A
Journal Paper	Submit journal paper describing how AFM characterization of viscoelasic properties can be used in micromechanical models	12/31/11	N/A	N/A
Journal Paper	Submit journal paper describing how AFM characterization of asphalt phases can be used to classify performance potential of asphalt binders relative to fatigue, aging susceptibility, and moisture damage	12/31/11	N/A	N/A
Final Research Report		2/28/12	N/A	N/A

Work Element F2e: Verification of the Relationship Between DSR Binder Fatigue Tests and Mixture Fatigue Performance (UWM)

Major Findings and Status

In Year 4, significant progress was made towards the development and implementation of the Linear Amplitude Sweep (LAS) test. Time Sweep (TS) and LAS tests were performed on asphalt binders from two transportation pooled fund studies (i.e., TP5-080 and TP5-146). Based on the experimental results obtained and the use of viscoelastic continuum damage (VECD) theory, it appears that there is a good correlation between LAS and TS fatigue law parameters. Moreover, rankings of the fatigue performance of binders based on LAS testing and VECD analysis were similar to the ranking of asphalt mixtures (i.e., which were prepared with the same binders) tested with uniaxial push-pull procedure. The comparison of the LAS testing procedure with the time sweep and mixture fatigue data indicates the potential of the success of the proposed accelerated procedure for simple and effective binder fatigue characterization.

Significant effort was put in revising the Excel template for VECD analysis of LAS data to make it more user-friendly. Previously, material integrity (e.g., $|G^*|\sin\delta$ as a function of damage (D)) was fitted using Excel solver. However, with this optimization method the quality of the fit was dependent on an initial guess for the power law parameters C_1 and C_2. Thus, to minimize error due to initial guess of parameters the power law equation that describes material integrity as function of damage was linearized using logarithmic transformation. This linearization allowed for the use of Excel's slope and intercept functions to directly determine model parameters C_1 and C_2 rather than using an iterative process. Furthermore, elimination of the need for the inter-conversion methods to determine the model parameter "α" was accomplished. The parameter α is calculated based on the un-damaged rheological properties of the binder (i.e., relaxation modulus). The research team found that to obtain α, storage modulus vs. frequency from frequency sweep data can be used directly instead of using the estimated relaxation modulus vs. time.

The use of time-temperature superposition (TTS) for the LAS test results was investigated in Year 4. It has been demonstrated in asphalt mixtures that TTS can be applied to VECD results through the use of reduced time. The research team used this concept and the normalization of the loss modulus in place of the absolute value as a material integrity parameter to be able to predict fatigue performance at other temperatures. The team found that damage curves predicted using TTS and measured curves at the reference temperature are very similar. Although predicted and measured curves appear to be close to each other, there are large differences in the fitted parameter *A*. Due to the sensitivity of the current closed-form solution for fatigue life, numerical solutions will be investigated for accurate prediction of number of cycles to failure at multiple temperatures from a single LAS test.

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

To reflect actual progress of this work element, the Year 5 and the 5-year Gantt charts have been updated to indicate extended work planned for subtasks F2e-3 and F2e-4. Also, Gantt charts have been updated to show that two journal papers were published in Year 3.

Year Five Work Plan

Subtask F2e-1: Evaluate binder fatigue correlation to mixture fatigue data

This subtask was completed in Year 3.

Subtask F2e-2: Selection of testing protocols

The linear amplitude sweep (LAS) was selected as the testing protocol for fatigue characterization of binders. This subtask was finalized in Year 4. An AASHTO standard of the selected testing protocol is currently under review.

Subtask F2e-3: Binder and mixture fatigue testing

Further investigation of the relationship between LAS results and asphalt mixture testing will be conducted. The research team will test mixtures using the Indirect Tensile Test (IDT) setup. A typical mix design with locally available aggregates will be used for mixture preparation. The research team will also complete a test matrix for mastics to determine the influence of mineral filler on fatigue performance.

Subtask F2e-4: Verification of surrogate fatigue test

The research team will continue verification/validation of the LAS test. The data used for verification include mixture fatigue tests and field performance from the LTPP program.

Subtask F2e-5: Interpretation and modeling of data

A user-friendly spreadsheet, based on VECD theory, is available for interpretation and modeling of binder fatigue data from the LAS test. This subtask was completed in Year 4.

Subtask F2e-6: Recommendations for use in unified fatigue damage model

The research team will investigate the use of numerical solutions for fatigue law parameters (i.e., *A* and *B*) in addition to the existing closed-form solution. The idea is to reduce the current sensitivity of fatigue life to C_1 and C_2. A unified VECD fatigue damage model will be submitted in Year 5. Main efforts during Year 5 will focus on writing and editing the final report.

Table for Decision Points and Deliverables

Date	**Deliverable**	**Description**
11/11	Draft Report	Report summarizing major findings for each subtask. The report includes: evaluation of correlations between binder and mixture fatigue performance, comparison between binder fatigue testing procedures, verification/validation of LAS test
2/12	Final Report	Final report on the development and implementation of the Linear Amplitude Sweep Test. It includes the latest AASHTO standard.

CATEGORY F3: MODELING

Work Element F3a: Asphalt Microstructural Model

Major Findings & Status

The detailed work plan was prepared as the initial part of the Year 2 Work Plan, which was approved by FHWA in August 2008 then reiterated in the Year 3 Work Plan. The complete work plan is accessible at the ARC website, www.ARC.unr.edu.

As detailed in the plan, a significant portion of the work is in partnership with Virginia Polytechnic and State University (VT), the National Institute of Standards and Technology (NIST), and the University of Rhode Island (URI). There is also significant collaboration with the Technological University of Delft (Delft) in the Netherlands. There was a substantial amount of contractual information and documentation required by the FHWA to establish the subcontracts with these parties which has taken place with all subcontracts presently in place.

The main work accomplished in this Work Element was to establish the big picture for a multiscale chemo-mechanical model of asphalt. The current thinking is described in a contribution to the Proceedings of the First International Workshop on Chemo-Mechanics of Bituminous Materials, which was held in Delft, the Netherlands in June 2009 (Kringos 2009; Greenfield 2009). In that paper, we described a broad framework for how coupling must occur across length and time scales. The key idea is for a simultaneous "push" (from smaller scales to larger) and "pull" (from larger scales to smaller) within models. Arrows indicating possible "pushes" and "pulls" are shown in figure F3a.1, which was also shown at the September 2009 ETG meeting. The pale arrows in the lower left indicate how molecule-scale simulations can be conducted to yield results for larger lengths at short times, shorter lengths at longer times, or some combinations ("push"). Guidance from rheology and phase structure models ("pull", darker arrow pointing down and to the left) is necessary to formulate the kinds of statistical averaging and simulation that can yield usable parameters. In other words, "pulls" from above help to recognize the "pushes" from below that yield functions and parameters that are found within and/or are useful for the larger scale models.

Not all "pulls" are viable. For example, rheology data can be described within a number of different parameterized models. Some of the models are based on well-defined molecular concepts, such as distributions of relaxation times, while others are described more as resembling curve fits. Only the approaches based on solid fundamentals provide a pathway to connect molecular-scale dynamics results to the rheology model parameters. Another example is that a phase field model can be devised to work (as in many formulations) with a simple double-well potential. Averaging over true molecular-scale simulations doesn't yield such simple results, however. Instead, a means of averaging the thermodynamics function that is simplified into a double-well free energy potential must be found. **Summarizing, the "pull" that can be obtained on the molecular scale as a feed "push" into the mesoscale is important to identify.**

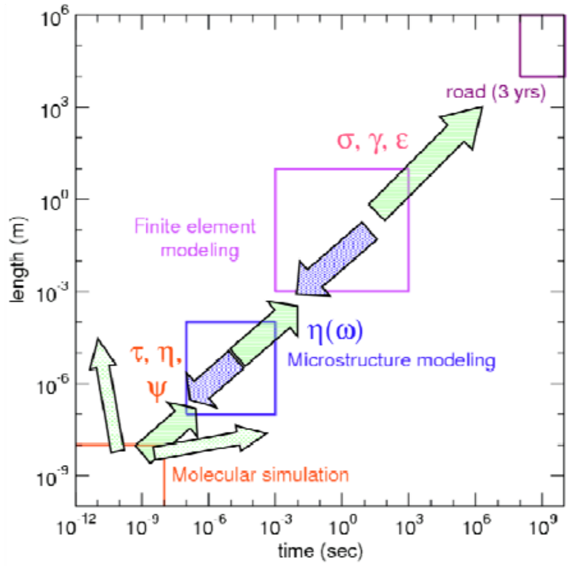

Figure F3a.1. "Push" and "pull" across length and time scales in modeling of asphalt chemical and mechanical properties across wide ranges of length and time scales.

A significant finding occurred when reanalyzing prior simulation results. The presence of a straight-chain C_{22} ordering effect (i.e. **spontaneous wax crystallization**) was recognized in a first-generation model asphalt (Zhang and Greenfield 2007) at 298 and 358 K but not at 400 and 443 K (0 and 85°C but not 127 or 170°C). The ordering occurred over times of 5 to 10 ns (1 ns ≡ 10^{-9} s) within a bulk model asphalt. (Surfaces had been precluded via periodic boundary conditions.) Preliminary information about this exciting event was shared at the Models ETG meeting. Further study is required to understand the crystallizations in detail.

Year Five Work Plan

Tasks	Specific Deliverables	Schedule
Subtask F3a-1. ab initio Theories, Molecular Mechanics/Dynamics and Density Functional Theory Simulations of Asphalt Molecular Structure Interactions (URI)	Sub-subtask F3a-1.1. Specify desired asphalt compositions and chemistries for testing multiscale asphalt modeling effort (large cluster simulations) (URI, WRI) Compositions have been chosen within the group but are not yet published. Hansen solubility parameter estimates have been made for each compound in the new models. Complete literature search. Sub-subtask F3a-1.2. Develop algorithms and methods for directly linking molecular simulation outputs and phase field inputs (URI, NIST) Progress on this task is limited to recognizing that it may be possible to achieve via an equation of state. This sub-subtask needs to remain in the work plan, and not having NIST on board will complicate accomplishing it. I haven't talked with Ed Garboczi or Jeff Bullard about this in a long time	3rd Quarter 2nd Quarter
Sub-subtask F3a-2.1. Collect information on available models and numerical methods suitable for phase field modeling(VT-WRI)	•A comprehensive literature •Identification of promising theory •Identification of corresponding numerical tool	Completed Completed Completed
Sub-subtask F3a-2.2. Phase-field parameter determination(VT-WRI)	•Identification of model parameters •Identification of parameter characterization methods •Performing parameter determination	Completed Completed 3rd Quarter
Sub-subtask F3a-2.3. Numerical solution of the phase-field equations(VT-WRI)	• Developing numerical algorithms • Computer code development • Development of result visualization method	2nd Quarter 4th Quarter U*
Sub-subtask F3a-2.4. Application of diffuse interface modeling to asphalt microstructure evolution(VT-WRI)	• Development of diffuse interface model • Phase distribution due to heating/re-solidification • Modeling of inter-phases diffusion	3rd Quarter 4th Quarter U*

Tasks	Specific Deliverables	Schedule
Sub-subtask F3a-2.5. Develop phase field models for characterizing asphalt emulsion and phase separation processes(VT-WRI)	• Formulating bulk and gradient energy • Modeling of emulsion process • Modeling of phase separation	3rd Quarter U* U*
Sub-subtask F3a-2.6. Phase-field modeling for fatigue cracking and self-healing processes(VT-WRI)	• Development of mesoscale cracking initiation, propagation and arrest criteria • Modeling of self-healing process • Performing experimental verification	3rd Quarter U* U*
Subtask F3a-3. Obtain temperature-dependent dynamics results for model asphalts that represent asphalts of different crude oil sources (URI)	These simulations are running now. The simulation runs will continue into next year. The data analysis will certainly continue into next year. Having 12 compounds and 5 temperatures per asphalt means 12x5 = 60 plots to analyze per property, and there are many properties. The results of those property analyses are what enable the comparisons listed in the bullet points.	4th Quarter
Subtask F3a-4. Simulate changes in asphalt dynamics after inducing representations of chemical and/or physical changes to a model asphalt (URI)	This has not yet been started.	
Subtask F3a-5. Molecular mechanics simulations of asphalt-aggregate interfaces (VT)	• Modeling of binder-aggregate compatibility • Modeling of interface shear behavior • Modeling of interface tensile behavior • Modeling of moisture damage	4th Quarter 4th Quarter 4th Quarter U*
Subtask F3a-6. Modeling of fatigue behavior at atomic scale (VT)	• Atomistic scale exploration of fatigue mechanism • Nano pore creation process • Modeling of fatigue in coupled physical-mechanical factors • Modeling of stiffness reduction at macro scale • Modeling of binder-mastic-mixture fatigue relationship	3rd Quarter 3rd Quarter U* 2nd Quarter 4th Quarter
Subtask F3a-7. Modeling of moisture damage (VT)	• Atomistic scale moisture damage mechanism • Void structure and mesoscale damage due to excess pore water pressure • Binder-mastics-mixture moisture damage using a multiscale approach	3rd Quarter 4th Quarter U*
Subtask F3a-8. ab initio Calculations of Asphalt Molecular Structures and Correlation to Experimental Physico-Chemical Properties of SHRP Asphalts (WRI-TUDelft)	• Computations • Correlations	3th Quarter 4th Quarter

U*---Unsure at this stage

Cited References

Greenfield, M. L., 2009, Bitumen at the Molecular Level: Molecular Simulations and Chemo-Mechanics, submitted to *Proceedings: International Workshop on Chemo-Mechanics of Bituminous Materials*, Delft, the Netherlands.

Kringos, N., 2009 (Editor), *Proceedings: International Workshop on Chemo-Mechanics of Bituminous Materials*, Delft, the Netherlands.

Zhang, L., and M. L. Greenfield, 2007, Analyzing properties of model asphalts using molecular simulation. *Energy Fuels*, 21: 1712-1716.

Table for Decision Points and Deliverables

Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
2 Journal papers	Paper describing phase separation in bitumen and its relationship to fatigue and self healing based on experiment and continuum mechanics modeling. (WRI-Delft). Paper describing self-ordering in bitumen at molecular level based on molecular mechanics simulations. (URI).	6/30/11	NA	N/A

Work Element F3b: Micromechanics Model (TAMU)

Subtask F3b-1: Model Development (TAMU, NCSU, UNL)

Major Findings & Status

For this subtask, we have worked on modeling to predict and to characterize fracture damage of asphalt mixtures. Our modeling includes development of a performance-predicting fracture model tailored for asphaltic media and relevant test methods to identify fracture properties of the model. The technique is based on cohesive zone approach to properly model initiation and propagation of physical cracks. The cohesive zone modeling simulates initiation and evolution of discrete cracks based on physically measured fracture properties in realistic length scales. Therefore, it can clearly provide a stand-alone damage modeling alternative to other ARC modeling efforts that are mostly based on continuum damage approaches which typically characterize damage using phenomenological internal state variables. The cohesive zone approach can effectively and accurately address inelastic fracture damage and failure of various asphaltic media including heterogeneous asphalt mixtures and asphalt pavement structures. In addition, the cohesive zone model can be incorporated with the influence of material inelasticity (viscoelastic and/or viscoplastic), nonlinear behavior, moisture-induced damage as presented in the Subtask M4a-1, and microdamage healing.

The developed cohesive zone model will be delivered in the form of UEL (User ELement) subroutine codes within a commercial finite element software, *ABAQUS* so that the model can be integrated with the Texas A&M's unified continuum damage module, PANDA by providing a powerful fracture engine. This enables to ultimately model nonlinear-viscoelastic-viscoplastic responses with microfracture to complete failure of asphalt mixtures and pavements.

Work during the 4th year at UNL has progressed final forms of the cohesive zone fracture model and relevant laboratory testing protocols. Validation of the model has also been pursued during the 4th year. Following bullets briefly summarize modeling efforts made during the 4th year.

- One of experimental efforts we have made during the 4th year for the modeling is the further elaboration to develop a proper mixing-compaction protocol to produce fine aggregate matrix (FAM) mixtures in asphalt concrete mixtures. This effort is to provide more appropriate mechanical properties (viscoelastic properties and cohesive zone fracture properties) of the FAM phase to accomplish the finite element-based microstructure modeling. Based on conventional asphalt concrete volumetric systems, we assumed that the asphalt concrete mixtures consist of two primary material phases – the elastic phase of aggregates and the viscoelastic phase of FAM with entrained air voids. The FAM production protocol includes determination of binder content and compaction density of FAM phase based on the volumetric properties of asphalt mixtures. The binder content to produce the FAM mixture was algebraically determined as the one remaining after excluding binder absorbed in the coarse aggregates and the thin film of binder covering coarse aggregates from the total binder in the bulk asphalt concrete mixtures. The compaction density of FAM mixture was sought by attempting different target air voids in the samples. Mechanical properties of the two phases, coarse aggregate phase and FAM phase with different amount of air voids, were experimentally determined by conducting quasi-static nanoindentation tests for aggregates and oscillatory torsional tests for cylindrical FAM specimens. Material properties of each phase were then used in the finite element simulation to predict dynamic moduli of mixtures. Simulations results were compared to experimental dynamic moduli of asphalt concrete mixtures so that the reasonableness of the FAM mixing-compaction protocol can be assessed. As we presented in quarterly reports, fair agreement between simulated moduli and measured moduli was observed. In spite of several assumptions made and some inevitable technical limitations, based on the reasonable agreement between the experimental dynamic moduli and the simulated ones, the current development of the FAM fabrication protocol and the computational micromechanics modeling approach, although not yet perfect, seems attractive for characterizing the mechanical properties of asphalt concrete mixtures. In brief, we have completed the FAM mixing-compaction-production protocol with refinement in the computational model as planned in for this year.
- In order to develop a fracture testing system to determine cohesive zone fracture properties of the FAM phase, we have further elaborated the testing protocol based on the semi-circular bending (SCB) fracture geometry. The SCB testing is practically attractive since it is very simple to perform and multiple testing specimens can be easily prepared via a routine process of mixing and Superpave gyratory compacting of asphalt mixtures. Furthermore, the SCB geometry is even more attractive considering the fracture testing of field cores. The SCB fracture testing was incorporated with a digital image correlation

(DIC) system. The DIC is an easy-to-use, non-contact technique that makes use of high-resolution video cameras to capture time-varying deformations of a specimen. Using image analyses, it monitors full-field deformation including crack tip behavior at a certain loading time. The DIC test results at the local fracture process zone were incorporated with numerical cohesive zone fracture modeling so that the locally identified fracture properties of FAM mixtures can be determined. The SCB fracture tests of FAM specimens were conducted at a wide range of loading rates to more accurately identify rate-related fracture characteristics of FAM phase in asphalt concrete mixtures. Slower loading speeds produced more compliant responses than faster cases which clearly indicated the rate-dependent mechanical behavior of FAM mixture at intermediate temperatures.

- To investigate if the rate-dependent global mechanical behavior of FAM mixtures is related to fracture process as well as material viscoelasticity, we have incorporated the SCB test results with numerical simulations that account for both material viscoelasticity and cohesive zone fracture. Cohesive zone fracture properties of a bilinear cohesive zone model were determined for the wide range of loading rates. This was attempted to separately identify the sources of rate dependency so as to better determine if the rate-dependent mechanical response is related to the fracture process. A strong agreement between experimental test results and numerical simulations of reaction force, crack mouth opening displacement (CMOD) and crack tip opening displacement (CTOD) was obtained. The resulting two fracture properties (i.e., cohesive strength and cohesive zone fracture energy) identified at the local fracture process zone were plotted as the applied loading rates varied. The trends presented rate-related nature of the fracture characteristics, which indicates that the rate-dependent fracture characteristics needs to be considered accordingly when modeling the mechanical performance of typical asphalt concrete mixtures and pavements in which a wide range of strain rates is usually associated due to the mixture's significant heterogeneity and the various loading conditions.
- During the 4th year we have developed a rate-dependent cohesive zone model. This is an essential part of our work as it allows us to simulate fracture in asphalt mixtures in a more realistic way by accounting for the rate-dependent fracture characteristics. Towards this challenging task, the first step we took was to implement the bilinear cohesive zone model proposed by Espinosa and Zavattieri (2003) in the form of a UEL (User ELement) subroutine code within a commercial finite element software, *ABAQUS*. The cohesive zone model by Espinosa and Zavattieri (2003) appears to be more appropriate than previously implemented cohesive zone models because of several attractive features including: (a) the model can reduce artificial compliance effects by providing an adjustable initial slope in the cohesive law; and (b) it allows clearer definition of two different fracture modes (i.e., normal and in-plane shear for 2-D simulations) and their mixed-mode fracture than other models previously implemented.
- To account for the observed rate-dependent fracture characteristics of asphalt mixtures, we extended the rate-independent intrinsic bilinear cohesive zone model proposed by Espinosa and Zavattieri (2003) to a rate-dependent cohesive zone model in the form of another *ABAQUS* UEL subroutine code. In the rate-dependent model, different sets of fracture properties (i.e., cohesive strength and cohesive zone fracture energy) are

assigned to each cohesive element according to the rate within which the pairs of cohesive element faces displace with respect to each other. The validity of the model has been investigated by comparing simulation results to SCB test results obtained at different loading rates.

- Another modeling tasks we have accomplished during the 4th year is a multiscale modeling to predict damage dependent mechanical behaviour of asphalt mixtures subjected to cyclic loading (such as fatigue damage). The multiscale modeling is exclusively unique and powerful when one models an object which would require a highly refined mesh with a huge degree of freedom due to its highly heterogeneous microstructure. Asphalt mixtures and structures (i.e., pavements) are classic examples of such since they contain thousands of irregularly shaped, randomly oriented aggregate particles along with numerous potential cracking sites. We have developed the multiscale computer code as a tool to maximize modeling efficiency by reducing (or minimizing) the amount of laboratory tests and computational costs but still satisfying a sufficient level of predicting accuracy. During this year, the multiscale model has been applied to bending beam fatigue tests of FAM mixtures by altering the mixtures' constituent properties. Model simulation results presented material-specific fatigue damage characteristics, and the analyses results clearly demonstrated the sensitivity of the approach to constituent material properties. The multiscale model could drastically reduce expensive laboratory fatigue tests, which, when performed in the traditional manner, require many replicates and do not define the cause of microstructural fatigue damage and failure.

Year Five Work Plan

In Year 5, we will work on the following remaining activities:

- Testing of core materials selected by ARC modeling teams with the suite of experimental protocols developed and elaborated during the previous years.
- Validation of the rate-dependent cohesive zone model.
- 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.
- Multiscale modeling and analyses to investigate the effects of several key design variables on the overall fracture performance of asphalt pavements. Parametric analyses of individual design variables and their mechanical sensitivity will be primarily targeted.
- A final report that comprehensively describes all activities performed for this project: model development, testing protocols, test results and analyses, integration of test results into the model, model simulations, model calibration/validation, and model applications.
- Presentations of findings and results at several significant places: conferences, meetings, and workshops, etc.

Table for Decision Points and Deliverables

Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
Seven journal papers	Cohesive zone fracture modeling of asphalt mixtures considering inelasticity, nonlinearity, rate-dependent fracture, and mixture microstructure: modeling methodology, constitutive theory, testing protocols, test data, model simulation/calibration/validation, user element (UEL) codes in ABAQUS, and user-friendly manuals.	03/31/09 07/30/09 09/30/09 07/30/10 07/30/10 07/30/10 08/30/11	Complete Complete Complete Complete Complete Complete No change	N/A
Models and Algorithm		3/31/11		
Draft report	Multiscale modeling of asphaltic mixtures and pavements: modeling methodology, constitutive theory, and parametric analyses of the model.	06/30/11	No change	N/A
Final report		12/31/11		

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

Major Findings & Status

We have completed significant work on the qualification, verification, calibration and validation of the PANDA model and its components (figure F3c.1). We present the work done so far using the phases of modeling and simulation presented by Oberkampf et al. (2004). The PANDA team wants to acknowledge that this approach of presenting the model follows the work done and documented for the asphalt pavements community by Dr. William Buttlar from the University of Illinois at Urbana-Champaign and Dr. Eshan Dave from the University of Minnesota, Duluth Campus. They presented this approach in several occasions including the RILEM meeting in Chicago in 2008 and the FHWA Modeling Expert Task Group meeting that was held at the University of Wisconsin-Madison in September 2011 (Dave and Buttlar 2010).

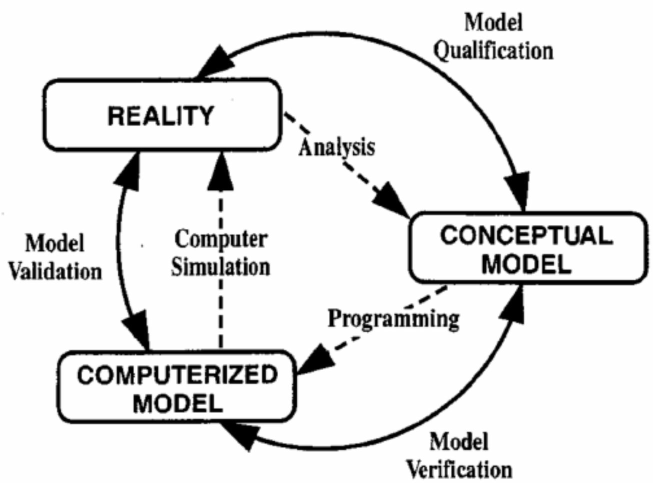

Figure F3c.1. Phase of modeling and simulation presented by Oberkampf et al. (2004) and Buttlar and Dave (2010).

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.

Table F3c.1. Qualification, verification, calibration and validation of the PANDA models (cont.).

Modeling Phase	Objective (after Oberkampf et al. 2004 and Dave and Buttlar 2010).	Progress
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).

Year Five Work Plan

Please refer to task V3c for the validation plan.

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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.

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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* (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.

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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.

Oberkampf, W. L., T. G. Trucano, and C. Hirsch, 2004, Verification, validation, and predictive capability in computational engineering and physics. *Applied Mechanics Review*, 57, 345-384.

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 for Decision Points and Deliverables

Type of Deliverable	**Description of Deliverable**	**Original Delivery Date**	**Revised Delivery Date**	**Reason for changes in delivery date**
PANDA Workshop	Workshop on PANDA Models and Validation Results	8/11	N/A	N/A
Draft Report	Documentation of PANDA Models and Validation	11/11	N/A	N/A
Final Report	Documentation of PANDA Models and Validation	3/12	N/A	N/A
UMAT Material	PANDA Implemented in Abaqus	3/12	N/A	N/A

Table of Decision Points and Deliverables for the Fatigue Program Area

<table>
<tr><th>Name of Deliverable</th><th>Type of Deliverable</th><th>Description of Deliverable</th><th>Original Delivery Date</th><th>Revised Delivery Date</th><th>Reason for changes in delivery date</th></tr>
<tr><td rowspan="2">F1a: Cohesive and Adhesive Properties</td><td>Journal Paper</td><td>Paper on relationship between ideal and practical work of fracture for aggregate-asphalt systems</td><td>6/11</td><td>N/A</td><td>N/A</td></tr>
<tr><td>Draft Report</td><td>Draft Report on Cohesive and Adhesive Properties</td><td>11/11</td><td>N/A</td><td>N/A</td></tr>
<tr><td rowspan="4">F1b-1: Nonlinear viscoelastic response under cyclic loading</td><td>Four journal papers</td><td rowspan="4">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.</td><td>12/30/08
3/31/10
9/30/10
12/31/11</td><td>Complete
Complete
3/31/11
No change</td><td>Development of the protocols required slightly more time than anticipated. A draft of the third paper is almost complete.</td></tr>
<tr><td>Models and Algorithm</td><td>3/31/09
6/30/10
12/31/11</td><td rowspan="3">3/31/12</td><td rowspan="3">It is more efficient and informative if the three different final reports, models and algorithms are consolidated into a single final report. The work at UT Austin that will make up the final report is 60% complete.</td></tr>
<tr><td>Draft report</td><td>12/31/08
12/31/11</td></tr>
<tr><td>Final report</td><td>6/30/08
3/31/12</td></tr>
<tr><td rowspan="2">F1b-2: Viscoelastic properties under monotonic loading</td><td>Draft Report</td><td>Documentation of PANDA Models and Validation Including the Method for Analysis of Viscoelastic Properties</td><td>11/11</td><td>N/A</td><td>N/A</td></tr>
<tr><td>Final Report</td><td>Documentation of PANDA Models and Validation Including the Method for Analysis of Viscoelastic Properties</td><td>3/12</td><td>N/A</td><td>N/A</td></tr>
<tr><td>F1c-2. Experimental Design</td><td>Report</td><td>Experimental Design Report</td><td>1/2009</td><td>Complete</td><td>N/A</td></tr>
</table>

Table of Decision Points and Deliverables for the Fatigue Program Area (cont.)

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
F1c-3: Develop a Transport Model of Binder Oxidation in Pavements	Presentation, Journal Paper	Contributions to a new thermal and oxygen transport model of binder oxidation in pavements	8/2009	Complete	N/A
	Two Journal Papers	Modeling pavement temperature for use in oxidation modeling	12/2010	Complete	N/A
	Presentation, Journal Paper	Contributions to Correlations of Oxygen Diffusivity in Asphalts and Mastics	12/2010	Complete	N/A
	Presentation, Journal Paper	A Fast-Rate, Constant-Rate reaction mechanism model	12/2011	N/A	N/A
	Journal paper	Incorporating air void size distribution into a pavement oxidation model	7/2011	N/A	N/A
	Journal paper	Modeling binder oxidation in pavements: Field Validation	3/2012	N/A	N/A
F1c-4:The Effects of Binder Aging on Mixture Viscoelastic, Fracture, and Permanent Deformation Properties	Journal paper	Relations between lab and/or field binder properties and their changes with oxidative aging and mixture fatigue properties	8/2011	N/A	N/A
F1c-5: Polymer Modified Asphalt Materials	Journal paper	Degradation kinetics of polymer modifiers in asphalt materials	3/2012	N/A	N/A
F1c: Aging (Unified Continuum Model for Aging)	Journal Paper	Document the aging model development and validation	4/11	N/A	N/A
	Journal Paper	Further validation of the aging model	11/11	N/A	N/A
	Draft Report	Draft Report on the aging modeling	03/12	N/A	N/A

Table of Decision Points and Deliverables for the Fatigue Program Area (cont.)

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
F1d – 1,2,3,4,5a,5b,8: Healing	Six journal papers	A mathematical model for self-healing 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 No change No change	
	Models and Algorithm		06/30/11	3/31/12	
	Draft report		06/30/10 06/30/11 12/31/11		It is more efficient and informative if the different final reports, models and algorithms are consolidated into a single final report. The final report is based on two theses: the thesis from Texas A&M University is complete and work for the thesis from UT Austin is 70% complete.
F1d-7: Coordinate with Atomic Force Microscopic (AFM) Analysis	Journal paper	Paper describing the phase-segregation nature of asphalt at the micro-nano scale		Complete	N/A
F1d-8: Coordinate Form of Healing Parameter with Micromechanics and Continuum Damage Models (TAMU)	Journal Paper	Formulating the micro-damage healing model based on micromechanics arguments within the framework of continuum damage mechanics	4/11		
	Journal Paper	Further validation of the micro-damage healing model	10/11		
	Draft Report	Draft Report on the self-healing modeling	03/12		

Table of Decision Points and Deliverables for the Fatigue Program Area (cont.)

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
F2d: Structural Characterization of Micromechanical Properties in Bitumen using Atomic Force Microscopy	Protocol for Measuring Viscoelastic Properties Using AFM	Protocol for preparing samples and taking measurements in AASHTO format – Protocol development complete, AASHTO format planned for 5/30/11	7/31/10	N/A	N/A
	Journal Paper	Submit ASCE Journal paper describing results of measurement of viscoelastic properties of various phases of three SHRP binders	3/31/11	N/A	N/A
	Evaluation of Impact of Aging and Moisture Conditioning	Complete	12/15/10	N/A	N/A
	Journal Paper	Submit journal paper describing how AFM characterization of viscoelasic properties can be used in micromechanical models	12/31/11	N/A	N/A
	Journal Paper	Submit journal paper describing how AFM characterization of asphalt phases can be used to classify performance potential of asphalt binders relative to fatigue, aging susceptibility, and moisture damage	12/31/11	N/A	N/A
	Final Research Report		2/28/12	N/A	N/A
F3a: Asphalt Microstructural Model	2 Journal papers	Paper describing phase separation in bitumen and its relationship to fatigue and self healing based on experiment and continuum mechanics modeling. (WRI-Delft). Paper describing self-ordering in bitumen at molecular level based on molecular mechanics simulations. (URI).	6/30/11	NA	N/A

Table of Decision Points and Deliverables for the Fatigue Program Area (cont.)

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
F3b-1: Micromechanics Model Development (Fatigue)	Seven journal papers	Cohesive zone fracture modeling of asphalt mixtures considering inelasticity, nonlinearity, rate-dependent fracture, and mixture microstructure: modeling methodology, constitutive theory, testing protocols, test data, model simulation/calibration/validation, user element (UEL) codes in ABAQUS, and user-friendly manuals.	03/31/09 07/30/09 09/30/09 07/30/10 07/30/10 07/30/10 08/30/11	Complete Complete Complete Complete Complete Complete No change	N/A
	Models and Algorithm		3/31/11		
	Draft report		06/30/11	No change	N/A
	Final report	Multiscale modeling of asphaltic mixtures and pavements: modeling methodology, constitutive theory, and parametric analyses of the model.	12/31/11		
F3c: Development of Unified Continuum Model	PANDA Workshop	Workshop on PANDA Models and Validation Results	8/11	N/A	N/A
	Draft Report	Documentation of PANDA Models and Validation	11/11	N/A	N/A
	Final Report	Documentation of PANDA Models and Validation	3/12	N/A	N/A
	UMAT Material	PANDA Implemented in Abaqus	3/12	N/A	N/A

Fatigue Year 5

		Year 5 (4/11-3/12)												Team
		4	5	6	7	8	9	10	11	12	1	2	3	
Material Properties														
F1a	**Cohesive and Adhesive Properties**													
F1a-1	Critical review of literature													TAMU
F1a-2	Develop experiment design													
F1a-3	Thermodynamic work of adhesion and cohesion													
F1a-4	Mechanical work of adhesion and cohesion													
F1a-5	Evaluate acid-base scale for surface energy calculations						JP							
F1b	**Viscoelastic Properties**													
F1b-1	Separation of nonlinear viscoelastic deformation from fracture energy under cyclic loading									JP	D		M&A,F	TAMU
F1b-2	Separation of nonlinear viscoelastic deformation from fracture energy under monotonic loading					JP	M&A,D						F	
F1c	**Aging**													
F1c-1	Critical review of binder oxidative aging and its impact on mixtures													TAMU
F1c-2	Develop experiment design													
F1c-3	Develop transport model for binder oxidation in pavements						JP			D	M&A		F	
F1c-4	Effect of binder aging on properties and performance						JP			D			F	
F1c-5	Polymer modified asphalt materials									D			F	
F1d	**Healing**													
F1d-1	Critical review of literature													TAMU
F1d-2	Select materials with targeted properties													TAMU
F1d-3	Develop experiment design						JP		JP	D		M&A	F	TAMU
F1d-4	Test methods to determine properties relevant to healing													TAMU
F1d-5	Testing of materials													TAMU
F1d-6	Evaluate relationship between healing and endurance limit of asphalt binders					JP				D	F			UWM
F1d-7	Coordinate with AFM analysis												F	WRI
F1d-8	Coordinate form of healing parameter with micromechanics and continuum damage models							JP		D			F	TAMU
Test Methods														
F2a	**Binder tests and effect of composition**													
F2a-1	Analyze Existing Fatigue Data on PMA													UWM
F2a-2	Select Virgin Binders and Modifiers and Prepare Modified Binder													
F2a-3	Laboratory Aging Procedures													
F2a-4	Collect Fatigue Test Data													
F2a-5	Analyze data and propose mechanisms				P			D			F			
F2b	**Mastic testing protocol**													
F2b-1	Develop specimen preparation procedures													TAMU
F2b-2	Document test and analysis procedures in AASHTO format													
F2c	**Mixture testing protocol**													
F2d	**Tomography and microstructural characterization**													
F2d-1	Micro scale physicochemical and morphological changes in asphalt binders													TAMU
F2e	**Verify relationship between DSR binder fatigue tests and mixture fatigue performance**													
F2e-1	Evaluate Binder Fatigue Correlation to Mixture Fatigue Data													UWM
F2e-2	Selection of Testing Protocols													
F2e-3	Binder and Mixture Fatigue Testing													
F2e-4	Verification of Surrogate Fatigue Test													
F2e-5	Interpretation and Modeling of Data													
F2e-6	Recommendations for Use in Unified Fatigue Damage Model								D		F			
Models														
F3a	**Asphalt microstructural model**									M&A			F	WRI
F3b	**Micromechanics model**													
F3b-1	Model development			D		JP	DP			F, SW		P		TAMU
F3b-2	Account for material microstructure and fundamental material properties			D						F				
F3c	**Develop unified continuum model**													
F3c-1	Analytical fatigue model for mixture design						M&A,D						F	TAMU
F3c-2	Unified continuum model			D			DP			F,SW				
F3c-3	Multi-scale modeling			D						F				
	Lattice Model						JP			JP			F	NCSU
	Continuum Damage to Fracture						JP			JP				

LEGEND

Deliverable codes	Deliverable Description
D: Draft Report	Report delivered to FHWA for 3 week review period.
F: Final Report	Final report delivered in compliance with FHWA publication standards
M&A: Model and algorithm	Mathematical model and sample code
SW: Software	Executable software, code and user manual
JP: Journal paper	Paper submitted to conference or journal
P: Presentation	Presentation for symposium, conference or other
DP: Decision Point	Time to make a decision on two parallel paths as to which is most promising to follow througjh
[x]	Indicates completion of deliverable x

- Work planned
- Work completed
- Parallel topic

	Fatigue Year 2 - 5	Year 2 (4/08-3/09)				Year 3 (4/09-3/10)				Year 4 (04/10-03/11)				Year 5 (04/11-03/12)				Team
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	
Material Properties																		
F1a	**Cohesive and Adhesive Properties**																	
F1a-1	Critical review of literature			JP														TAMU
F1a-2	Develop experiment design																	
F1a-3	Thermodynamic work of adhesion and cohesion																	
F1a-4	Mechanical work of adhesion and cohesion						JP			D	F							
F1a-5	Evaluate acid-base scale for surface energy calculations														JP			
F1b	**Viscoelastic Properties**																	
F1b-1	Separation of nonlinear viscoelastic deformation from fracture energy under cyclic loading			D,JP	M&A				JP	I&A,F,J	JP		P			JP,D	F,M&A	TAMU
F1b-2	Separation of nonlinear viscoelastic deformation from fracture energy under monotonic loading			JP	M&A				JP				JP		JP,M&A	D	F	
F1c	**Aging**																	
F1c-1	Critical review of binder oxidative aging and its impact on mixtures																	TAMU
F1c-2	Develop experiment design			D		F												
F1c-3	Develop transport model for binder oxidation in pavements		P		P, JP		P		P, JP		P,JP	JP	JP		JP	D, M&A	F	
F1c-4	Effect of binder aging on properties and performance				JP, P		JP	D	F						JP	D	F	
F1c-5	Polymer modified asphalt materials						P									D	F	
F1d	**Healing**																	
F1d-1	Critical review of literature																	TAMU
F1d-2	Select materials with targeted properties																	TAMU
F1d-3	Develop experiment design														JP	JP.D	F,M&	TAMU
F1d-4	Test methods to determine properties relevant to healing			JP					JP	D	F							TAMU
F1d-5	Testing of materials						JP				JP							TAMU
F1d-6	Evaluate relationship between healing and endurance limit of asphalt binders	DP				DP	JP	DP			JP		JP,P		JP	D	F	UWM
F1d-7	Coordinate with AFM analysis									JP							F	WRI
F1d-8	Coordinate form of healing parameter with micromechanics and continuum damage models															JP,D	F	TAMU
Test Methods																		
F2a	**Binder tests and effect of composition**																	
F2a-1	Analyze Existing Fatigue Data on PMA		DP															UWM
F2a-2	Select Virgin Binders and Modifiers and Prepare Modified Binder		DP															
F2a-3	Laboratory Aging Procedures																	
F2a-4	Collect Fatigue Test Data		P		JP		P		P				P, DP, JP					
F2a-5	Analyze data and propose mechanisms				P			P				P			P	D	F	
F2b	**Mastic testing protocol**																	
F2b-1	Develop specimen preparation procedures		D								F							TAMU
F2b-2	Document test and analysis procedures in AASHTO format		D								F							
F2c	**Mixture testing protocol**		D, JP	F	P,JP	JP	P	P	JP	P	P	JP	P					
F2d	**Tomography and microstructural characterization**																	
F2d-1	Micro scale physicochemical and morphological changes in asphalt binders						JP						JP					TAMU
F2e	**Verify relationship between DSR binder fatigue tests and mixture fatigue performance**																	
F2e-1	Evaluate Binder Fatigue Correlation to Mixture Fatigue Data																	UWM
F2e-2	Selection of Testing Protocols					DP, D	F			D	F							
F2e-3	Binder and Mixture Fatigue Testing																	
F2e-4	Verification of Surrogate Fatigue Test											D	F, DP					
F2e-5	Interpretation and Modeling of Data		JP		P		JP		P		JP		M&A					
F2e-6	Recommendations for Use in Unified Fatigue Damage Model												P			D	F	
Models																		
F3a	**Asphalt microstructural model**							JP								M&A	F	WRI
F3b	**Micromechanics model**																	
F3b-1	Model development				JP				JP			P,JP	P,M&A	D	JP,DP	F, SW	P	TAMU
F3b-2	Account for material microstructure and fundamental material properties													D		F		
F3c	**Develop unified continuum model**																	
F3c-1	Analytical fatigue model for mixture design														M&A,D		F	TAMU
F3c-2	Unified continuum model			JP				JP				JP	M&A	D	DP	F, SW		
F3c-3	Multi-scale modeling											JP	M&A	D		F		
	Lattice Model														JP	JP	F	NCSU
	Continuum Damage to Fracture														JP	JP		

LEGEND

Deliverable codes	Deliverable Description
D: Draft Report	Report delivered to FHWA for 3 week review period.
F: Final Report	Final report delivered in compliance with FHWA publication standards
M&A: Model and algorithm	Mathematical model and sample code
SW: Software	Executable software, code and user manual
JP: Journal paper	Paper submitted to conference or journal
P: Presentation	Presentation for symposium, conference or other
DP: Decision Point	Time to make a decision on two parallel paths as to which is most promising to follow througjh
[x]	Indicates completion of deliverable x

Work planned

Work completed

Parallel topic

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

There are four sub-elements to this work element. The first three are focused on analytical micromechanical models of binder, modified mastic and asphalt mixtures. The fourth is an analytical model of asphalt mixture response and damage. Progress has been made on the micromechanical models of modified mastics and asphalt mixtures and the analytical model of asphalt mixture response and damage. Application of the latter two models to measured laboratory data has confirmed the accuracy, flexibility and robustness of these models to represent accurately the laboratory-measured properties. The work on the modified mastic models awaits confirmation in the next year's work plan.

The forward and inverse self-consistent micromechanics model of an asphalt mixture, when applied to test data on an asphalt mixture and its binder derived the stiffness of the aggregate. The analytically derived result showed that aggregates become stiffer with increasing frequency, meaning that they are viscoelastic. After recovering from that initial discovery and reviewing the literature of geophysicists, rock mechanics and petroleum engineers, we found that they have been modeling rocks as viscoelastic for over a quarter of a century and that we should not have been surprised at this result. We also found that with porous limestone aggregates in hot mix asphalt, ultraviolet light showed that the lighter and less polar components of the asphalt were selectively absorbed into the interior of the aggregate particles. This was confirmed by a series of tests run by the Chemistry Department at Texas A&M using Laser Desorption Ionization-Ion Mobility-Mass Spectrometry (LDI-IM-MS) that there is a chromatographic effect within the aggregate with the lighter and less polar components in the center and the heavier and more polar components toward the surface or left on the surface outside the aggregate. This helps to explain the observed analytical result that as a mixture ages, the aggregates become stiffer and less dependent on frequency. It also suggests that the heavier and more polar asphalt molecules that are left behind on the aggregate surface may form a coating which assists in resisting moisture damage.

A further test on the aggregates was run by coring large aggregates into small (2-inch high X 1-inch diameter) columns and testing them for creep both before and after soaking them in hot asphalt. Another surprise was that the soaked limestone sample was less stiff and more viscoelastic than the original sample. All of these findings suggest that the micromechanics model of a mixture needs to consider the aggregate to be viscoelastic and instead of using binder properties, use the viscoelastic properties of the mastic or modified binder.

Using short term monotonically increasing tensile loading on an asphalt mixture at low levels of strain, we were able to use Laplace Transforms to convert the stress, axial strain, and radial strain measurements with time into frequency-dependent complex moduli and Poisson's Ratios. The test runs for no more than twenty seconds and the data are reliable between 5 and 20 seconds. Running this test at three different temperatures allows us to generate the complete master curves of both magnitude and phase angle of the complex modulus of the undamaged material and their time-temperature shift functions. These shift functions were different for the magnitude than for the phase angle. The Poisson's Ratio was found to be independent of frequency but dependent only upon the temperature. Each set of test data is digitized and gives us about forty or fifty data points with frequency at each temperature level. This very simple and accurate test procedure gives us a very efficient test protocol for determining the undamaged properties of an asphalt mixture, and is the basis from which all damage is inferred. When the sample is tested undamaged in both tension and compression, it is then ready to be subjected to a testing protocol that is intended to do damage.

We have also completed the formulation, testing, and analysis of the undamaged compressive viscoelastic and anisotropic properties of a mixture. Following the same procedure as described above, a single sample is tested with creep loading in compression, tension, and indirect tension at three different temperatures to produce the master curves (both magnitude and phase angle) of the vertical and horizontal compressive and tensile complex moduli and Poisson's Ratios. The vertical compressive modulus was found to be over twice as large as the horizontal at all frequencies of the master curves. The compressive phase angles peaked around 40 degrees and the tensile phase angle peaked around 75 degrees. The magnitude of the horizontal complex Poisson's Ratio rose to nearly 1.0 which is in accord with anisotropic elasticity theory. As with the tensile test, we use the Laplace Transform to determine the frequency dependent master curves. The complete characterization of the undamaged mixture in compression can be done in one day on a single sample.

In preparation for the tests on asphalt mixtures to determine the different kinds of damage and the effects of moisture and aging on the original properties and subsequent damage, we developed a complete analysis of a laboratory test of a mixture being tested with extended cycles of tension and compression, developing both fracture and plastic damage. The new method of analysis of the accumulation of damage applies the fundamental definition of pseudo-strain to arrive at the measures of fracture. This requires the use of the undamaged relaxation modulus and the damaged creep compliance of the mixture. With this new and more streamlined formulation, we no longer need to use the two types of dissipated pseudo-strain energy, W_{R1} and W_{R2}. Instead, we can separate the crack growth from the plastic deformation within the test data itself. This makes the analysis of the test data more straightforward and streamlined. We can produce the Paris' Law coefficients, A and n, and the growth of the cracking damage density which is used in the PANDA pavement damage analysis model. Healing also requires a more fundamental approach than was used previously. In this case, it was realized that when load is removed from the mixture, it leaves behind an internal compressive state of stress that forces the cracks closed as it reduces with time to zero. Taking guidance from tests on polymers that we found in the literature, we devised a way of using creep and recovery tests to measure the internal stresses at different levels of recovery. Then, using the rate of relaxation of the internal stress, it is possible to calculate the actual rate of closure of the cracks that had developed in the mixture. Running these new healing tests on mixes with different binders (AAD and AAM) we found the crack closure curves were strikingly different. The ability to measure the crack closure curve (as it is called by Schapery in his theory of crack closure and bonding) of a mix is one of the two essential parts needed to complete the healing convolution integral for mixtures suggested by Wool and O'Connor, who refer to it as the Wetting Distribution Function. The other part is what is referred to by Wool and O'Connor as the Intrinsic Healing Function.

The same fundamental approach was applied to the damaged compressive properties of asphalt mixtures. Starting with the fundamental definition of pseudo-strain makes it very simple to separate the elastic, plastic, viscoelastic, viscoplastic, and what we call viscocracking strains. Actual measurements have shown that cracking does not occur in mixtures in compression until they reach what is called the "tertiary" stage. Very little, if any, non-linear viscoelastic strain occurs in compression. With the test protocol that we have set up, we can now determine all of the Perzyna plasticity properties of the mixture in both the vertical and horizontal directions. The fracture that occurs in the tertiary phase of permanent deformation is sufficiently distinct to permit the determination of the Paris' Law properties, A and n, and cracking damage density. As with the tensile properties, the use of the fundamental definition of pseudo-strain has led to a great simplification of the analytical calculations and to the accuracy of the results. All of these improvements come at no increase in the testing time, efficiency or accuracy.

The new test and analysis methods that we use in tension are called the Viscoleastic Characterization (VEC) in the undamaged state and the Repeated Direct Tension (RDT) test in the damaging tension tests. In compression, we call the undamaged state test the Anisotropic Viscoelastic Characterization (AVEC) test and in the damaged state, we call it the Creep and Repeated Direct Compression (CRDC) test.

In tension, we use the percent air voids and the initial dissipated pseudo strain energy to determine the initial mean radius of the air voids and the number of them. The accumulated changes in dissipated pseudo-strain energy with repeated loads are used to determine the growth of the mean crack radius and to determine the Paris' Law parameters, A and n, and the growth of the cracking damage density directly from the test data. The resulting values of A and n compared well with previously measured and published values and with values calculated from Schapery's theory of crack growth in viscoelastic materials. The new test protocol is run on a single sample from which is determined the undamaged master curves (magnitudes and phase angles) of both the Complex Modulus and Poisson's Ratio, the initial mean radius of the air voids and the number of air voids. With the new test protocol, the damaging load cycles produce the growth of those air voids with repeated loads, and finally the fracture parameters, A and n.

In compression, we use the undamaged resilient modulus of the mixture and the damaged creep compliance of the same mixture, both measured on the same sample as the test proceeds. As noted above, the analysis that we now do permits us to determine the Perzyna plasticity properties, including the viscosity, exponent, the hardening parameters. Furthermore, with our new formulation, we can calculate the non-associated flow rule parameters as a function of the commonly measured cohesive shear strength and friction angle of the mixture. This will make the input parameters to the PANDA pavement damage analysis model much easier to get and will relate them to more commonly used engineering properties of mixtures. Finally, with our new formulation, we are no longer limited to friction angles between 0 and 22 degrees as in the standard ABAQUS software. This has been a serious limitation since most asphalt mixtures have friction angles in excess of 40 degrees. Our new formulation allows us to use friction angles between 0 and 90 degrees.

A further study of the initial mean air void radius was compared with the results of the X-Ray Computed Tomography scan of the same sample. It was found that the mean air void radius as determined by the fracture energy approach was somewhat smaller than the minimum size of air void that can be detected by the X-Ray CT apparatus and the number of such air voids was about twice the number that was determined by the X-Ray CT. Using the results of the two sets of measurements together, it is possible to determine the two Weibull parameters of the initial air void distribution and to determine the change of these two parameters as the mean crack size grows with repeated loads.

A very useful simplification was introduced to obtain the intrinsic anisotropic characteristics of a mixture from a scan of the perimeter of a core or a cylindrical lab-compacted sample and it works very well. The sample is placed on a rotator (previously used for cooking hotdogs) and rotated beneath a $100 digital scanner. The image that is produced of the aggregates on the sample surface provides a larger number of particles than the X-Ray Computed Tomography method does. Image analysis provides the shape, area, and orientation of each particle from which is derived the microstructural fabric tensor measure, Δ. The result is comparable in accuracy to what is obtained from an X-Ray CT scan and can be afforded by any engineering laboratory.

Thanks to the study we were able to make of the Dynamic Shear Rheometer (DSR) data on binders and mastics that were sent to us by Professor Hussain Bahia of the University of Wisconsin, we were able to develop master curves of both the magnitude of the shear modulus and phase angle of mastics and binders. We derived a new set of phase angle master curves which we call the β-curves which fit the data better than any others that we have found in the literature.

The modeling of modified mastics was done by computing the interactions of a mathematical particle model and the surface tension characteristics of different neat and aged binders. The particle model was varied through a wide range of shapes and sizes and a wide range of asphalt binders to find the compressive stress that is induced between particles by the surface tension of the asphalt that holds them together. Over 150,000 runs were made to generate the characteristic shapes of asphalt binder-particle interaction. One interesting finding of this is that particles smaller than 75μ are held together by most asphalts with a compressive stress greater than 1000kPa, the size of the tensile stress that is generated in pavement surfaces by truck tires. With this model, the effects of aging, chemical modification of the binder and particle shape and size can be studied and the relative effects can be evaluated.

Year Five Work Plan

Subtask E1a-1: Analytical Micromechanical Models of Binder Properties

We have received DSR data from Professor Hussain Bahia from the University of Wisconsin on both binders and mastics and have determined the modulus and phase angle master curves of the binders of all of the combinations that we received. We expect to receive other data from Dr. Bhasin from the University of Texas at Austin who has also run a series of DSR tests on other combinations of binders and mastics. We expect to use these data to determine if the forward and inverse self-consistent micromechanics model can infer the mechanical effects of the filler on the properties of the mastic. It may also be able to infer the mechanical properties of the filler itself. If they are consistent, they can be catalogued and used in the design of mastics. If successful, this approach can help to design the mastic to have the desired mechanical properties.

Subtask E1a-2: Analytical Micromechanical Models of Modified Mastic Systems

We have already received an extensive data base from Professor Hussain Bahia containing DSR test data for both neat binders and their companion mastics. In this fifth year, we will use the volumetric concentrations of the binder, filler and air in the mastic to determine the contributions of the filler on the properties of the mastic. If this is as successful as has been the forward and inverse self-consistent micromechanics model in inferring the properties of aggregates in an asphalt mixture, it may be possible to determine the mechanical contribution of the filler to the properties of the mastic. This has implications for the use of the self-consistent micromechanics model in mixtures. In order to determine the properties of aggregates from measurements of mixtures it may be necessary to use the properties of mastics, instead of binder to obtain accurate aggregate properties. Chemical modifiers will also have an effect on the mechanical properties of the mastic and we should be able to tell their effects by the use of this same model. We will also use the particle model and interact it with the properties of the binders to investigate to what extent this is capable of explaining the effect of fillers on the properties of the mastic.

Subtask E1a-3: Analytical Models of Mechanical Properties of Asphalt Mixtures

We have formulated the protocol and are in the process of making the laboratory measurements of the anisotropic viscoelastic undamaged properties of a mixture in compression. As with the tensile characterization of mixtures, this will provide us with the complete master curves of the vertical and horizontal magnitude and phase angles of the complex moduli, complete with the time-temperature shift functions for each. We will also obtain the temperature dependence of the horizontal and vertical Poisson’s Ratios and their frequency dependence. This protocol is intended to be used to measure the undamaged viscoelastic properties of an asphalt mixture in preparation for subsequent conditioning and testing that will induce either aging or fracture or plastic deformation and healing.

As an adjunct to these undamaged protocols, we expect in this fifth year to conduct a series of tests and analyses on Fine Aggregate Mixtures in the Dynamic Mechanical Analyzer (DMA) to determine the effect of relative humidity on moisture damage. The reason for this is clear: relative humidity can be computed and predicted with existing models such as the Enhanced

Integrated Climatic Model that is currently being used in the Mechanistic Empirical Pavement Design Guide. In being able to model moisture damage in the field, it is important to be able to relate the moisture damage to a condition that can be predicted reliably with existing (and future) models. In anticipation of these tests on the Fine Aggregate Mixtures (FAM), we have calculated the theoretical Adhesive and Cohesive Bond Energy as it varies with the level of Relative Humidity. It will be the objective of these tests to determine if the pattern predicted by the theoretical Bond Energies is matched by the measurements. The tests will be run in tension instead of the torsion which has been the practice with DMA testing in the past. This permits the direct measurements of actual material, fracture and healing properties of the FAM mixture. The non-uniform state of stress in the torsion test did not permit the determination of material properties but only indices.

Together with the success that we have had with measuring the fracture properties of mixtures in tension we are now making damaging compression tests to measure the incremental anisotropic viscoplastic strains with repeated loads. In this fifth year, we will conduct these compressive tests on a variety of asphalt mixtures to characterize the viscoplastic damage characteristics of these mixes. All estimates of damage must proceed as a departure from the properties of the mixtures in an undamaged state in both compression and tension. We have completed the mechanics formulation of the compression characterization of the anisotropic viscoplastic damage and are prepared to analyze the compressive tests in accordance with these formulations. We will be able to determine all of the Perzyna plasticity properties, the hardening function coefficients, and the non-associative flow rule properties α and β.

The test protocol that we have worked out to test field cores has proven capable of measuring the master curves of the complex moduli and Poisson's ratios at the top and bottom of an existing pavement layer and to determine the stiffness gradient of the mixture with depth into the pavement. This ability to measure the mixture stiffness with depth is expected to close the loop with DSR measurements that have been made on extracted binders taken from thin slices of field cores. As a preliminary observation of the results made to date, it appears that the higher the percent of air voids, the deeper the aged stiffness occurs beneath the pavement surface. We will continue to make these measurements on the field-aged cores that we receive from the ARC test pavements and provide this information to those who are researching the effects of aging. The measured effects of field aging of mixtures will provide target values for the PANDA pavement performance prediction model to match.

Depending upon the findings we make in the previous two tasks on binders and mastics, we will make a decision on whether it is necessary to extract the aggregate properties from tests on mixtures and binders or mixture and mastics. The extraction will be made with the forward and inverse self-consistent micromechanics model. We will seek out properties of asphalt mixtures with various aggregates in order to begin on a catalog of aggregate properties. It is becoming apparent from the studies we have made of the effects of absorbed asphalt on the mechanical properties of the aggregate itself and the possible surface coatings left behind on the surface of the aggregates by selective absorption that the absorption properties of the aggregates may be a subtle, unexpected, but important characteristic of aggregates.

The self-consistent micromechanics model may prove to be a better model for determining the aged properties of an asphalt mixture by combining the properties of the aggregate with the aged properties of the mastic than any of those currently reported in the technical literature. Its success so far suggests that this may prove to be a good use for this model in determining the aged properties of a mix from the aged properties of its components.

Subtask E1a-4: Analytical Model of Asphalt Mixture Response and Damage

The model of the response, the growth of microcracks and plastic deformation and of healing that has been demonstrated in the series of tests noted above will be further enhanced to incorporate two and three-dimensional effects. Both cracking and plastic deformation are affected by an apparent change of modulus and phase angle of the asphalt mixture. Healing engenders an apparent change in both of these quantities and thus healing affects the growth rate of both cracking and plastic deformation.

A new formulation of the analyses of the tension and compression test data makes use of the fundamental definition of pseudo-strain and has proven to be simple and efficient to apply to both kinds of test data. The tests we have run on a variety of asphalt mixtures have verified these formulations. Analysis of the test data with the newly formulated set of dissipated pseudo-strain energy, cracking, plastic deformation, and healing characteristics of a mixture will produce a refined final product. These tests will support the efforts in other tasks related to aging, fatigue, and moisture damage. An effort will be made to determine if an improvement can be made in the current formulations of the thermal coefficient of expansion and contraction of an asphalt mixture using the principles of self-consistent micromechanics.

In this fifth year, we will continue to work together with the part of the team which is assembling the PANDA model of pavement performance to try out our measured engineering material properties, both damaged and undamaged, to see if predictions of pavement performance made with these measured material properties will produce realistic predicted results. The cracking output will be in the form of color contours of the size and density of cracks in each of the finite elements used in the computations. The viscoplasticity deformation output will be in the form of color contours of total accumulated movements after a given number of passes of traffic loads.

Table for Decision Points and Deliverables

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Projected Delivery Date	Revised Delivery Date	Reason for Changes Associated with the Deliverable
Characterization of asphalt mixtures using controlled-strain repeated direct tension test	Journal Paper	Journal paper prepared that describes the measurement and analysis method to characterize asphalt mixtures using controlled-strain repeated direct tension test	07/01/10	02/02/11	The analysis method was changed due to the new development work
Characterization of fatigue damage in asphalt mixtures using pseudo stain energy	Journal Paper	Journal paper prepared that describes the method to characterize and quantify the fatigue damage using pseudo strain energy	08/01/10	02/20/11	More tests are needed to obtain the essential material properties
Model fatigue crack growth in asphalt mixtures	Journal Paper	Journal paper prepared that describes the method to model the evolution of the damage density		03/20/11	
Determine the healing properties of asphalt mixtures using controlled-strain repeated direct tension test	Journal Paper	Journal paper prepared that describes the method to measure and model the healing rate of asphalt mixtures with fatigue damage		04/20/11	
Determine the healing properties of asphalt mixtures using tensile creep and recovery test	Journal Paper	Journal paper prepared that describes the method to efficiently measure and model the healing rate of asphalt mixtures with creep damage		05/20/11	
Influence of aging on the fatigue resistance and healing properties of asphalt mixtures	Journal Paper	Journal paper prepared to examine the effect of aging on the fatigue and healing properties of asphalt mixtures		09/01/11	
Model and Algorithm	Model and Algorithm	The model and algorithm for testing and analysis of damaged asphalt mixtures in tension		09/01/11	
Nondestructive Characterization of Anisotropic Viscoelastic Properties of Undamaged Asphalt Mixtures under Compressive Loading	Journal Paper	A Paper written by TAMU researchers that state the testing protocols and analysis methods to obtain the comprehensive properties of the undamaged asphalt mixtures in compression.	Completed		

Table for Decision Points and Deliverables (cont.)

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Projected Delivery Date	Revised Delivery Date	Reason for Changes Associated with the Deliverable
Microstructure-Based Inherent Anisotropy of Asphalt Mixtures	Journal Paper	A Paper that describes a characterization parameter and an easily done test for the inherent anisotropy	Completed		
Interpretation of Parameters in Microstructure-Based Viscoplastic Model of Asphalt Mixture	Journal Paper	A paper that provides the parameter inputs of the viscoplastic model within the PANDA program based on basic material properties		9/30/2011	
Viscoelastic and Viscoplastic Characterization of Asphalt Mixtures in Compression	Journal Paper	A paper that provides a fast technique to conduct the decomposition of the viscoelasticity and viscoplasticity and supplies the material parameter inputs for the PANDA program		6/30/2011	
Continuum Damage Permanent Deformation Analysis for Asphalt Mixtures	Final Report	Ph.D. dissertation at TAMU that describes the viscoplastic mechanism for permanent deformation of the asphalt mixtures and provides the testing protocols and analysis methods to acquire the input parameters of the PANDA program.	12/31/2010	12/31/2011	Time is needed to make the product compatible with the PANDA program
Evaluation of the Stiffness Gradient in the Field aged asphalt samples	Journal Paper	The paper will describe the analysis methods for stiffness gradient prediction and finite element simulation model of test	07/31/2010	04/20/11	Testing more samples from different locations were needed
Fatigue damage characterizations of asphalt using the overlay tester	Journal Paper	The paper will use the strain energy concepts together with finite element modeling to find A and n parameters		05/20/11	
Develop a RDT DMA Testing Protocol	Technology Transfer	This new testing protocol is stress controlled repeated tension testing method and will be used to replace the previous torsional DMA testing method	08/15/2010	02/15/2011	New DMA Machine Arrive Late
Standardize Testing Procedure for Specifications	AASHTO Specification	Develop a Standard Specification to use as a comparative test to evaluate fracture properties, healing and moisture damage of FAM		09/30/2011	

Table for Decision Points and Deliverables (cont.)

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Projected Delivery Date	Revised Delivery Date	Reason for Changes Associated with the Deliverable
Model FAM Fatigue Crack Growth under Different Relative Humidity	Journal Paper	This paper will characterize the moisture damage of FAM conditioned under 5 different relative humidities		04/15/2011	
Characterize FAM Bond Energy under Different Relative Humidity	Journal Paper	This paper describes a new method to back calculate the bond energy of FAM by the means of fatigue cracking modeling		06/15/2011	
Develop a New DMA Testing Protocol for Compression	AASHTO Specification	Develop a Standardized testing method to use as a comparative test to evaluate compressive properties of FAM		09/15/2011	
Characterize Permanent Deformation of FAM under Different Relative Humidity	Journal Paper	This paper will characterize the permanent deformation of FAM conditioned under 5 different relative humidities		03/31/2012	
Self-Consistent Micromechanics Model of Asphalt Mixtures	Journal Paper	This paper describes the inverse and forward self-consistent micromechanics models of asphalt mixtures.	Published (ASCE Journal of Materials in Civil Engineering)		
Crack Size Distribution in Asphalt Mixtures	Journal Paper	This paper presents the Weibull distribution models of crack size in asphalt mixtures at different numbers of load applications.	Accepted for publication (Transportation Research Record)		

Work Element E1b: Binder Damage Resistance Characterization (DRC) (UWM)

Subtask E1b-1: Rutting of Asphalt Binders

Major Findings and Status

Year 4 activities focused on evaluating effects of various concentration and type of modifiers to achieve 2 target PG grades, and to study the response to repeated creep testing (MSCR) at several combinations of stresses and temperatures. The modifiers used included elastomeric and plastomeric modifiers, a ground tire rubber, as well as the elastomeric combined with a cross-linking agent. The additional blends of all modifiers showed that continuous grade of the rolling thin film oven (RTFO)-aged material is not completely linear and that linear interpolation of percent modifier required to achieve the targeted continuous grade was not consistent. Therefore, a nonlinear relationship to achieve the targeted continuous grade within $\pm$ 0.25 ^{o}C target high-temperature grade was developed.

To further capture the behavior of the binder under repeated loads at different stress levels it was decided to extend the number of cycles from the commonly accepted 100 to 1000 cycles at each stress level. The testing matrix included two replicates for each test at 46 ^{o}C, 58 ^{o}C and 70 ^{o}C and at stress levels of 100, 3200 and 10,000 Pa. The required amounts of each modifier to result in a two-grade increase (PG76) are 3.2, 4.7 and 7.1 percent for the elastomer, plastomer and GTR, respectively. In addition to binder testing, the plan in Year 4 was to include mastic (filler + binder) testing. The work on mastic preparation and testing is under way.

Analysis of the MSCR test results collected for binders in year 4 indicates that modified binders vary in their nonrecoverable creep compliance (J_{nr}) and percent recovery (%R) values depending on temperature, stress level and modifier type. The plastomer modifier exhibited levels of overall J_{nr} value and the %R values that are comparable to the elastomeric modifier at lower temperatures. However, the plastomeric modified binders showed the highest sensitivity to change in stress level among all binders. The sensitivity of all binders to stress increased with temperature. The analysis of the Repeated Creep and Recovery (RCR) results showed that with increasing the stress level from 100 Pa to 3200 Pa and then to 10000 Pa, the performance order of different modifiers gets reversed. This change of performance in the RCR test was similar to the MSCR results, but perhaps the stress level in MSCR did not go high enough to see the change of ranking of modified binders based on the J_{nr} values. Further testing to clarify the stress and temperature sensitivity of the modifiers is warranted.

Modeling the binder results to a previously defined model (Delgadillo and Bahia 2010) provided a reasonable prediction for the strain of the elastomer-modified binder used in this study and for mastics that incorporate the same binder.

Mixture testing was also conducted in Year 4 using two very different coarse and fine gradations with a 19.5-mm nominal maximum aggregate size (NMAS), as required by the Wisconsin DOT specifications. The same gradations were used for both limestone and granite aggregate sources utilizing equivalent amounts of material passing the No. 200 sieve. After determination of the optimum asphalt content for each combination of aggregate type and gradation, the percent reduction in air voids from the total specimen to the cut and cored specimen was determined. There was no clear distinction between the reduction in air voids of fine and course gradations due to cut and core, with the average reduction of about 1.75 percent. In addition, image analysis was used to evaluate and quantify the aggregate structure in terms of aggregate orientation, contact points, and spatial segregation. The results revealed a clear distinction between gradations based on the normalized contact points and orientation, even though cored samples had similar percent air voids. These observations are indicative of the need for studying internal aggregate structure to further identify specimen properties beyond density and perhaps explain performance.

Flow number (FN) testing was conducted for both fine and coarse gradations of limestone using each of the four binders 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 test at low stress levels.

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

Additional time was spent on mixture preparation for washing the aggregates, conducting DSR accuracy checks between different makes and models and on obtaining consistent air voids for mixtures, particularly for mixes made with GTR binder. These issues have all been resolved, although they consumed a good amount of time and led to shifting some of the work into the Year 5 work plan. No major implication in terms of the deliverables is expected.

Year 5 Work Plan

Subtask E1b-1-1: Literature review

This subtask was completed during Year 2.

Subtask E1b-1-2: Select materials and develop work plan

This subtask was completed during Year 2.

Subtask E1b-1-3: Conduct testing

The remaining MSCR and RCR testing of mastics will be conducted at 70 °C, 58 °C and 46 °C. This will allow for direct comparison at a high and intermediate temperature as well as temperature equivalent to mixture testing. In addition, a small subset of binders with specific combination of J_{nr} and %R will be formulated. The subset will include binders with high and low J_{nr} for similar %R and also high and low %R for a given value of J_{nr}. These combinations are required to clearly show the importance of %R for rutting resistance. In addition, the RCR testing will be conducted at stress levels of 100, 3200 and 10000 Pa for this combination to study the effect of high number of cycles. FN testing of mixtures will continue to take place at 46 °C and stress levels of 345 and 1034 kPa on the granite aggregate samples for the neat binder, as well as the new set of binders (the testing will be identical to tests done on the limestone mixtures).

Subtask E1b-1-4: Analysis and interpretation

The results of the remaining mastics will be analyzed to determine possible relationships between mastics and mixtures of coarse-graded granite aggregate for FN testing. MSCR modeling of the binders and mastics will continue. The focus will be placed on studying the importance of %R at various J_{nr} values and the role of stress level at various temperatures.

Subtask E1b-1-5: Standard testing procedure and recommendation for specifications

Standard testing procedures to quantify effect of %R, stress, and temperature will be developed based on the results collected in this study. Recommendations for considering %R, stress and temperature in selecting of binders will be formulated.

Cited References

Delgadillo, R. and H. Bahia, 2010, The Relationship between Nonlinearity of Asphalt Binders and Asphalt Mixture Permanent Deformation. *International Journal of Road Materials and Pavement Design*, 11 (3), 653-680.

Table for Decision Points and Deliverables

Date	**Deliverable**	**Description**
04/11	Presentation	Possible models that accounts for multiple modifiers.
07/11	Draft Report	Draft report of the binder, mastic and mixture results.
09/11	Journal Paper	Journal paper.
01/12	Final Report	Final report to cover all the activities of the project.

Subtask E1b-2: Feasibility of Determining Rheological and Fracture Properties of Asphalt Binders and Mastics Using Simple Indentation Tests (Modified Title)

Major Findings and Status

In Year 4 the research team finished the modification of the indentation test to measure creep compliance and to perform creep and recovery tests. Two new components were added to the previous test setup: a counterbalance system to improve contact and flexibility of loading and an automatic data acquisition system to improve resolution of measurements. Due to the importance of the initial contact of the indenter with the asphalt sample surface, part of the focus of the modified setup was to improve the contact method. Previously, the mark left by the glycerin on the sample surface was used to confirm indenter contact. In the new procedure, the pulley and counterweights enables the shaft and indenter to float freely. Thus, when the indenter shaft is lowered toward the sample surface upon contact the displacement sensor attached to the shaft shows a miniscule negative deflection, which indicates sample contact.

The research team also developed a load-controlled indentation finite element (FE) model in ABAQUS. The load-controlled indentation model is capable of simulating the experimental conditions of the indentation test. Simulations indicated the importance of size effects. The size effects observed in the experiment were simulated using FEM and a simple method to account for this effect was developed.

The creep compliance of different binders measured at 20 and 30°C with the Dynamic Shear Rheometer (DSR) were compared to measurements obtained from the indentation tests. Similar results between the DSR and the modified indentation test indicate that linear visco-elastic properties can be measured with this modified penetration method if size effects are taken into account. Also, a Burgers model was used to fit the creep data obtained from the indentation experiments to estimate the non-recoverable creep compliance (J_{nr}). The estimated J_{nr} from indentation tests at 30°C were compared to MSCR test results at 30 and 64°C. MSCR tests at 30 °C showed a poor correlation, as the material did not completely recover in 9 seconds, while MSCR tests at 64°C showed a fairly good correlation for both stress levels. The research team performed creep and recovery tests with the modified indentation/penetration device. Typical results for the creep and recovery test of the binders clearly showed the effect of modification. The modified binders show lower displacements which indicate the stiffening effect of the modifiers. Furthermore, the binder modified with SBS seems to have higher elastic recovery in comparison to the neat and CBE modified binder.

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

The completion of this work element has been postponed due to significant delays in receiving the modified test setup from the machine shop, as well as technical difficulties in initial design that required further modifications of the testing setup. The research team plans to double the efforts in completing the experimental matrix as well as finalizing the procedure during Year 5. The aforementioned delays caused the collaborative effort between the University of Minnesota and UW-Madison on measuring fracture properties with indentation test to be move to Year 5 as well.

The 5-year Gantt chart has been updated to indicate that journal papers are now planned for Q1 and Q3 of year 5. Furthermore, due to the delays discussed, the delivery dates for the draft and final report for this work element have been shifted to Q3 and Q4 of Year 5.

Year 5 Work Plan

Subtask E1b-2i: Literature review

This subtask has been completed.

Subtask E1b-2ii: Proposed Superpave testing modifications

The research team will work with the research group at the University of Minnesota on modifications of the Bending Beam Rheometer (BBR) to run indentation tests for characterization of fracture properties at low temperature.

Subtask E1b-2iii: Preliminary testing and correlation of results

The research team completed the indentation test matrix for asphalt binders in Year 4. The team plans to complete the test matrix of mastic samples with the modified indentation/penetration device in Year 5. The team also plans to use the indentation device for creep and recovery tests with 1:9 proportions for the loading and unloading time.This will be carried out in the first quarter of Year 5.

Subtask E1b-2iv: Feasibility of using indentation tests for fracture and rheological properties

Work will focus on assessing the repeatability of the modified indentation/penetration device with new procedure that initially avoids the use of the clutch. Efforts will also continue on optimization of the sample geometry with finite element (FE) modeling. Final sample geometry and proposed test procedure will be recommended by the end of Year 5.

Table for Decision Points and Deliverables

Date	Deliverable	Description
04/11	Journal Paper	Paper on the use of indentation test for characterization of asphalt binders.
10/11	Presentation	Presentation summarizing implementation of indentation tests for rheological characterization of asphalt binders.
10/11	Draft Report	Report on finite element simulations of the indentation test and correlations with DSR results.
01/12	Final Report	Report on finite element simulations of the indentation test and correlations with DSR results.

Work Element E1c: Warm and Cold Mixes

Subtask E1c-1: Warm Mixes (UWM)

Major Findings and Status

Efforts in Year 4 focused on evaluation of asphalt mixture workability and the performance implications of the reduced short term aging due to reduced production temperatures. Workability results indicate that WMA additives were successful in reducing the temperature sensitivity of mixes compacted in the Superpave Gyratory Compactor (SGC). Conversely, HMA exhibited a sharp decrease in workability at compaction temperatures below 90°C. Previous work established that this difference in workability is not observed in measurements of asphalt binder viscosity. As a result, continued development of the asphalt lubricity test procedure focused on evaluation of the relationship between mixture compaction and binder lubricity at similar temperature ranges. The sensitivity of binder lubricity and testing temperature was found similar to that observed for mixture compaction. Furthermore, a statistical model including lubricity, viscosity, and mixture gradation was developed to identify the binder and mixture properties that most significantly influence mixture workability. Results showed that at lower temperatures asphalt binder lubricity has significant impact. As temperature increases, the effects of lubricity diminish and viscosity of binder showed more influence on compaction. However, across all testing temperatures, mixture gradation was found to have the most significant impact.

For the limited data set collected it is clear that the role of warm mix additives and lubricity is highly gradation specific.

Potential concerns about rutting performance due to the reduced production temperatures associated with WMA were evaluated using both asphalt binder and mixture performance. Asphalt binder properties were measured after various short term aging temperatures and modeled in accordance with the FHWA aging model presented in the NCHRP 9-43 Interim Report. Results indicate that both the $G^*/\sin\delta$ and J_{nr} from MSCR test results are significantly impacted by reduced aging temperatures. Furthermore, differences were observed between the FHWA model and the model developed using the experimental data in this study. The differences are relatively high, and the reductions in production temperature that could cause a decrease of one PG grade differed by 10°C. Mixture Flow Number results and qualitative observation of the samples after testing confirmed the potential for reduced rutting resistance due to reduced aging.

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

The research team continues to work with the Wisconsin Department of Transportation (WisDOT) to provide field projects for evaluation of WMA placed in Wisconsin. To date, WisDOT has not presented any opportunities for WMA field trials, but a trial section in a military base in Wisconsin was successfully monitored and analyzed. The research team will continue to work with WisDOT and, if possible, incorporate results into a draft final report. Delivery of this task is dependent on the ability to test on field projects, thus impacts on future work are unknown.

Re-design of the Asphalt Lubricity Fixture delayed testing approximately three months. The level of effort will be increased early in Year 5 to allow for completion of the evaluation of this test procedure. The Gantt Chart for Subtask E1c-1iii was extended to reflect this delay.

Year 5 Work Plan

Subtask E1c-1i: Effects of warm mix additives on rheological properties of binders

This subtask is complete. Findings indicate that most WMA additives have little impact on asphalt binder performance properties as evaluated using standard PG Grading and the MSCR test. The exception is wax based additives, which cause an overall stiffening effect, improving high temperature performance and reducing low temperature properties. It is expected that rheological evaluation of binders modified with WMA additives will continue to support other subtasks. Where applicable, newly developed test methods, specifically the Bitumen Bond Strength (BBS) test and Single Edged Notched Beam (SENB) test, will also be used to supplement previous findings.

Results will be summarized and provided as a draft report. The Gantt chart has been modified to indicate that this information will be incorporated into the draft report upon completion of Subtask E1c-1iii.

Subtask E1c-1ii: Effects of warm mix additives on mixture workability and stability

Work will continue under this subtask focused on analysis of mixture compaction data collected in Year 4 and continued development of the asphalt binder lubricity test. Specific activities related to the asphalt binder lubricity test include: establishing the repeatability of the test and ruggedness of testing parameters (temperature, normal force, and speed) and defining the dependence of lubricity test output on WMA additive concentration. Lubricity test results will be used in conjunction with asphalt binder viscosity and mixture properties to define the factors that most significantly influence mixture workability.

Results will be summarized and provided in the aforementioned draft report.

Subtask E1c-1iii: Mixture performance testing

Literature review and involvement with the FHWA Warm Mix Technical Working Group identified the impacts of reduced aging temperatures and moisture damage as the two major performance issues unique to WMA. The research team at UW Madison will continue to address the issue of reduced aging using both asphalt binder and mixture performance testing. Impacts on high and low temperature performance will be addressed using mixture flow number and thermal stress restrained specimen (TSRST) short and long term aged at reduced temperatures. In addition, asphalt binder high temperature and fracture properties will be measured to supplement mixture testing results.

The research team at University of Nevada-Reno will evaluate moisture damage through comparison of the dynamic modulus of unconditioned samples to those subjected to one and three freeze thaw cycles. The experimental plan includes a control HMA mix, HMA produced at WMA conditions, and mixes using three different WMA types. Bitumen Bond Strength Testing will be conducted by UW Madison to assess the ability of the BBS test to serve as an indicator for moisture susceptibility.

Results will be summarized and provided as a separate draft report. The Year 5 Gantt Chart was modified to indicate that these results will be combined with Subtasks E1c-1iv – E1c-1v in the draft final report.

Subtask E1c-1iv: Develop revised mix design procedures

This subtask will be coordinated pending the publication of the final report for NCHRP 9-43. It is anticipated that the report will be published in 2011 Q1.

Any recommended modifications to the NCHRP 9-43 proposed design procedure will be communicated in the mixture performance draft report.

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.

Results will be summarized and provided as part of the mixture performance draft report.

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

Major Findings and Status

Efforts in Year 4 were focused on laboratory evaluation of emulsions and the entire chip seal system. Emulsion evaluation included testing during various stages of curing as well as recovered emulsion residues. The most significant result of this work element was the introduction of a standard test method for measuring the adhesion and cohesion of the bond between asphalt and aggregate. The method called the Bitumen Bond Strength (BBS) test, proposed for evaluating the adhesive properties of emulsions and residues, was accepted by the AASHTO Subcommittee on materials and sent for ballot in the fall of 2010. Developmental efforts to support the test procedure found that the BBS test is able to rank different materials and demonstrate the development of bond strength with increasing curing time. BBS results also correlated well with the percent aggregate loss measured by the sweep test, allowing for recommendation of a minimum pull off tensile strength to achieve adequate performance. In application of the test to a performance selection framework, it was found that it is more appropriate to test materials at equal moisture loss rather than equal curing times. Additional testing will be conducted to incorporate this finding into the testing procedure and emulsion evaluation framework. Furthermore, BBS testing on emulsion residues showed considerable gains in strength after the residue recovery procedure and found latex and polymer modified systems to be less susceptible to moisture damage than unmodified emulsions.

The Brookfield Rotational Viscometer was used to evaluate emulsion viscosity and its shear rate dependence. Based on the results it is recommended that an upper limit of 60°C be placed on testing temperature to prevent emulsion breaking during testing. Also, 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.

Detailed investigation of the ASTM D7000 Sweep Test procedure was conducted to evaluate sensitivity to gradation, aggregate mineralogy, emulsion type, and emulsion application rate. The data indicates that the method is not sensitive to emulsion application rate. As a result, it was determined that the test is most appropriate for design and not field acceptance. It was also recommended that the gradation limits specified in the standard be modified to ensure that tests are conducted on samples that are representative of aggregates to be used in the field.

In conjunction with the FHWA emulsion task force, the research team defined a performance evaluation framework for emulsion residues using the DSR and the BBS. Testing includes both recovered and PAV aged residues. Six emulsions representative of materials used for chip seals in Wisconsin were sampled to allow for evaluation of the framework. Preliminary results indicate that the multiple stress creep and recovery (MSCR) test has the best potential as a high temperature specification test due to the ability of both the J_{nr} and % Recovery parameters to differentiate between materials. The test was sensitive to both emulsion and modification type. A modified PAV procedure was developed and validated to use smaller samples of residual binders and a procedure to estimate the S-m values at low grade temperatures from DSR testing at 5-10 ^{o}C was developed and verified.

Detailed literature review of studies on cold mixtures was started in Year 4. Contact with key researchers in this field at major specialty chemical companies as well as the Association of Emulsion Manufacturers was established.

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

Implementation of the emulsion testing framework identified the need to compare BBS results for materials based on moisture loss rather than curing time. Testing will be conducted to substantiate these findings and identify an appropriate level of moisture loss for proper material evaluation. It is anticipated that this delay will not impact submission of the draft final report summarizing emulsion evaluation for chip seals.

The research challenges associated with evaluation of emulsions for spray applications delayed the start for the investigation of cold mix asphalt. Activities related to spray grade emulsions are close to completion. The focus of Year 5 will be on CMA under an accelerated schedule to meet project deadlines.

The duration of Subtasks E1c-2i, E1c-2iii, E1c-2iv, and E1c-2v have been extended to reflect activities related to cold mix asphalt.

Year 5 Work Plan

Subtask E1c-2i: Review of literature and standards

Review of literature and standards has been divided into two categories.

- Emulsions for spray applications: Literature related to emulsion and system performance evaluation for chip seals has been collected and synthesized. Specific topics include: evaluation of emulsion construction properties, emulsion residue recovery methods, emulsion residue performance properties, and chip seal design methodologies and performance evaluation.
- Emulsions for mixing applications: As stated in the Y4 work plan efforts will focus on emulsions for Cold In Place Recycling (CIR) and Cold Mix Asphalt. Review and synthesis of mix design procedures and performance evaluation for these applications is currently underway.

A draft literature review report summarizing literature and standards for both these applications, designated as D6 in the Gantt chart was originally scheduled for delivery in March 2010. The decision was made to delay this deliverable and include it in the draft report for all efforts related to emulsion evaluation for chip seals. This information will be included in the draft final reports for emulsion evaluation for chip seals and cold mixes designated as WE1c-2-D8 and WE1c-2-D9 in the Table of Deliverables, respectively.

Subtask E1c-2ii: Creation of advisory group

This task is complete. Throughout the duration of the project communication will continue with advisory group partners through meetings and involvement in the FHWA Emulsion Task Force.

Subtask E1c-2iii: Identify tests and develop experimental plan

In cooperation with the Emulsion Task Force, an experimental framework for evaluation of emulsion and residue properties has been developed for evaluation of chip seal performance. The tests selected and experimental design will be modified to account for the unique aspects of emulsion performance related to cold mixes pending completion of the CMA literature review.

The final testing framework and experimental design for both applications will be summarized in draft final reports WE1c-2-D8 and WE1c-2-D9.

Subtask E1c-2iv: Develop material library and collect materials

The research team plans to continue to use emulsions produced by local suppliers for laboratory evaluation.

Subtask E1c-2v: Conduct testing plan

Evaluation of Emulsion Properties for Chip Seal: Testing is underway and planned for completion in 2011 Q1. Results will be summarized in draft final report WE1c-2-D8.

Evaluation of Emulsion Properties for Mixing Applications: Tests will be conducted pending completion of the CMA literature review and experimental plan. It is anticipated that testing will begin in 2010 Q2. Results will be summarized in draft final report WE1c-2D9.

Subtask E1c-2vi: Develop performance selection guidelines

Performance selection guidelines for emulsion used in chip seals and mix applications will be developed based on the results of SubtaskE1c-2v.

Subtask E1c-2vii: Validate performance guidelines

The research team will coordinate with the local suppliers who provided emulsions for Subtask E1c-2iv to identify field section in-service for one to three years. The emulsion residue will be sampled from the section in various places and evaluated using the DSR emulsion residue test methods previously defined. Results will allow the research team to assess the ability of newly proposed residue recovery methods to estimate in-place residue properties in the field.

Subtask E1c-2viii: Develop CMA mix design guidelines

Results of previous tasks will be applied in development of mix design guidelines for cold mix asphalt (CMA). Specific considerations include: appropriate emulsion and aggregate selection guidelines, determination of optimum water and emulsion contents, compaction procedures and air void criteria and selection of the final mix design. Mix design guidelines will be developed based on the concept of providing a workable mix with early stability gain to meet traffic needs.

Subtask E1c-2ix: Develop CMA performance guidelines

The research team will develop a performance testing framework that defines appropriate time to trafficking based on the relationship between development of strength and moisture loss. Mixing conditioning and aging procedures will also be defined to evaluate in-service performance. There is potential that a number of performance tests for HMA will be applicable to evaluation of CMA.

Results for subtasks E1c-2vii and E1c-2ix will be provided in draft final report WE1c-2-D9.

Table for Decision Points and Deliverables

Date	**Deliverable**	**Description**
06/30/2011	WE1c-2-D8: Draft report	Evaluation of Emulsion Properties for Chip Seal Applications
08/01/2011	Journal papers (1)	Related to mix design for CMA or Emulsion Performance Properties
10/30/2011	WE1c-2-D9: Draft report	CMA performance guidelines
01/15/2012	Presentation	Related to emulsion performance properties and CMA performance guidelines
01/31/2012	Final report	Emulsion and CMA final reports

CATEGORY E2: DESIGN GUIDANCE

Work Element E2a: Comparison of Modification Techniques (UWM)

Major Findings and Status

The research team compared the Multiple Stress Creep and Recovery (MSCR) test results with the current guidelines for % Recovery and J_{nr} presented in AASHTO TP70-09. The results indicated that many binders commonly used fall below the required limit for elastic modifiers.

The relationship between the percent recoveries, %R, of the MSCR test at 3.2 kPa and the energy of the Binder Yield Energy test (BYET) was investigated. It was shown that poor relationships between these two parameters exist. The post peak behavior was analyzed by introducing a new parameter: energy at γ=2000% (BYE20). The effect of temperatures on the energy was taken into account by two new parameters: BYET energy/G* (BYEpeak/G*) and BYET energy at γ=2000% /G* (BYE20/G*). An improved correlation between %R and BYET energy was obtained when the comparison was made in terms of BYE20 and BYE20/G*.

The SENB results at two different temperatures indicate that, in general, modification increaseed fracture energy. It was also found that the asphalt source plays a significant role in the fracture properties. The relation between fracture energy, stiffness and m-value measured with the Bending Beam Rheometer (BBR) was investigated. It was shown that a poor relationship between the fracture energy and the BBR results exist for the binders tested.

The research team decided to include two new tests in the experimental matrix: Linear Amplitude Sweep (LAS), to measure the fatigue performance, and Bitumen Bond Strength (BBS) to investigate the bond strength between asphalt and aggregate and the binder susceptibility to moisture damage.

The LAS was performed at two temperatures: intermediate PG temperature and PG intermediate plus 10°C. The results indicated that as temperature increases, the fatigue law parameter “A” increases, parameter “B” decreases and the number of cycles to failure increases. Also, it was found that sensitivity of LAS parameters to temperature is binder-specific.

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

The research team had difficulties in obtaining some of the planned binders. As a consequence, the binders were obtained from different providers.

Year 5 Work Plan

Subtask E2a-1: Identify modification targets and material suppliers

This subtask was completed during Year 3.

Subtask E2a-2: Test material properties

The team will continue work on this subtask following the schedule shown in the Gantt charts. In addition to the tests proposed and approved in the Year 4 work plan, two new tests (LAS and BBS) are proposed.

Subtask E2a-3: Develop model to estimate level of modification needed and cost index

Based on the testing results from subtask E2a-2, the team will develop a model to help estimate the level of binder modification needed and provide a costing index.

Subtask E2a-4: Write asphalt modification guideline/report on modifier impact over binder properties

This subtask will focus on developing a guideline for use of different modifiers to help improve the modifier selection process and to reduce the risk of negatively impacting construction and performance of asphalt pavements.

Table for Decision Points and Deliverables

Date	Deliverable	Description
10/11	Draft Report	Report summarizing major findings for each subtask.
01/12	Final Report	Final report on comparison of different modification techniques.

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

Major Findings and Status

The work during Year 4 focused on the validation of the testing and analysis procedure developed for estimating the RAP binder properties without the need for extraction and recovery.

An extensive verification testing program using two artificial recycled asphalt pavement (RAP) materials and two virgin binder grades was designed to verify that estimated continuous grades are equal to the known values of laboratory-aged binders used in producing the artificial RAP. The results indicate that the estimated continuous grade for low and intermediate temperatures were within 2.5°C, while it was within 6°C for high temperatures. These are all on the conservative side.

To isolate the source of discrepancy of high temperature grade estimation, different gap settings and several other factors were tested in an attempt to resolve this issue. These factors include: conditioning time of the blended mortar samples was increased to allow more complete blending of the RAP and fresh binders, the fresh binder source was changed to isolate potential blending chemistry problems, aggregate gradation was tested after the ignition oven to isolate potential aggregate effect and total asphalt content was increased to assure no aggregate interlock was occurring. It was found that increasing the total asphalt content from about 35% to 50% produced a smaller difference between estimated and measured continuous grade values.

Testing was also completed for multiple binders as well as modified fresh binders and RAP sources. The analysis of these results confirmed earlier findings that the fresh binder-RAP blending relationship is highly dependent on both the source of RAP and composition of fresh binder. This is particularly true when modified fresh binders are used. The analysis procedure was also applied to a combination of RAS and RAP blends with fresh binder to test linearity in the PG with percent blending. A surface RAP/RAS/fresh binder blending chart was prepared, and a specific recommendation for using the change rate of true grade temperature as a function of RAP content was made. Results in Year 4 clearly show that the tiered system used in requiring change in PG grade when using more than 15% RAP could be misleading. Changes in PG grade are clearly binder source and RAP/RAS source specific and that rate of change in PG grade could vary by an order of magnitude depending on combinations of binder and recycled materials.

Investigation into the feasibility of using the Single-Edge Notched Bending (SENB) test (developed in task E2d) to analyze effect of RAP materials on low temperature fracture began in Year 4. The standard Bending Beam Rheometer (BBR) geometry modified with a small notch was used for SENB testing. Preliminary testing confirmed expected trends in both strength and ductility.

Under subtask E2b-3, materials from two projects in UTAH have been received. Testing of the received materials has started following the experimental plan for the RAP mixing experiment.

Under subtask E2b-5, extracted/recovered asphalt binders from the Manitoba PTH8 field-produced and lab-produced mixtures were tested to determine their rheological properties. Additionally, all mixes were evaluated in terms of their dynamic modulus and their resistance to thermal cracking using the TSRST test. Additionally, the moisture resistance of the various mixtures was evaluated at multiple freeze-thaw cycles. An update was presented at the RAP ETG meeting in Oklahoma City, Oklahoma. A paper summarizing the current findings was presented at the 90th TRB annual meeting and was recommended for publication in the TRR journal.

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

Variability in SENB fracture testing data has not allowed significant progress for this work element. Testing apparatus changes are currently being completed under task E2d and testing will resume as soon as possible.

Year 5 Work Plan

Subtask E2b-1: Develop a System to Evaluate the Properties of RAP Materials

E2b-1.a: Develop a System to Evaluate the Properties of RAP Aggregates

None.

E2b-1.b: Develop a System to Evaluate the Properties of the RAP Binder

Work in Year 5 will focus on the following:

1. Estimating the fracture properties of the RAP binders. The Single-Edge Notched Bending (SENB) testing protocol will be used to evaluate the fracture properties of the RAP binder.
2. Glass transition temperature (Tg) testing will also be carried out, and a procedure to obtain the Tg for the RAP binders will be developed.

Subtask E2b-2: Compatibility of RAP and Virgin Binders

Major Findings and Status

Determining the degree to which the RAP component of asphalt mixes with a virgin asphalt component in a RAP modified binder is a complex problem. Directly related to the mixing is determining the asphalt components in the RAP that are being mobilized by the new asphalt and determining the compatibility of the resultant asphalt/RAP blend. Fortunately, the degree of mixing, the RAP components mobilized, and the compatibility of recycled and virgin materials should be directly related. In addition to determining compatibility, there is much to gain from determining some fundamental chemical properties of the virgin, recycled, and mixed materials. For instance, if only a fraction of the asphalt component of RAP actually mixes with the new binder, what fraction is it? Is the fraction that mixes representative of the entire RAP binder or does it contain a disproportionate amount of asphaltenes or waxes, for example? These questions are being answered using chromatographic separations developed at WRI and the results can be applied to determining RAP/Virgin asphalt compatibilities for the composition of material that is most likely to exist in a pavement.

Extraction and characterization of RAP from four RAP sources, South Carolina, California, Iowa, and Manitoba has been completed with two different solvents with different solubility parameters. Following RAP characterization, virgin binders were selected to blend with the RAP binders at concentrations of 0, 15, and 40%. The virgin binders represent one compatible asphalt and one asphalt that is less compatible based on known properties. Characterization of the blended materials is progressing using Automated Flocculation Titrimetry (AFT), chromatography, and rheology.

Year 5 Work Plan

Characterization of the RAP materials, virgin asphalts, and the blends using Automated Flocculation Titrimetry (AFT), chromatography, and rheology will be continued to determine the RAP components that are mobilized or solublized by the virgin asphalt, the compatibility of the blends, and the effects on rheological properties. The goal of this effort is to better understand the fundamental chemistry of the mixing of RAP asphalt with virgin asphalt that will lead to better analysis and prediction of blended asphalt properties. From the fundamental understanding, rapid characterization test methods can be developed to accurately define RAP properties and used with virgin asphalt properties to ascertain the resultant asphalt properties in the mix. More detail of the work plan is contained in the Year 4 Work Plan.

Subtask E2b-3: Develop a Mix Design Procedure

Complete the experimental plan for this subtask. A follow-up plan will be developed based on the findings of this experiment and work will begin shortly after.

Subtask E2b-4: Impact of RAP Materials on Performance of Mixtures

Work for year 5 will consist of collecting the fundamental properties for the field RAP mixes. The dynamic modulus data for the Manitoba mixes will be used to backcalculate the properties of the blend asphalt binders using the Hirsh model and the Huet-Sayegh model. Additionally, the measured data will be used to validate the RAP mortar procedure.

Subtask E2b-5: Field Trials

Continue to work with state agencies to construct field test sections to evaluate the performance of HMA containing high RAP contents. Continue to work on Manitoba mixes.

Table for Decision Points and Deliverables

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for Changes in Delivery Date
E2b-1: Develop a System to Evaluate the Properties of RAP Materials	Practice	Recommend the most effective methods for extracting RAP aggregates based on their impact on the various properties of the RAP aggregates and the volumetric calculations for the Superpave mix design.	12/10	04/11	Additional testing and verifications were required for some of the reported data
	Journal paper	Summarizing results and findings of fracture testing of RAP binders.	07/11	N/A	N/A
	Draft report	Report on the developed testing and analysis procedure system to estimate the RAP binder properties from binder and mortar testing including fracture results.	10/11	N/A	N/A
	Final report		01/12	N/A	N/A
E2b-3: Develop a Mix Design Procedure	Journal paper	Summarizing results and findings of the laboratory mixing experiment.	10/11	N/A	N/A
	Draft report	Report summarizing the laboratory mixing experiment.	02/12	N/A	N/A
	Final report		03/12	N/A	N/A
E2b-4: Impact of RAP Materials on Performance of Mixtures And E2b-5: Field Trials	Draft report	Report summarizing the laboratory and field performance of field mixtures.	02/12	N/A	N/A
	Final report		03/12	N/A	N/A

Work Element E2c: Critically Designed HMA Mixtures (UNR)

Major Findings and Status

During Year 4, the evaluation of the recommended pulse time and deviator and confining stresses continued. Repeated load flow number testing was performed for three laboratory-produced mixtures (i.e. PG64-22, PG58-22, and PG52-22 mix). The flow number was evaluated at different temperatures and three air voids levels: 2, 4 and 7%.

The work on converting the pulse duration in time domain for a given pavement response into frequency domain continued to be investigated. The Fast Fourier Transformation (FFT) is being used to convert the pavement responses from time domain to frequency domain. The concept of predominant frequency(ies), f_p, to predict all components of the pavement responses was verified for different pavement structures and conditions. The frequencies for the asphalt sub-layers as proposed by the MEPDG procedure were determined and compared to the predominant frequencies determined by the FFT analysis. A presentation was made to the TRB AFD80 committee during the 90th annual meeting.

Under Subtask E2c.3, the UNR team collaborated with the Flow Number Task Force of the Asphalt Mixture and Construction Expert Task Group to develop a work plan for the evaluation of flow number (repeated load test) criteria for asphalt concrete mixture design. The proposed experiment was developed with the objective of evaluating five promising flow number approaches summarized in table E2c.1 to recommend a simple approach for use in mixture design. The scope of the proposed experiment included collecting appropriate flow number test data, analyzing the rutting resistance using the various approaches, then comparing the rutting resistance for a limited number of field mixtures which are known to have acceptable rutting performance for their design traffic level.

Table E2c.1. Promising approaches for rutting resistance from flow number test data.

Method	Air Voids	Temperature	Confining Stress, psi	Deviatoric Stress, psi	Pulse	Criteria
NCHRP 9-33 (*AAT, 2009)*	7 %	50 % reliability high pavement temperature from LTPPBind at depth of 20 mm for surface courses and top of layer for other layers	0	87	0.1 sec with 0.9 sec dwell	Flow number > critical value as a function of traffic
NCAT (*Willis et al. 2009*)	7 %	50 % reliability PG grade – 6 °C	10	70	0.1 sec with 0.9 sec dwell	Flow number > critical value as a function of traffic and allowable rut depth
NCHRP 9-30A (*NCHRP, 2010)*)	Avg.; In Place (Specs.)	Option A: 3 Temps. (50% reliability PG minus 5°C, 20°C, mid-range). Option B: Effective temperature based on rutting (MEPDG).	10	70	0.1 sec with 0.9 sec dwell	Slope and intercept of permanent deformation curve < critical values as a function of traffic (rut depth < threshold value).
UNR (*Hajj et al. 2010*)	7 %	Effective temperature for rutting	Variable*	Variable*	Variable*	Slope and intercept of permanent deformation curve < critical values as a function of traffic
NCHRP 9-26A	7%	3 temperatures: Binder high PG, PG minus 6°C, PG minus 12°C	0	29	0.1 sec with 0.9 sec dwell	Rutting calculated from Minimum Strain Rate at 3 temperatures, aging index, and pavement temperature frequencies < critical rutting

* using developed predictive equations.

Flow number testing is being performed at the AASHTO Materials Reference Laboratory (AMRL) and at the UNR laboratory. A total of nine HMA mixtures are being evaluated using each of the six approaches (table E2c.2). In Year 4, only six mixtures have been received. Work is undergoing to test the mixtures that have been received. An update on the testing progress and for the preliminary findings was provided at the ETG meeting in Phoenix, Arizona.

Table E2c.2. Materials information.

Mix #	Traffic	Binder Grade	Region	Supplier	comments	Received
1	<3	PG 58-28	No. Central	Erv Dukatz – Mathy Const.	MN - WI	Yes
2		PG 64-22	So. East	Todd Whittington-NCDOT	NC	Yes
3		PG 67-22	So. East	Dale Rand - TXDOT	TX	Yes
4	<10	PG 58-28*	No. Central	Erv Dukatz –Mathy Const.	MN - WI	Yes
5		PG 64-22*	Central	Todd Lynn- APEC	MO / KA	No
6		PG 67-22*	Central	Jim Musselman - FLDOT	FL	Yes
7	>30	PG 64-22*	No. East	NJDOT	Frank Fee	No
8		PG 67-22*	So. East	Randy West	NCAT track sec.	Yes
9		PG 70-16*	West (desert)	Adam Hand		No

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

None

Year 5 Work Plan

Subtask E2c-1: Identify the Critical Conditions

Work for Year 5 will consist of completing the 3D-Move analysis for non-uniform loading conditions that are described in the experimental plan for this subtask. Complete the evaluation of predominant frequencies in the asphalt layer.

Subtask E2c-2: Conduct Mixtures Evaluations

Work for Year 5 will consist of completing the permanent deformation characteristics of laboratory-produced and field-produced mixtures under the testing conditions identified in Subtask E2c-1. The impact of air-voids, gradation, and binder type on the asphalt mixture critical temperature will be summarized.

Subtask E2c-3: Develop a Simple Test

Work for Year 5 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 5 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

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for Changes in Delivery Date
E2c-2: Conduct Mixtures Evaluations	Draft report	Approach to identify critical conditions of HMA mixtures	09/11	N/A	N/A
	Final report		09/11	N/A	N/A
E2c-3: Develop a Simple Test	Journal paper	Critical conditions of various types of HMA mixtures.	08/11	N/A	N/A
	Draft report	Report summarizing the evaluation of mixtures from the Flow Number Task Force group.	11/11	N/A	N/A
	Final report		12/11	N/A	N/A
E2c-4: Develop Standard Test Procedure	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.	12/11	N/A	N/A
E2c-5: Evaluate the Impact of Mix Characteristics	Draft report	Report summarizing the impact of mixture characteristics on the critical condition of the HMA mixes	02/12	N/A	N/A
	Final report		03/12	N/A	N/A

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

Major Findings and Status

In Year 4, under subtask E2d-1, additional work regarding the air and pavement temperature profiles analyses for the NATC WesTrack project in Nevada and the identified LTPP Seasonal Monitoring Pavement (SMP) sections were conducted. A final draft report that summarizes the findings will be prepared. LTPP sections that are located in proximity to the evaluated LTPP SMP sections were identified and the UNR team is currently checking for the materials availability at the MRL.

Final adjustments were made to the new dilatometric test device of binders and the full binder test matrix was carried out. All binders were also tested using the Asphalt Binder Cracking

Device (ABCD). Results indicated the existence of a relationship between the glass transition temperature (T_g) and the critical cracking temperature measured by the ABCD.
The test matrix for the asphalt mixture glass transition measurement was also completed. The glass transition temperature values for binders and mixture were compared and found to be in the same range.

Development of the Single-Edge Notched Bending (SENB) test procedure continued in Year 4 and the research team is ready to prepare a draft standard for the test. New sample geometry, which adds a notch to the beams made using common Bending Beam Rheometer (BBR) molds, was adopted. This solved the adhesion problem between the binder and the metal bars reported previously for some binders and mastics as well as eliminating the stress discontinuity in the interface between the metal bars and the binders observed in the finite element modeling. The SENB binder test matrix was completed and results were compared to parameters measured from other low temperature tests. Good correlations between the SENB fracture load, deformation, and energy and the creep stiffness from the BBR were observed. The T_g also correlated with the SENB fracture energy. Furthermore, it was seen that a relatively good relationship exists between the SENB and the mixture Semi Circular Bending (SCB) test results, but not with the Disc Compact Tension (DCT) test. This is thought to be due to differences in loading rates.

This year the team successfully integrated the mixture glass transition test and the Thermal Stress Restrained Specimen Test (TSRST) into one unified testing device. The T_g-TSRST device can simultaneously test two mixture beams produced from gyratory compacted samples, one unrestrained from which the change in length with temperature (and consequently the glass transition temperature) is measured, and another which is restrained from which the thermal stress buildup is measured. The stress buildup, glass transition temperature, α_l and α_g can be simultaneously measured and used to form a comprehensive picture of the low temperature performance of the asphalt mixture.

The significant amount of control and flexibility possible with the new Tg-TSRST system allowed the research team to design a mixture thermal relaxation procedure in which the temperature was lowered and then maintained at a low isothermal conditioning temperature for a few hours. The unrestrained beam continued to contract at isothermal conditions, while the thermal stress in the restrained beam continued to build up significantly early in the conditioning time, after which it started to gradually relax.

Experimental data from literature and from tests performed in Year 4 were used to study physical hardening in binders. It was observed that the rate of physical hardening does not increase indefinitely as temperature decreases, but rather it peaks at the glass transition temperature. These results were used to show that the effect of physical hardening can be explained as a creep behavior. Thus, a modified creep model capable of predicting the change in physical hardening rate with conditioning time and temperature was developed.

Calculations of theoretical stress buildup in the tested binders based on BBR creep data after 1 hr and 72 hrs of isothermal conditioning showed that the ranking of the top four performers at 1 hr conditioning completely changed after 72 hr conditioning. These results, along with results of the

TSRST-Relaxation test described previously, show that the effect of physical hardening and isothermal conditioning on thermal stress build-up needs to be further investigated.

A numerical procedure was developed to determine the relaxation modulus (E_R) from the stress-build curve as measured by the TSRST test. An algorithm was written in MATLAB that would allow to numerically find E_R for any shape of stress build-up.

Under Subtask E2d-3.a, the UNR team continued the long-term oven aging experiment and measured the mass loss and gain of the various asphalt binders. Additionally, the aged asphalt binders were being tested for rheological properties.

Under subtasks E2d-3.b and c, significant progress was made by completing the E* testing in compression. Further improvements into the E* in tension have led to preliminary test results with a test protocol that is nearly complete.

The Thermal Stress Restrained Specimen (TSRST) had been added to subtasks E2d-3.b and c in year 4, with all the samples being prepared and undergoing their respective aging cycles in the ovens. At the same time the TSRST samples were being prepared, mixture sample to be tested for the coefficient of thermal expansion, α, were also made and are undergoing their respective aging cycles as well.

Further progress has been made in the extraction and recovery of the asphalt binders after the E* compression testing. To date, nearly 70% of the 254 extractions have been completed. Following that progress, carbonyl area measurements, CA, have been completed on nearly 25% of the experimental plan. Similarly, 15% of the binders have been tested for low shear viscosity (LSV) and binder master curve utilizing the DSR.

Utilizing a portion of the test matrix from subtasks E2d-3.b, a paper was submitted, presented, and is to be published by TRB. "Oxidative Aging of Asphalt Binders in Hot-Mix Asphalt Mixtures" was the title which was co-authored by Nathan Morian (NDOT), Elie Y. Hajj (UNR), Charles J. Glover (Texas A&M), and Peter E. Sebaaly (UNR).

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

To reflect actual progress of this work element, the 5-year Gantt charts have been updated to indicate that one of the journal papers initially planned for the 2nd quarter of year 4 was moved to the 4th quarter of the same year. This update has no effect on the year 5 work plan and Gantt chart.

The logistical delays caused by the DSR being out of commission and difficulties with the E* tension software appear to have been sufficiently resolved. Both testing procedures are underway and appear to be functioning adequately. Although the testing in these areas is behind the anticipated schedule, it appears that schedule is on track to finish in 2012.

The release of the draft AASHTO test method for the TSRST test for asphalt mixtures has been delayed due to issues with specimens breaking at the end. Effort is currently undergoing to evaluate different type of glues.

Year 5 Work Plan

Subtask E2d-1: Identify Field Sections

Completed. No work on this subtask is planned for Year 5.

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

Work for Year 5 will consist of collecting the materials for the identified sections and conduct the experimental plan of subtask E2d-2.

Subtask E2d-3: Identify an Evaluation and Testing System

With the majority of the Year 4 test matrices completed, the research team will continue to explore 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.

A number of SENB tests on mastics will be performed to complete the Year 4 SENB test matrix, which was delayed to be coordinated with mastic tests to be performed in other ARC work elements.

The effect of cooling rate and the initial staring temperature on the TSRST test results and relaxation modulus will be evaluated.

E2d-3.a: Evaluate Long-Term Aging of Asphalt Binders Subjected to Free Atmospheric Oxygen
Continue the experiment to evaluate the aging characteristics (oxidation and hardening kinetics) of asphalt binders when aged in forced convection (horizontal airflow) ovens. The materials used in the experimental design are shown in table E2d.1. Currently, all binders in the matrix have been aged. These binders are now being tested for rheologic properties (i.e., low shear viscosity) and aging characteristics (i.e., carbonyl measurements).

Table E2d.1. Materials for long-term aging experiment (E2d-3.a).

Asphalt binder	Additives
PG64-22	none
	10% hydrated lime by weight
	20% hydrated lime by weight
	3% SBS polymer
PG64-28	Polymer modified

E2d.3.b: Evaluate the Impact of Aggregate Absorption on the Aging of the Asphalt Binder
Continue the work on this subtask according to the following experimental plan.

Table E2d.2. Experimental plan for aggregate absorption experiment (E2d-3.b).

Source (Minerology)	Gradation	Aggregate Absorption	Binder	Film Thickness	Air Void	Binder Content	Opt Binder
Lockwood, NV (Rhyolite)	Int.	2.71	64-22	Var.	7	4.5	5.18
				9	7	5.38	
	Int.		64-28	Var.	7	4.5	5.11
				9	7	5.22	
Colorado (Granite/ Gneiss)	Int.	0.87	64-22	Var.	7	4.5	4.36
				9	7	3.61	
	Int.		64-28	Var.	7	4.5	4.40
				9	7	3.65	
California (Var./Gravel)	Int.	4.48	64-22				6.65
				9	7	7.44	
	Int.		64-28				6.10
				9	7	7.51	

Activities on the mixtures will include continuation of TSRST and coefficient of thermal expansion sample aging in ovens, E* testing in tension, and TSRST testing. Following the mixture tests, the samples will then be extracted and recovered for DSR, FTIR, and SENB testing. All of these samples are currently undergoing or have finished their respective aging cycles, so the samples may be sent to the University of Wisconsin-Madison for testing as soon as the specific experimental matrix has been determined.

E2d-3.c: Evaluate the Impact of HMA Mix Characteristics on the Aging of the Asphalt Binder
The current experimental plan including the selected aggregate sources for this subtask is in accordance with the following table E2d.3.

Table E2d.3. Experimental plan for mix characteristics experiment (E2d-3.c).

Source	Gradation	Binder	Film Thickness	Air Voids	Binder Content
Lockwood, NV (Rhyolite)	Int.	64-28	9	4 7 11	5.22
	Fine	64-28	9	7	6.0
Utah (Var./Gravel)	Int.	64-28	9	4 7 11	3.79
	Fine	64-28	9	7	5.22
California (Var./Gravel)	Int.	64-22	9	4 7 11	7.44
	Fine	64-22	9	7	7.51
WesTrack	Coarse (Andesite)	64-22	9.21	4 7 11	5.10
	Fine (Gravel/ Weath. And.)	64-22	9	7	5.20

The testing procedure and planned tasks for year 5 from subtasks E2d-3.c follows the same procedure as subtasks E2d-3.b. Similarly, the E* compression testing has been completed which leaves the E* tension, TSRST, LSV, binder master curve, FTIR, SENB, and coefficient of thermal expansion testing remaining to be completed in year 5.

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 4. 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 5 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 TSRTS test, T_g measurements of asphalt binders and mastics, the unified T_g-TSRST device and for the SENB test.

Table for Decision Points & Deliverables

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for Changes in Delivery Date
E2d-2: Identify the Causes of the Thermal Cracking	Draft report	Report summarizes the testing and findings for materials from LTPP sections.	12/11	N/A	N/A
	Final report		03/12	N/A	N/A
E2d-3: Identify an Evaluation and Testing System	Journal paper	Thermal cracking characterization of mixtures by means of the unified Tg-TSRST device.	07/11	N/A	N/A
	Draft report	Low Temperature Cracking Characterization of Asphalt Binders by Means of the Single-Edge Notch Bending (SENB) Test	04/11	N/A	N/A
	Final report		10/11	N/A	N/A
E2d-4: Modeling and validation of the Developed System	Journal paper	Field validation of testing procedure and model using LTPP sections' performance.	07/11	N/A	N/A
	Draft report	Thermal cracking characterization of mixtures by means of the unified Tg-TSRST device.	10/11	N/A	N/A
	Final report		01/12	N/A	N/A
	Model	Model that can effectively simulate the long-term properties of HMA mixtures in the intermountain region and assess the impact of such properties on the resistance of HMA mixtures to thermal cracking.	03/12	N/A	N/A
E2d-5: Develop a Standard	Journal paper	Thermal cracking characterization of mixtures by means of the unified Tg-TSRST device.	07/11	N/A	N/A
	Draft standard	Draft standards for the use of the SENB, binder Tg and the Tg-TSRST device.	10/11	N/A	N/A
	Final standard		01/12	N/A	N/A
	Draft standard	Draft standard for the use of the TSRST with cylindrical specimens compacted using the SGC.	03/11	09/11	Delayed due to issues with specimens breaking at the edge.
	Final standard		01/12	N/A	N/A

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.

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>Year Five Work Plan</u>

Subtask E2e-2: Design and Execute Laboratory Testing Program

Laboratory testing was initiated in Year4 and will be completed in Year 5.

Subtask E2e-3: Perform Engineering and Statistical Analysis to Refine Models

Work on this task for the Continuum Damage Fatigue Model was initiated in Year 4 and will be completed in Year 5. Work on this task for the Hirsch Model, Resistivity Model, and Permeability Model will be started and completed in Year 5.

Subtask E2e-4: Validate Refined Models

The refined models will be validated in Year 5 using data from various sources. 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 and Continuum Damage Fatigue 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.

Table for Decision Points & Deliverables

Date	Deliverable	Description
9/1/2011	Journal Paper	Improved Continuum Damage Fatigue Model
1/1/2012	Draft Report	Draft report documenting Work Element E2e
1/1/2012	Models	Improved composition to engineering property models • Hirsch Model for Dynamic Modulus • Resistivity Model for Rutting Resistance • Continuum Damage Fatigue Model • Permeability
3/31/2012	Final Report	Final report documenting Work Element E2e
9/1/2012	Journal Paper	Improved composition to engineering property models for HMA design

Table for Decision Points and Deliverables for the Engineered Materials Program Area

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Projected Delivery Date	Revised Delivery Date	Reason for Changes Associated with the Deliverable
E1a- Characterization of asphalt mixtures using controlled-strain repeated direct tension test	Journal Paper	Journal paper prepared that describes the measurement and analysis method to characterize asphalt mixtures using controlled-strain repeated direct tension test	07/01/10	02/02/11	The analysis method was changed due to the new development work
E1a- Characterization of fatigue damage in asphalt mixtures using pseudo stain energy	Journal Paper	Journal paper prepared that describes the method to characterize and quantify the fatigue damage using pseudo strain energy	08/01/10	02/20/11	More tests are needed to obtain the essential material properties
E1a- Model fatigue crack growth in asphalt mixtures	Journal Paper	Journal paper prepared that describes the method to model the evolution of the damage density		03/20/11	
E1a- Determine the healing properties of asphalt mixtures using controlled-strain repeated direct tension test	Journal Paper	Journal paper prepared that describes the method to measure and model the healing rate of asphalt mixtures with fatigue damage		04/20/11	
E1a- Determine the healing properties of asphalt mixtures using tensile creep and recovery test	Journal Paper	Journal paper prepared that describes the method to efficiently measure and model the healing rate of asphalt mixtures with creep damage		05/20/11	
E1a- Influence of aging on the fatigue resistance and healing properties of asphalt mixtures	Journal Paper	Journal paper prepared to examine the effect of aging on the fatigue and healing properties of asphalt mixtures		09/01/11	
E1a- Model and Algorithm	Model and Algorithm	The model and algorithm for testing and analysis of damaged asphalt mixtures in tension		09/01/11	
E1a- Nondestructive Characterization of Anisotropic Viscoelastic Properties of Undamaged Asphalt Mixtures under Compressive Loading	Journal Paper	A Paper written by TAMU researchers that state the testing protocols and analysis methods to obtain the comprehensive properties of the undamaged asphalt mixtures in compression.	Completed		

Table of Decision Points and Deliverables for the Engineered Materials Program Area (cont.)

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Projected Delivery Date	Revised Delivery Date	Reason for Changes Associated with the Deliverable
E1a- Microstructure-Based Inherent Anisotropy of Asphalt Mixtures	Journal Paper	A Paper that describes a characterization parameter and an easily done test for the inherent anisotropy	Completed		
E1a- Interpretation of Parameters in Microstructure-Based Viscoplastic Model of Asphalt Mixture	Journal Paper	A paper that provides the parameter inputs of the viscoplastic model within the PANDA program based on basic material properties		9/30/2011	
E1a- Viscoelastic and Viscoplastic Characterization of Asphalt Mixtures in Compression	Journal Paper	A paper that provides a fast technique to conduct the decomposition of the viscoelasticity and viscoplasticity and supplies the material parameter inputs for the PANDA program		6/30/2011	
E1a- Continuum Damage Permanent Deformation Analysis for Asphalt Mixtures	Final Report	Ph.D. dissertation at TAMU that describes the viscoplastic mechanism for permanent deformation of the asphalt mixtures and provides the testing protocols and analysis methods to acquire the input parameters of the PANDA program.	12/31/2010	12/31/2011	Time is needed to make the product compatible with the PANDA program
E1a- Evaluation of the Stiffness Gradient in the Field aged asphalt samples	Journal Paper	The paper will describe the analysis methods for stiffness gradient prediction and finite element simulation model of test	07/31/2010	04/20/11	Testing more samples from different locations were needed
E1a- Fatigue damage characterizations of asphalt using the overlay tester	Journal Paper	The paper will use the strain energy concepts together with finite element modeling to find A and n parameters		05/20/11	
E1a- Develop a RDT DMA Testing Protocol	Technology Transfer	This new testing protocol is stress controlled repeated tension testing method and will be used to replace the previous torsional DMA testing method	08/15/2010	02/15/2011	New DMA Machine Arrive Late
E1a- Standardize Testing Procedure for Specifications	AASHTO Specification	Develop a Standard Specification to use as a comparative test to evaluate fracture properties, healing and moisture damage of FAM		09/30/2011	

Table of Decision Points and Deliverables for the Engineered Materials Program Area (cont.)

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Projected Delivery Date	Revised Delivery Date	Reason for Changes Associated with the Deliverable
E1a- Model FAM Fatigue Crack Growth under Different Relative Humidity	Journal Paper	This paper will characterize the moisture damage of FAM conditioned under 5 different relative humidities		04/15/2011	
E1a- Characterize FAM Bond Energy under Different Relative Humidity	Journal Paper	This paper describes a new method to back calculate the bond energy of FAM by the means of fatigue cracking modeling		06/15/2011	
E1a- Develop a New DMA Testing Protocol for Compression	AASHTO Specification	Develop a Standardized testing method to use as a comparative test to evaluate compressive properties of FAM		09/15/2011	
E1a- Characterize Permanent Deformation of FAM under Different Relative Humidity	Journal Paper	This paper will characterize the permanent deformation of FAM conditioned under 5 different relative humidities		03/31/2012	
E1a- Self-Consistent Micromechanics Model of Asphalt Mixtures	Journal Paper	This paper describes the inverse and forward self-consistent micromechanics models of asphalt mixtures.	Published (ASCE Journal of Materials in Civil Engineering)		
E1a- Crack Size Distribution in Asphalt Mixtures	Journal Paper	This paper presents the Weibull distribution models of crack size in asphalt mixtures at different numbers of load applications.	Accepted for publication (Transportation Research Record)		

Table of Decision Points and Deliverables for the Engineered Materials Program Area (cont.)

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for Changes in Delivery Date
E2b-1: Develop a System to Evaluate the Properties of RAP Materials	Practice	Recommend the most effective methods for extracting RAP aggregates based on their impact on the various properties of the RAP aggregates and the volumetric calculations for the Superpave mix design.	12/10	04/11	Additional testing and verifications were required for some of the reported data
	Journal paper	Summarizing results and findings of fracture testing of RAP binders.	07/11	N/A	N/A
	Draft report	Report on the developed testing and analysis procedure system to estimate the RAP binder properties from binder and mortar testing including fracture results.	10/11	N/A	N/A
	Final report		01/12	N/A	N/A
E2b-3: Develop a Mix Design Procedure	Journal paper	Summarizing results and findings of the laboratory mixing experiment.	10/11	N/A	N/A
	Draft report	Report summarizing the laboratory mixing experiment.	02/12	N/A	N/A
	Final report		03/12	N/A	N/A
E2b-4: Impact of RAP Materials on Performance of Mixtures And E2b-5: Field Trials	Draft report	Report summarizing the laboratory and field performance of field mixtures.	02/12	N/A	N/A
	Final report		03/12	N/A	N/A
E2c-2: Conduct Mixtures Evaluations	Draft report	Approach to identify critical conditions of HMA mixtures	09/11	N/A	N/A
	Final report		09/11	N/A	N/A
E2c-3: Develop a Simple Test	Journal paper	Critical conditions of various types of HMA mixtures.	08/11	N/A	N/A
	Draft report	Report summarizing the evaluation of mixtures from the Flow Number Task Force group.	11/11	N/A	N/A
	Final report		12/11	N/A	N/A
E2c-4: Develop Standard Test Procedure	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.	12/11	N/A	N/A
E2c-5: Evaluate the Impact of Mix Characteristics	Draft report	Report summarizing the impact of mixture characteristics on the critical condition of the HMA mixes	02/12	N/A	N/A
	Final report		03/12	N/A	N/A
E2d-2: Identify the Causes of the Thermal Cracking	Draft report	Report summarizes the testing and findings for materials from LTPP sections.	12/11	N/A	N/A
	Final report		03/12	N/A	N/A

Table of Decision Points and Deliverables for the Engineered Materials Program Area (cont.)

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for Changes in Delivery Date
E2d-3: Identify an Evaluation and Testing System	Journal paper	Thermal cracking characterization of mixtures by means of the unified Tg-TSRST device.	07/11	N/A	N/A
	Draft report	Low Temperature Cracking Characterization of Asphalt Binders by Means of the Single-Edge Notch Bending (SENB) Test	04/11	N/A	N/A
	Final report		10/11	N/A	N/A
E2d-4: Modeling and validation of the Developed System	Journal paper	Field validation of testing procedure and model using LTPP sections' performance.	07/11	N/A	N/A
	Draft report	Thermal cracking characterization of mixtures by means of the unified Tg-TSRST device.	10/11	N/A	N/A
	Final report		01/12	N/A	N/A
	Model	Model that can effectively simulate the long-term properties of HMA mixtures in the intermountain region and assess the impact of such properties on the resistance of HMA mixtures to thermal cracking.	03/12	N/A	N/A
E2d-5: Develop a Standard	Journal paper	Thermal cracking characterization of mixtures by means of the unified Tg-TSRST device.	07/11	N/A	N/A
	Draft standard	Draft standards for the use of the SENB, binder Tg and the Tg-TSRST device.	10/11	N/A	N/A
	Final standard		01/12	N/A	N/A
	Draft standard	Draft standard for the use of the TSRST with cylindrical specimens compacted using the SGC.	03/11	09/11	Delayed due to issues with specimens breaking at the edge.
	Final standard		01/12	N/A	N/A

Engineered Materials Year 5

	Year 5 (4/2011-3/2012)												Team
	4	5	6	7	8	9	10	11	12	1	2	3	
(1) High Performance Asphalt Materials													
E1a: Analytical and Micro-mechanics Models for Mechanical behavior of mixtures													TAMU
E1a-1: Analytical Micromechanical Models of Binder Properties			P			JP			D,JP			F	
E1a-2: Analytical Micromechanical Models of Modified Mastic Systems			P			JP			D		SW, M&A	F	
E1a-3: Analytical Models of Mechanical Properties of Asphalt Mixtures			P			JP			D,JP		SW, M&A	F	
E1a-4: Analytical Model of Asphalt Mixture Response and Damage			P						D		SW, M&A	F	
E1b: Binder Damage Resistance Characterization													UWM
E1b-1: Rutting of Asphalt Binders													
E1b-1-1: Literature review													
E1b1-2: Select Materials & Develop Work Plan													
E1b1-3: Conduct Testing													
E1b1-4: Analysis & Interpretation													
E1b1-5: Standard Testing Procedure and Recommendation for Specifications	P			D		JP				F			
E1b-2: Feasibility of determining rheological and fracture properties of asphalt binders and mastics using simple indentation tests (modified title)													UWM
E1b-2i. Literature Review													
E1b-2ii. Proposed SuperPave testing modifications													
E1b-2iii. Preliminary testing and correlation of results	JP												
E1b-2iv. Feasibility of using indentation tests for fracture and rheological properties							D			F			
E2a: Comparison of Modification Techniques													UWM
E2a-1: Identify modification targets and material suppliers													
E2a-2: Test material properties													
E2a-3: Develop model to estimate level of modification needed and cost index													
E2a-4: Write asphalt modification guideline/report on modifier impact over binder properties							D			F			
E2c: Critically Designed HMA Mixtures													UNR
E2c-1: Identify the Critical Conditions													
E2c-2: Conduct Mixtures Evaluations						D,F							
E2c-3: Develop a Simple Test					JP			D	F				
E2c-4: Develop Standard Test Procedure									D, F				
E2c-5: Evaluate the Impact of Mix Characteristics											D	F	
E2d: Thermal Cracking Resistant Mixes for Intermountain States													UNR/UWM
E2d-1: Identify Field Sections													
E2d-2: Identify the Causes of the Thermal Cracking									D	P		F	
E2d-3: Identify an Evaluation and Testing System	D			JP			F			P			
E2d-4: Modeling and Validation of the Developed System				JP			D			F, P			
E2d-5: Develop a Standard				JP			D			F, P			
E2e: Design Guidance for Fatigue and Rut Resistance Mixtures													AAT
E2e-1: Identify Model Improvements													
E2e-2: Design and Execute Laboratory Testing Program						JP							
E2e-3: Perform Engineering and Statistical Analysis to Refine Models													
E2e-4: Validate Refined Models													
E2e-5: Prepare Design Guidance									D			F	
(2) Green Asphalt Materials													
E2b: Design System for HMA Containing a High Percentage of RAP Material													UNR
E2b-1: Develop a System to Evaluate the Properties of RAP Materials				JP			D, P			F			
E2b-2: Compatibility of RAP and Virgin Binders		P											WRI
E2b-3: Develop a Mix Design Procedure							JP, P				D	F	
E2b-4: Impact of RAP Materials on Performance of Mixtures											D	F	
E2b-5: Field Trials											D	F	
E1c: Warm and Cold Mixes													UWM
E1c-1: Warm Mixes													
E1c-1i: Effects of Warm Mix Additives on Rheological Properties of Binders													
E1c-1ii. Effects of Warm Mix Additives on Mixture Workability and Stability				D			F						
E1c-1iii. Mixture Performance Testing													
E1c-1iv. Develop Revised Mix Design Procedures													
E1c-1v. Field Evaluation of Mix Design Procedures and Performance Recommendations							D			F			
E1c-2: Improvement of Emulsions' Characterization and Mixture Design for Cold Bitumen Applications													UWM/UNR
E1c-2i: Review of Literature and Standards													
E1c-2ii: Creation of Advisory Group													
E1c-2iii: Identify Tests and Develop Experimental Plan													
E1c-2iv. Develop Material Library and Collect Materials.													
E1c-2-v. Conduct Testing Plan													
E1c-2-vi. Develop Performance Selection Guidelines			D							F			
E1c-2-vii. Validate Performance Guidelines													
E1c-2-viii. Develop CMA Mix Design Guidelines													
E1c-2ix. Develop CMA Performance Guidelines					JP		D			F			

Deliverable codes	Deliverable Description
D: Draft Report	Report delivered to FHWA for 3 week review period.
F: Final Report	Final report delivered in compliance with FHWA publication standards
M&A: Model and algorithm	Mathematical model and sample code
SW: Software	Executable software, code and user manual
JP: Journal paper	Paper submitted to conference or journal
P: Presentation	Presentation for symposium, conference or other
DP: Decision Point	Time to make a decision on two parallel paths as to which is most promising to follow througjh

Work planned
Work completed
Parallel topic

Engineered Materials Year 2 - 5	Year 2 (4/08-3/09)				Year 3 (4/09-3/10)				Year 4 (04/10-03/11)				Year 5 (04/11-03/12)				Team
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	
(1) High Performance Asphalt Materials																	
E1a: Analytical and Micro-mechanics Models for Mechanical behavior of mixtures																	TAMU
E1a-1: Analytical Micromechanical Models of Binder Properties				P, JP	JP	P	P	JP		P		P	P	JP	D, JP	F	
E1a-2: Analytical Micromechanical Models of Modified Mastic Systems				P, JP	JP	P	P			P		P	P	JP	D	F, SW, M&A	
E1a-3: Analytical Models of Mechanical Properties of Asphalt Mixtures	P	P,JP		P, JP	JP	P	P	M&A		P, JP(3)	JP (2)	P, M&A	P	JP(2)	D, JP	F, SW, M&A	
E1a-4: Analytical Model of Asphalt Mixture Response and Damage				P, JP	JP	P	P					P	P		D	F, SW, M&A	
E1b: Binder Damage Resistance Characterization																	UWM
E1b-1: Rutting of Asphalt Binders																	
E1b-1-1: Literature review																	
E1b1-2: Select Materials & Develop Work Plan	DP, P		P														
E1b1-3: Conduct Testing			P			JP		P	DP								
E1b1-4: Analysis & Interpretation		JP	P	JP		JP		P			JP						
E1b1-5: Standard Testing Procedure and Recommendation for Specifications										P		DP	P	D, JP		F	
E1b-2: Feasibility of Determining rheological and fracture properties of asphalt binders and mastics using simple indentation tests (modified title)																	
E1b-2i. Literature Review						D											
E1b-2ii. Proposed SuperPave testing modifications or new testing devices						P											
E1b-2iii. Preliminary testing and correlation of results								D		JP			JP				
E1b-2iv. Feasibility of using indentation tests for fracture and rheological properties						JP		P				P, D			D	F	
E2a: Comparison of Modification Techniques																	UWM
E2a-1: Identify modification targets and material suppliers				DP		DP											
E2a-2: Test material properties								P		P							
E2a-3: Develop model to estimate level of modification needed and cost index																	
E2a-4: Write asphalt modification guideline/report on modifier impact over binder properties												JP			D	F	
E2c: Critically Designed HMA Mixtures																	UNR
E2c-1: Identify the Critical Conditions		JP		D, F		JP	D	F									
E2c-2: Conduct Mixtures Evaluations								D				JP		D, F			
E2c-3: Develop a Simple Test														JP	D, F		
E2c-4: Develop Standard Test Procedure															D, F		
E2c-5: Evaluate the Impact of Mix Characteristics																D, F	
E2d: Thermal Cracking Resistant Mixes for Intermountain States																	UWM/UNR
E2d-1: Identify Field Sections			D, F	D, F	D	F											
E2d-2: Identify the Causes of the Thermal Cracking															D	F, P	
E2d-3: Identify an Evaluation and Testing System					DP	JP	DP, D			JP		JP, P	D	JP	F	P	
E2d-4: Modeling and Validation of the Developed System										JP		P		JP	D	F, P	
E2d-5: Develop a Standard														JP	D	F, P	
E2e: Design Guidance for Fatigue and Rut Resistance Mixtures																	AAT
E2e-1: Identify Model Improvements																	
E2e-2: Design and Execute Laboratory Testing Program																	
E2e-3: Perform Engineering and Statistical Analysis to Refine Models														JP			
E2e-4: Validate Refined Models															M&A		
E2e-5: Prepare Design Guidance															D	F	
(2) Green Asphalt Materials																	
E2b: Design System for HMA Containing a High Percentage of RAP Material																	UNR
E2b-1: Develop a System to Evaluate the Properties of RAP Materials		JP		P	D	D, F	D		P, JP	JP	P			JP	D, P	F	
E2b-2: Compatibility of RAP and Virgin Binders													P				
E2b-3: Develop a Mix Design Procedure								D			D				JP, P	D, F	
E2b-4: Impact of RAP Materials on Performance of Mixtures																D, F	
E2b-5: Field Trials										JP						D, F	
E1c: Warm and Cold Mixes																	
E1c-1: Warm Mixes																	
E1c-1i: Effects of Warm Mix Additives on Rheological Properties of Binders.																	UWM
E1c-1ii. Effects of Warm Mix Additives on Mixture Workability and Stability		P	D	F,DP						JP			D			F	UWM
E1c-1iii. Mixture Performance Testing						JP		P, DP	DP, P								UW/UNR
E1c-1iv. Develop Revised Mix Design Procedures																	UW/UNR
E1c-1v. Field Evaluation of Mix Design Procedures and Performance Recommendations															D	F	UW/UNR
E1c-2: Improvement of Emulsions' Characterization and Mixture Design for Cold Bitumen Applications																	UWM
E1c-2i: Review of Literature and Standards		JP, P, D	F		D1	D3		D6									
E1c-2ii: Creation of Advisory Group																	
E1c-2ii: Identify Tests and Develop Experimental Plan				P, DP	D1		D4										
E1c-2iv. Develop Material Library and Collect Materials.																	
E1c-2v. Conduct Testing Plan						JP	D5	P		JP		P					
E1c-2vi. Develop Performance Selection Guidelines										JP		P					
E1c-2vii. Validate Guidelines						D2							D			P, F	
E1c-2viii. Develop CMA Mix Design Procedure																	
E1c-2ix. Develop CMA Performance Guidelines														JP	D	P, F	

Deliverable codes	Deliverable Description
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DP: Decision Point	Time to make a decision on two parallel paths as to which is most promising to follow througjh

Work planned
Work completed
Parallel topic
Delayed

PROGRAM AREA: VEHICLE-PAVEMENT INTERACTION

CATEGORY VP1: WORKSHOP

Work Element VP1a: Workshop on Super-Single Tires (UNR)

This work element is complete.

CATEGORY VP2: DESIGN GUIDANCE

Work Element VP2a: Mixture Design to Enhance Safety and Reduce Noise of HMA (UWM)

Major Findings and Status

In Year 4 the research team continued efforts for studying the effect of macro-texture on noise and friction. The laser profilometer measurement procedure was improved by installing a motor to provide a fixed scanning rate and by detailed evaluation of the laser spot size. For friction properties, the British Pendulum was used to study effects of polishing and aggregate gradation.

The procedure for the abrasion/polishing of asphalt mix specimens was also modified during Year 4 by using a standard polishing sheet and fixed rotating device.

Significant effort was put toward selecting an appropriate absorption-measuring device. A new device was purchased and calibrated and is currently fully operational. Samples shared with the University of Pisa, Italy, for surface profile measurements and absorption coefficient, were used to compare noise as well as macro-texture measurements. Some differences were observed and attributed to a difference in laser spot size, measurement and data filtering methods. This issue was studied and continues to be evaluated to determine if laser spot size and details of analysis for texture spectra need to be revised.

Some effort was also put into comparison to field measuring equipment. The Dynamic Friction Tester and Circular Track Meter, on loan from FHWA, were set up, calibrated and used on a few trial pavement sections. Plans for field measurements of sections from which samples have been collected were developed. The plan includes comparing surface characteristics of field and lab produced samples. This is considered very critical to establish validity of using lab compacted samples in this study to simulate field conditions.

A journal paper was written to summarize the progress and share with the research community. Significant delays slowed progress; Equipment and testing procedures are not finalized yet due to various issues resulting from size of laser spot, method or referencing position and needed resolution for analysis.

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

The work progress for Year 4 was significantly delayed due to unforeseen problems with purchasing a KUNDT tube for noise measurements. Although hardware was simple to get, software issues and using it with new Windows versions caused major problems. In addition, the laser spot size and variability due to manual operation caused some delays and re-design of the laser system. The progress of this task will have to be accelerated to catch up with the 5-year plan.

Year Five Work Plan

Subtask VP2a-1: Evaluate common physical and mechanical properties of asphalt mixtures with enhanced frictional skid characteristics

The literature review of the salient physical and mechanical characteristics of the pavement mixtures with improved skid characteristics was started and will be completed in the first half of Year 5.

Subtask VP2a-2: Evaluate pavement macro- and microtextures and their relation to tire and pavement noise-generation mechanisms

Based on the analysis of data collected to-date it is clear that comparison to field conditions is important to establish validity of using gyratory compacted samples. This work will start as soon as spring conditions allow field testing. A detailed plan has been developed and will be executed in early months of Year 5.

Subtask VP2a-3: Develop a laboratory testing protocol for the rapid evaluation of the macro- and micro-texture of pavements

The protocol developed and tested in Year 3 and Year 4 indicates that the laser profilometer measurements could replace the sand-patch method and provide detailed data for texture spectrum analysis. Comprehensive Excel spreadsheets have been developed for the analysis. In Year 5 a sensitivity study in which changes in spectrum due to changes in gradation and voids content will be completed. There are initial models relating spectrum parameters to gradation; these models will be validated with data collected and attempts to develop mix design criteria to optimize texture will be considered.

Subtask VP2a-4: Run parametric studies on tire-pavement noise and skid response

The testing for macro-texture and friction has been completed. It was clearly observed that noise measurements for dense graded mixes do not show sensitivity to gradation. The noise measuring experiment will be revised based on testing a few coarse and fine graded mixes with extreme gradations. If noise absorption of the different mixes using the impedance tube will show important trends, this task will continue; however, if no trends are observed, a shift to open graded mixes will be followed in the revised testing plan.

Subtask VP2a-5: Establish collaboration with established national and international laboratories specialized in transportation noise measurements. Gather expertise on measurements and analysis

UW–Madison researchers continue contact with the asphalt research group in University of Pisa, Italy. Professor Losa from this university visited UW–Madison in Year 4. In addition, the research team will be attending the training workshop for the Skidsafe program in Delft University in September 2011. The collaboration with this project will be evaluated in Year 5 and plans for exchange of ideas and testing plans will be developed, if appropriate.

Subtask VP2a-6: Model and correlate acoustic response of tested tire-pavement systems

Results obtained in Year 5 from subtasks VP2a-4 and VP2a-5 will be correlated to pavement mixture design parameters such as gradation, maximum aggregate size, angularity and binder type. The obtained physical/engineering correlations can be used to construct numerical models for the evaluation and estimation of frictional skid, and for pavement-tire noise-reduction designs. The emphasis in Year 5 will be placed developing new design guidelines for asphalt mixture design protocol.

Subtask VP2a-7: Proposed optimal guideline for design to include noise reduction, durability, safety and costs

Developed guidelines will be shared with State departments of transportation and nationally recognized laboratories and centers to collect feedback about the practicality and merits of the holistic pavement mixture design methods being proposed.

Table for Decision Points and Deliverables

Date	**Deliverable**	**Description**
May 2011	Presentation	Laboratory Testing Protocol
August 2011	Journal Paper	Model for Acoustic Response Of Tire-Pavement systems
September 2011	Presentation	Guidelines for optimal acoustic and friction mix design
October 2011	Draft Final	Draft Final Report for the work element
January 2012	Final	Final Report

CATEGORY VP3: MODELING

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

Major Findings and Status

During year 4, several versions of *3D-Move Analysis* software were released. 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. The original beta-version of the 3D-Move Analysis (ver 1.0) was released in June 2010. Product testing revealed under certain pavement layer configurations and vehicle loading conditions (e.g., unrealistic thicknesses and vehicle speeds) can lead to numerical instability as a direct result of under or overflow of computer memory. Though almost all such cases are unrealistic, controls have been provided such that numerical instability is avoided. In addition, the time steps used in the computation of response histories for the cases of high vehicle speeds were not sufficiently low to capture the important peaks of the responses. Under high vehicle speeds the duration of the response histories are quite short and they require much lower time steps to reproduce the continuous time histories of any response. A modified beta-version 1.1 of 3D-Move that accounts for the above issues was released on July 27, 2010.

In 3D-Move, the output is provided in two formats: Text and Excel. An inconsistency has inadvertently occurred when these two formats were integrated. The inconsistency was present only in the Excel file, while the Text file output was correct. The origin of the problem was traced to the allocation of the columns when the data sharing between Text and Excel output files occurred. Further, there were concerns about the units of the 3D-Move responses being not prominently displayed. These issues have been corrected and a modified beta-version of 3D-Move (ver 1.2) was released on August 29, 2010.

Two major bugs were reported by three users with the version 1.2 of the software: 1) error in creating the Load and Materials file, and 2) error in creating the Master Curve. The origin of the first bug was traced to the error in creating the files in temporary directory in some of the computers. The origin of the second bug was traced to the 32 bit and 64 bit compatibility issues. When running the *3D-Move Analysis* software in 64 bit Windows operating system, the program was not able to support the third party tool used to develop the master curve that was created in a 32 bit environment. Both of the bugs have been identified and fixed in the new version of 3D-Move that is scheduled for release in year 5. However a patch file was provided to the three users that have encountered those bugs in their runs.

To provide users guidance and feedback, an internet based forum “3D-Move Discussion Group” has been created and it can be accessed using the URL http://3d-move.finddiscussion.com/. This site is dedicated to collecting the feedback, comments, issues, and concerns etc. of individuals who are evaluating and/or using 3D-Move.

Work has been undergoing to incorporate different models for specifying the master curve of the viscoelastic material (i.e. asphalt layer). The models have been subdivided into two categories according to the approach used: (1) Laboratory Data and (2) Model Equation. While the first category requires laboratory-measured material data, the second category uses equations for which model constants need to be specified. The following lists the various options that will be available in 3D-Move:

- Laboratory Data
    1. Symmetrical Sigmoidal Function (MEPDG)
    2. Non-Symmetrical Sigmoidal Function
    3. Symmetrical Sigmoidal Function(AMPT)
    4. Huet-Sayegh Model
    5. User Input (Interpolation)
- Model Equation
    1. Witczak Model
    2. Huet-Sayegh

Work has also been undergoing to integrate MEPDG and VESYS performance models in 3D-Move. Pavement performance evaluation requires the knowledge of the maximum pavement responses at specific depths throughout the pavement. Extensive analyses for different pavement structures, material properties and loading configurations have been conducted using the *3D-Move Analysis* software in attempt to determine the critical locations for the various pavement responses that are essential for the evaluation of pavement performance. The critical locations for various loading configurations (i.e. single, dual, dual tandem and tridem) and uniform tire contact pressure distributions (i.e. circular, rectangular, square and elliptical) have been determined. Those critical locations aided in eliminating unnecessary response points which optimized the run time of the software with the performance analysis option.

The impact of the contact stress distributions and patterns on pavement responses and pavement performance were assessed based on the fatigue and rutting performance of asphalt pavements using the *3D-Move Analysis* Software. Four contact stress distributions were analyzed: non-uniform, uniform circular, uniform ellipse and uniform square. Overall, a significant difference was observed between pavement critical responses and performance computed with the non-uniform and uniform contact stress distributions.

The accuracy of estimating the non-uniform contact stress distribution at a given load level, from measured contact stress distributions using the linear interpolation/extrapolation, was evaluated for selected cases. Data is currently being analyzed and summarized.

With the help of FHWA, the list of participants in the 3D-Move verification plan has been identified. The verification plan that was proposed in year 4 work plans was initiated and will be implemented in order to evaluate the potential for errors, bugs, and difficulties involved in using the software for pavement analysis purposes.

As of February 11, 2011, the *3D-Move Analysis* software has been downloaded by over hundred and twenty registered users from around the world. Figure VP3a.1 shows the distribution of the 3D-Move users by country of origin.

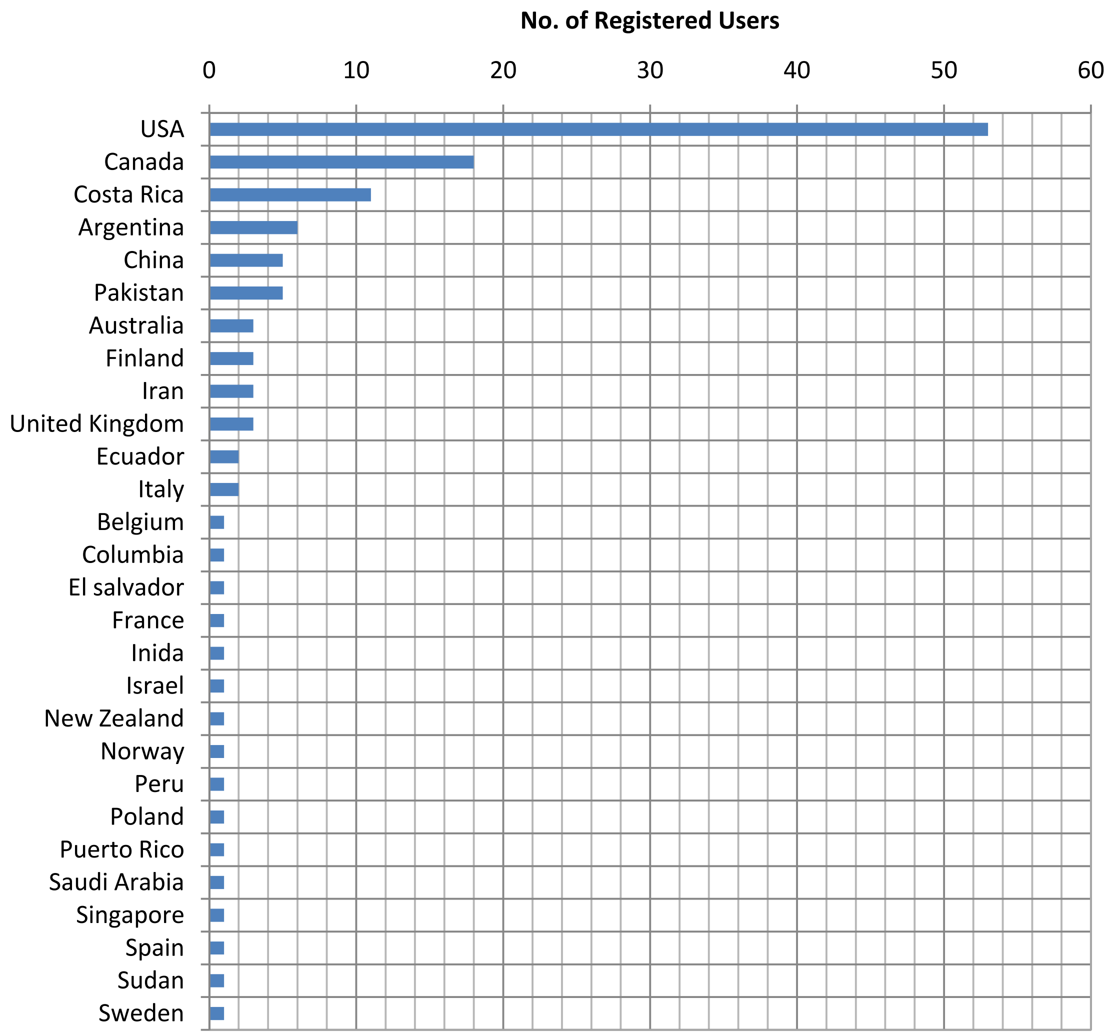

Figure VP3a.1. 3D-Move users' distribution by countries.

Year 5 Work Plan

Work will continue to finalize the form that would include the various input options for a viscoelastic material. Work will also continue to finalize and implement the performance analysis module. The critical locations for the evaluation of pavement performance will be determined for non-uniform contact stress distributions. Preset pavement response points at the critical locations for both uniform and non-uniform contact stress distributions will be incorporated into the *3D-Move Analysis* software.

A new version 2.0 of the 3D-Move program is to be released in Year 5. It is anticipated that the new version will have the various models for specifying the master curve of the viscoelastic material and the performance analysis module. The UNR team will continue on assisting user's with issues ranging from software operations, concepts clarifications, and bugs.

The UNR team will conduct an Evaluation, Verification and Validation of the *3D-Move Analysis* software in three phases.

Phase I: Operational Evaluation:
The operational evaluation plan proposed in the year 4 ARC Work Plan will be completed. It is anticipated that the plan will help identifying potential errors, bugs, and difficulties involved in using the software for pavement analysis purposes. The plan is to address the following key questions:

- Can users successfully generate the assigned examples in the 3D-Move software?
- Is the software status clear to users at all times?
- Are the input steps logically organized and grouped for the users?
- Are the pictures and illustrations used in the various windows helpful to users and do they facilitate the software use/understanding?
- Was the help menu useful and easy to navigate?
- Is the output format clear and provide the necessary information for the analysis of the data?
- What are the main benefits of using the software?
- In what case studies does the user perceive a great use of the software?
- Will the agency/user be willing to adopt the software for their pavement analysis?
- What are the user recommendations for modification or enhancement to make the software more useful and practical?

The results of the Operational Evaluation will be summarized in a short report along with a proposed action plan and will be submitted to FHWA for review and comments. The UNR team will execute the approved action plan.

Phase II: Verification:
This phase will consist of a verification of selected *3D-Move Analysis* pavement responses with measured field data. Datasets that include vehicle dynamics and sufficient laboratory characterization and documentation will be identified in year 5. The UNR team with the guidance of FHWA will identify potential suitable datasets for this purpose.

Phase III: Validation:
This phase will consist of validating the findings from Phase II with an independent dataset.

Subtask VP3a-1: Dynamic Loads

Work for Year 5 will consist of publishing the findings from the study on the effect of stress distributions and patterns and braking condition on pavement responses and performance. Summarize the impact of using actual measured data versus the use of interpolated or extrapolated stress distributions on the responses and performance of typical HMA pavements.

Subtask VP3a- 2: Stress Distribution at the Tire-Pavement Interface

No work planned for year 5. All the data that has been collected on non-uniform contact pressure distribution were already incorporated into the 3D-Move to form a built-in database.

Subtask VP3a-3: Pavement Response Model

Work for Year 5 will consist of continuing the work on the *3D-Move Analysis* model to improve it and eliminate errors and bugs. A new form will be implemented for the viscoelastic material properties inputs. Additionally, the asphalt pavement performance analysis module will be completed and included into 3D-Move version 2.0.

Subtask VP3a-4: Overall Model

Work for Year 5 will consist of continuing the work on the overall model that combines the dynamic loads, contact pressure distributions at the tire-pavement interface, and the pavement response model. The Evaluation, Verification and Validation of the *3D-Move Analysis* software will be conducted. A second operational evaluation plan is anticipated after the release of the version 2.0 of the software to evaluate the new features of 3D-Move. The observations and suggestions made by the participants in the Operational Evaluation plan and other users will be assessed and actions will be taken to improve the *3D-Move Analysis* software. UNR team will continue to maintain and assist users through the "3D-Move Discussion Group."

Table for Decision Points & Deliverables

Date	**Deliverable**	**Description**
06/11	Software	Release of version 2.0 of the 3D-Move pavement response model
12/11	Draft Report	Summarizing *3D-Move Analysis* software
03/12	Software	Release of a final version of the 3D-Move pavement response model
03/12	Final Report	Summarizing *3D-Move Analysis* software

Vehicle-Pavement Interaction Year 5	Year 5 (4/2011-3/2012)												Team
	4	5	6	7	8	9	10	11	12	1	2	3	
(1) Workshop													
VP1a: Workshop on Super-Single Tires													UNR
(2) Design Guidance													
VP2a: Mixture Design to Enhance Safety and Reduce Noise of HMA													UWM
VP2a-1: Evaluate common physical and mechanical properties of asphalt mixtures with enhanced frictional skid characteristics													
VP2a-2: Evaluate pavement macro- and micro-textures and their relation to tire and pavement noise-generation mechanisms													
VP2a-3: Develop a laboratory testing protocol for the rapid evaluation of the macroand micro-texture of pavements			P										
VP2a-4: Run parametric studies on tire-pavement noise and skid response													
VP2a-5: Establish collaboration with established national laboratories specialized in transportation noise measurements. Gather expertise on measurements and analysis													
VP2a-6: Model and correlate acoustic response of tested tire-pavement systems					JP	P							
VP2a-7: Proposed optimal guideline for design to include noise reduction, durability, safety and costs						P	D			F			
(3) Pavement Response Model Based on Dynamic Analyses													
VP3a: Pavement Response Model to Dynamic Loads													UNR
VP3a-1: Dynamic Loads													
VP3a-2: Stress Distribution at the Tire-Pavement Interface													
VP3a-3: Pavement Response Model													
VP3a-4: Overall Model			SW						D			F, SW	

Deliverable codes	Deliverable Description
D: Draft Report	Report delivered to FHWA for 3 week review period.
F: Final Report	Final report delivered in compliance with FHWA publication standards
M&A: Model and algorithm	Mathematical model and sample code
SW: Software	Executable software, code and user manual
JP: Journal paper	Paper submitted to conference or journal
P: Presentation	Presentation for symposium, conference or other
DP: Decision Point	Time to make a decision on two parallel paths as to which is most promising to follow througjh

Work planned
Work completed
Parallel topic

Vehicle-Pavement Interaction Years 2 - 5	Year 2 (4/08-3/09)				Year 3 (4/09-3/10)				Year 4 (04/10-03/11)				Year 5 (04/11-03/12)				Team
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	
(1) Workshop																	
VP1a: Workshop on Super-Single Tires																	UNR
(2) Design Guidance																	
VP2a: Mixture Design to Enhance Safety and Reduce Noise of HMA																	UWM
VP2a-1: Evaluate common physical and mechanical properties of asphalt mixtures with enhanced frictional skid characteristics				DP													
VP2a-2: Evaluate pavement macro- and micro-textures and their relation to tire and pavement noise-generation mechanisms				DP													
VP2a-3: Develop a laboratory testing protocol for the rapid evaluation of the macroand micro-texture of pavements		M&A											P				
VP2a-4: Run parametric studies on tire-pavement noise and skid response						JP		D	JP								
VP2a-5: Establish collaboration with established national laboratories specialized in transportation noise measurements. Gather expertise on measurements and analysis																	
VP2a-6: Model and correlate acoustic response of tested tire-pavement systems										JP, P				JP, P			
VP2a-7: Proposed optimal guideline for design to include noise reduction, durability, safety and costs												P		P	D	F	
(3) Pavement Response Model Based on Dynamic Analyses																	
VP3a: Pavement Response Model to Dynamic Loads																	UNR
VP3a-1: Dynamic Loads			JP														
VP3a- 2: Stress Distribution at the Tire-Pavement Interface																	
VP3a-3: Pavement Response Model						SW, v. β					JP						
VP3a-4: Overall Model											SW		SW		D	F, SW	

Deliverable codes	Deliverable Description
D: Draft Report	Report delivered to FHWA for 3 week review period.
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Work planned
Work completed
Parallel topic

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 occurred in September 2008, September 2009, and September 2010. 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. Just after the third annual monitoring in September 2010, the YNP Maintenance Supervisor contacted WRI to express an interest in obtaining some testing on the WMA sections. He has now consented to core sampling for the fourth annual monitoring in September 2011.

Year 5 Work Plan

It is planned to monitor and sample the YNP WMA site in September 2011. The first annual monitoring of the Manitoba WMA site is planned for the Fall of 2011 (see Work Element V1b).

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

Major Findings and Status

Additional comparative pavement performance sites are being sought, mainly with states where existing LTPP SPS-5 and SPS-9 sections are going out of service.

The ARC and Manitoba Infrastructure &Transportation collaborated to plan and construct two new comparative pavement performance sites in the province of Manitoba, Canada. One site used two different amounts of RAP with two different asphalt grades and the second site used warm-mix additives. Construction on the RAP comparative pavement performance site was completed in October 2009. The RAP site is on provincial highway 8 about 10 km north of Gimli. The total project length is about 28 km (17 miles) but the ARC sections were placed in about 5 km (3.1 miles) of the project.

The second comparative performance project site in Manitoba using warm-mix additives was completed in July 2010. The project has sections of HMA, Advera, Sasobit, and Evotherm DAT. The WMA site is on provincial highway 14 between the towns of Winkler and Plum Coulee. The monitoring of the Manitoba WMA site will be reported under Work Element V1a.

Extensive sampling of all construction materials from both Manitoba projects was conducted and the materials were sent to the ARC researchers and to the FHWA MRL in Sparks, Nevada.

<u>Year 5 Work Plan</u>

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. Contact with Chris Abadie of Louisiana DOT was made at TRB. Louisiana has some interest in constructing comparative sections using RAP and follow up on this will occur.

Performance monitoring and sampling of the comparative pavement sections in Arizona, Kansas, Minnesota, and the RAP sections in Manitoba are planned for in 2011. 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.

CATEGORY V2: ACCELERATED PAVEMENT TESTING

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

<u>Major Findings and Status</u>

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.

Year 5 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 V3a: Continual Assessment of Specification (UWM)

Major Findings and Status

In Year 4, the research team succeeded in building a good collaboration with the Western Cooperative Test Group (WCTG), the Rocky Mountain Asphalt User-Produce Group (RMAUPG), state highway agencies and industry to validate the findings of the Asphalt Research Consortium (ARC) and to improve Superpave PG+ specifications.

As a result of this on-going collaboration, a database for measured binder properties was established. The database includes information on binder performance using current PG specification, PG+ and new testing methods developed in the ARC project (e.g., Linear Amplitude Sweep, Single Edge-Notch Bending, etc). The database was also 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 run the tests and collect relevant data. The participation in monthly testing is on a volunteer basis and thus the number of participating labs varies from month to month. Also, the binder grades available in the database represent the commonly used grades used in field projects. Significant amount of work was done for improving the data collection system used in the monthly round-robin binder testing coordinated by the WCTG. Also, the transition to an online reporting system for the WCTG round-robin test results was completed. The reporting form for the Multiple-Stress Creep and

Recovery (MSCR) test was modified to identify sources of variability by adding the make and model of Dynamic Shear Rheometer (DSR) used by the laboratory.

A total of nine binders were tested in Year 4. The results show that the variability of the majority of the standard PG tests is acceptable, suggesting that these test methods have been well integrated into common laboratories. However, with the exception of the elastic recovery test at 25ºC, the variability of all PG+ tests results are very high. This indicates the need for inclusion of additional measures to successfully implement PG+ specifications. Among all PG+ tests, results for the MSCR test are the most variable. In an attempt to identify sources of variability, modifications to existing data collection templates were implemented.

Loose mix samples to be used in mixture testing (e.g., flow number, dynamic modulus, and indirect tension fatigue tests) were obtained by the WCTG from field projects located in Oregon, Utah, Colorado and New Mexico. In Year 4, ten loose mix samples were identified by the WCTG. Out of the ten mixes, the research team batched, compacted and tested three mixes for flow number and dynamic modulus. Note that mixture samples were compacted to 7% air voids, which are the expected in-place target air voids.

Efforts were also directed to evaluate use pattern of PG+ binder specifications throughout the country. Initial observations indicate that while most states specify at least one PG+ test, with elastic recovery (ER) test being the most popular, specifications and test procedures often differ from one state to another.

It is important to note that as a result of the collaboration between the WCTG, the RMAUPG, state highway agencies, industry and UW-Madison, a valuable database is now available for validation and evaluation of current and new technologies. This collaboration is helping to achieve one of the major objectives of ARC, which is to complement the current PG specification system with new fundamental tests such as MSCR, Linear Amplitude Sweep (LAS), and Single Edge Notch Bending (SENB), and to move away from non-fundamental tests, such as ductility and elastic recovery tests.

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

To reflect actual progress of this work element, the Year 5 and 5-year Gantt charts have been updated to indicate extended work planned for subtask V3a-1. Also, Gantt charts have been updated to show that a draft and final report will be delivered in Q2 and Q3 of Year 5, respectively.

Year Five Work Plan

Subtask V3a-1: Evaluation of the PG-Plus practices and the motivations for selecting the "plus" tests

This subtask was completed in Year 3. A draft and final report on the benefits of PG+ and newly developed ARC tests (e.g., LAS, SENB, etc) in comparison to PG tests will be completed in Year 5.

Subtask V3a-2: Detailed analysis of all PG-Plus tests being proposed or in use today, documentation of benefits and costs of these tests, and comparison with new tests

This subtask was completed in Year 3. A journal paper on repeatability issues of current PG and PG+ binder tests will be submitted in Q3 of Year 5.

Subtask V3a-3: Development of protocols for new binder tests and database for properties measured

Although the main components of this subtask were completed in Year 4, the research team will continue updating the database as new test results become available. New testing procedures such as MSCR, LAS, and SENB will be further developed. The collection of data for the WCTG database established in Year 4 will continue into Year 5.

Subtask V3a-4: Development of specification criteria for new tests based on field evaluation of construction and performance

Efforts will continue on testing of the WCTG loose mix samples for dynamic modulus, fatigue and flow number. The research team anticipates having mixture testing data linked to binder test results and eventually to field sections. Also, binder testing using standard PG, PG+ and recently developed tests will continue in Year 5 on a monthly basis. The cooperation with state highway agencies and industry to validate the findings of the research activities will continue.

Subtask V3a-5: Interviews and surveys for soliciting feedback on binder tests and specifications

The joint effort between the WCTG, the RMAUPG and UW-Madison will continue to include feedback from their member laboratories about specifications and binder tests. Specifications for the new binder tests will be submitted to department of transportation (DOT) personnel around the country. Interviews with DOT personnel and the WCTG board regarding the proposed specifications will be conducted.

Table for Decision Points and Deliverables

Date	Deliverable	Description
5/11	Presentation	To request feedback on binder tests and specifications at the Rocky Mountain Asphalt User/Producer Group conference
6/11	Presentation	Conference call with WCTG board about progress and update of binder PG and PG+ database.
12/11	Journal Paper	On repeatability issues of current PG and PG+ binder tests.
9/11	Draft Report	Detailed analysis of PG and PG+ tests
12/11	Final Report	Benefits of PG+ and new ARC tests in comparison to PG tests. Repeatability of PG+ and newly developed ARC procedures
12/11	Draft Report	Report summarizing collaboration between Western Cooperative Test Group (WCTG), the Rocky Mountain Asphalt User-Produce Group (RMAUPG) and UW-Madison.
1/12	Final Report	Development and maintenance of database for evaluation of PG, PG+, and new ARC tests.

Work Element V3b: Validation of the MEPDG Asphalt Materials Models using New MEPDG Sites and Selected LTPP Sites (UNR, UWM)

Subtask V3b-1: Design and Build Sections

Major Findings and Status

The ARC researchers faced hesitation from the DOTs to built MEPDG test sections. Therefore, no new MEPDG test sections were constructed. The UNR team shifted the year 4 and 5 budgets allocated for the appropriate subtasks into the subtasks for warm mix (E1c-1) and cold mix (E1c-2).

Year 5 Work Plan

No work on this subtask is planned for Year 5.

Subtask V3b-2: Additional Testing

No work on this subtask is planned for Year 5. (See Subtask V3b-1 for explanation).

Subtask V3b-3: Select LTPP Sections (Start Year 1 thru Year 5)

Major Findings and Status

The research team worked on the validation of the Linear Amplitude Sweep (LAS) test by comparing testing results of Long Term Pavement Performance (LTPP) binders with field performance. A total of 25 binders were tested using LAS procedure and results were analyzed with viscoelastic continuum damage theory (VECD). The LTPP binders were tested at the PG intermediate grade and pavement intermediate temperature. The pavement distress indicator used by LTPP for fatigue cracking is cracked area per 500 meters of pavement length section. LTPP cracked area measurements were normalized by pavement thicknesses and compared to the number of cycles to failure predictions at 4% strain (figure V3b-3.1). With the exception of binder 09-0902 (i.e., description of LTPP binders are presented in previous quarterly reports), the number of cycles to failure from LAS testing correlated well with field measurements. This provides promising evidence that the LAS test is capable of measuring asphalt binder contribution to mixture fatigue.

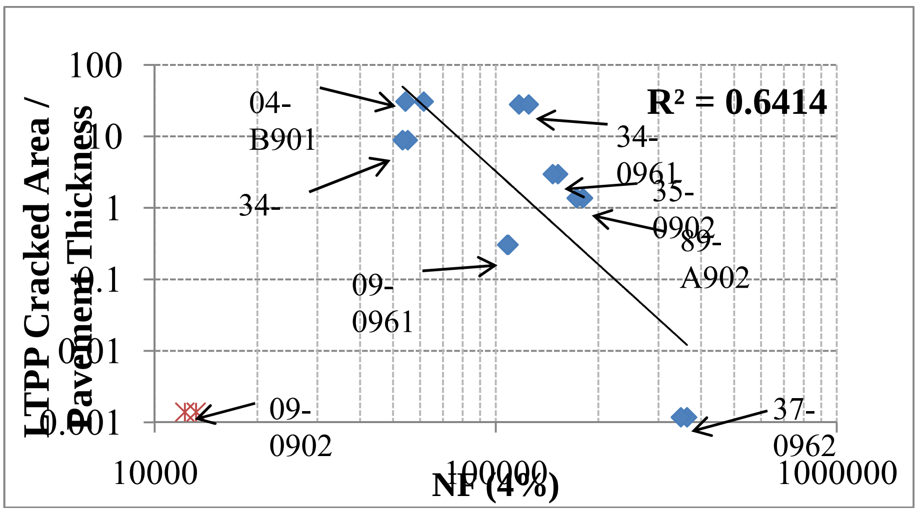


Figure V3b-3.1. Graph. Fatigue cracking vs. LAS number of cycles to failure.

Furthermore, a good correlation using a power law relationship was observed between the fatigue law parameter, A_{35}, and the measured fatigue cracking. Generally, an increase in the parameter A_{35} generally indicates an increase in fatigue resistance. Note that there are other factors besides binder fatigue performance that affect fatigue crack resistance such as pavement structure, traffic and aggregate gradation.

The effect of aging on the fatigue performance of LTPP binders was investigated in Year 4. The results indicate that laboratory aging changes significantly and systematically the relationship between number of cycles to failure and strain level. Six LTPP binders were tested at five aging levels: un-aged, RTFO-aged, PAV-aged, double PAV-aged and quadruple PAV-aged. Note that double PAV-aged and quadruple PAV-aged consisted of 40 hours and 80 hours of pressure vessel aging, respectively. It appears that aging improve binder fatigue resistance at low strain levels but deteriorates fatigue resistance at high strain levels. It was observed also that the fatigue performance of modified binders were less sensitive to aging.

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

To reflect actual progress of this work element, the 5-year Gantt charts have been updated to indicate that a journal paper will be submitted for publication in the second quarter of Year 5.

Year Five Work Plan

Subtask V3b-3: Select LTPP sites to validate new binder testing procedures

The research team will develop limits for fatigue LAS parameters A_{35} and B for specification purposes based on comparison between experimental results and field performance. Validation of the Single Edge Notch Bending (SENB) and Bitumen Bond Strength (BBS) tests will be accomplished by testing selected LTPP binders for which distress measurements for low-temperature cracking and moisture damage (i.e., stripping) are available. The testing matrix for this validation effort (table V3b-3.1) will be completed by the end of second quarter.

Table V3b-3.1. Test matrix for validation of SENB and BBS tests with LTPP binders.

SENB		
Variables	**Factors**	**Description**
Binder	6	LTPP binders with different thermal cracking performance
Temperature	2	-12 and -24°C
Replicates	3	To determine repeatability of testing
Total	**36**	
BBS		
Binder	6	LTPP binders with different stripping performance
Aggregate	2	Limestone and Granite
Conditioning time	2	0 (dry) and 24 hr (water)
Replicates	3	To determine repeatability
Total	**72**	

Table for Decision Points and Deliverables

Date	Deliverable	Description
8/11	Journal Paper	Validation of test procedures developed in thermal cracking and moisture damage work elements using LTPP binders.
12/11	Draft Report	Report summarizing characterization of LTPP binders by means of the Linear Amplitude Sweep (LAS), Single Edge-Notch Beam (SENB) and Bitumen Bond Strength (BBS) tests.
1/12	Final Report	Final report on validation/verification of fatigue, thermal cracking, and moisture damage procedures using LTPP binders.

Subtask V3b-4: Testing of Extracted Binders from LTPP Sections

No work planned.

Subtask V3b-5: Review and Revisions of Materials Models

No work on this subtask is planned for Year 5. (See Subtask V3b-1 for explanation).

Subtask V3b-6: Evaluate the Impact of Moisture and Aging on Material Properties in MEPDG

No work on this subtask is planned for Year 5. (See Subtask V3b-1 for explanation).

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. These work elements outline what has already been accomplished in the development of the constitutive models that are implemented in PANDA. 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). At this stage, most of our emphasis is being placed on validation PANDA against the comprehensive ALF experimental data. The information presented in this section is keyed to the document “Validation of ARC Damage Models”. That document was presented as a standalone document and was also summarized on pp. 194 – 201 of the Year 4 work plan and will not be repeatd here. However, some of the information and tests have been revised based on the findings of the verification work that we accomplished during Year 4. These are addressed in the following paragraphs and sections.

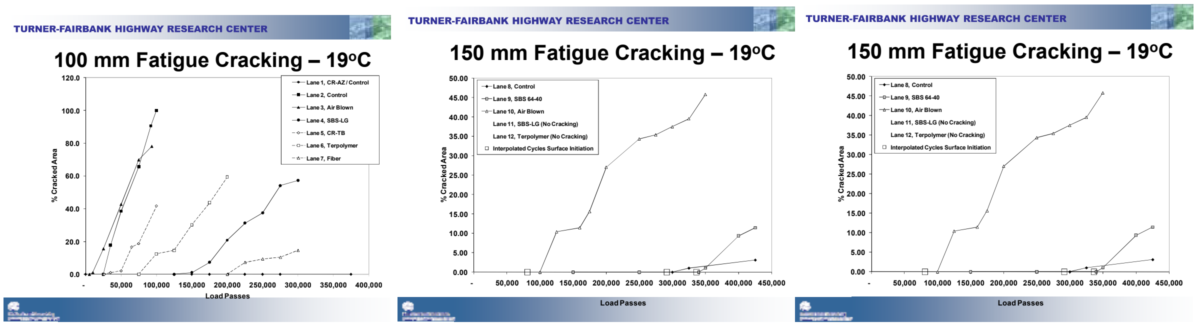
We completed analysis of the Nottingham database for the verification and validation of the ARC models (Abu Al-Rub et al. 2010a, 2011b; Huang et al. 2011a; Darabi et al. 2011a, 2011b). We are currently focusing on the use of experimental measurements that were carried out in an earlier study at North Carolina State University by Dr. Richard Kim and his co-workers to calibrate and validate the PANDA models (See table V3c.1). Two types of creep recovery tests were analyzed to determine the model parameters. The first one is the various loading test (VL) which involved the use of different stress levels while keeping the loading and unloading time periods constant throughout the test. This test was used to identify the viscoelastic and viscoplastic hardening parameters of the model. The constant loading period and stress test (CLT) was used to characterize the softening behavior of the mixture. In this test, the stress level, loading period, and unloading period were kept constant throughout the test. The analysis method used to determine the model parameters has proven to be capable of separating the recoverable and irrecoverable components of the model without requiring long rest periods. 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). The results have shown that the model can prediction experimental measurements with reasonable accuracy.

Table V3c.1. Summary of ALF mixture data.

Type of Test	**Temperature, ^{0}C**	**Loading Rate**	**Level of Confinement, kPa**	**Binders and Performance Grade**
Complex Modulus	Variable	Variable	Variable	1. Unmodified PG 70-22 2. Crumb Rubber Blend – PG 76-28 3. Styrene-Butadiene-Styrene – PG 70-28 4. Ethylene Terpolymer – PG 70-28
Controlled Crosshead Rate Test in Compression	5	5.75 x 10^{-5} to 9.60 x 10^{-6}	0	
			500	
	25	1.35 x 10^{-2} to 5.00 x 10^{-4}	0	
			500	
	40	3.01x 10^{-2} to 1.00 x 10^{-3}	0	
			500	
	55	2.99 x 10^{-2} to 1.00 x 10^{-3}	0	
			500	
Controlled Crosshead Rate Test in Tension	5	5.05 x 10^{-5} to 1.05 x 10^{-5}	0	
			500	
	25	5.00 x 10^{-4} to 1.35 x 10^{-2}	0	
			500	
	40	3.00 x 10^{-2} to 3.00 x 10^{-4}	0	
			500	
Variable Creep and Recovery Tests in Compression	55	Variable	0	
			140	
			500	

We are now working on the simulation of the ALF wheel tracking data. These data include: 1) Rutting profiles as a function of loading cycles, 2) Percent cracking as a function of loading cycles. In addition, there is a vast amount of laboratory data from accelerated loading tests

(Hamburg, Asphalt Pavement Analyzer), flow number, and flow time that are will be used in the PANDA validation. The fatigue results of the ALF experiment are shown in figure V3c.2, while the rutting results of the ALF experiment are shown in figure V3c.3.



TURNER-FAIRBANK HIGHWAY RESEARCH CENTER

Ranked Fatigue Cracking

		Load Passes to Surface Crack Initiation	Load Passes to 25m Cumulative Crack	Load Passes to 25% Cracked Area
Lane 3	Air Blown	6,648	32,336	33,654
Lane 2	Control	22,728	44,311	40,250
Lane 5	CR-TB	40,178	100,297	81,818
Lane 6	Terpolymer	79,915	139,583	141,667
Lane 4	SBS-LG	140,857	208,349	210,000
Lane 7	Fiber	185,484	375,516	379,032
Lane 1	CR-AZ / Control	>375,000	541,405	525,075

		Load Passes to Surface Crack Initiation	Load Passes to 25m Cumulative Crack	Load Passes to 25% Cracked Area
Lane 10	Air Blown	80,984	197,496	195,455
Lane 8	Control	291,667	1,385,417	1,341,667
Lane 9	SBS 64-40	336,326	675,602	516,091
Lane 12	Terpolymer	>400000	4,704,085	3,285,555
Lane 11	SBS-LG	>673000	9,390,351	6,682,329

Figure V3c.1. Results of the ALF fatigue experiments.

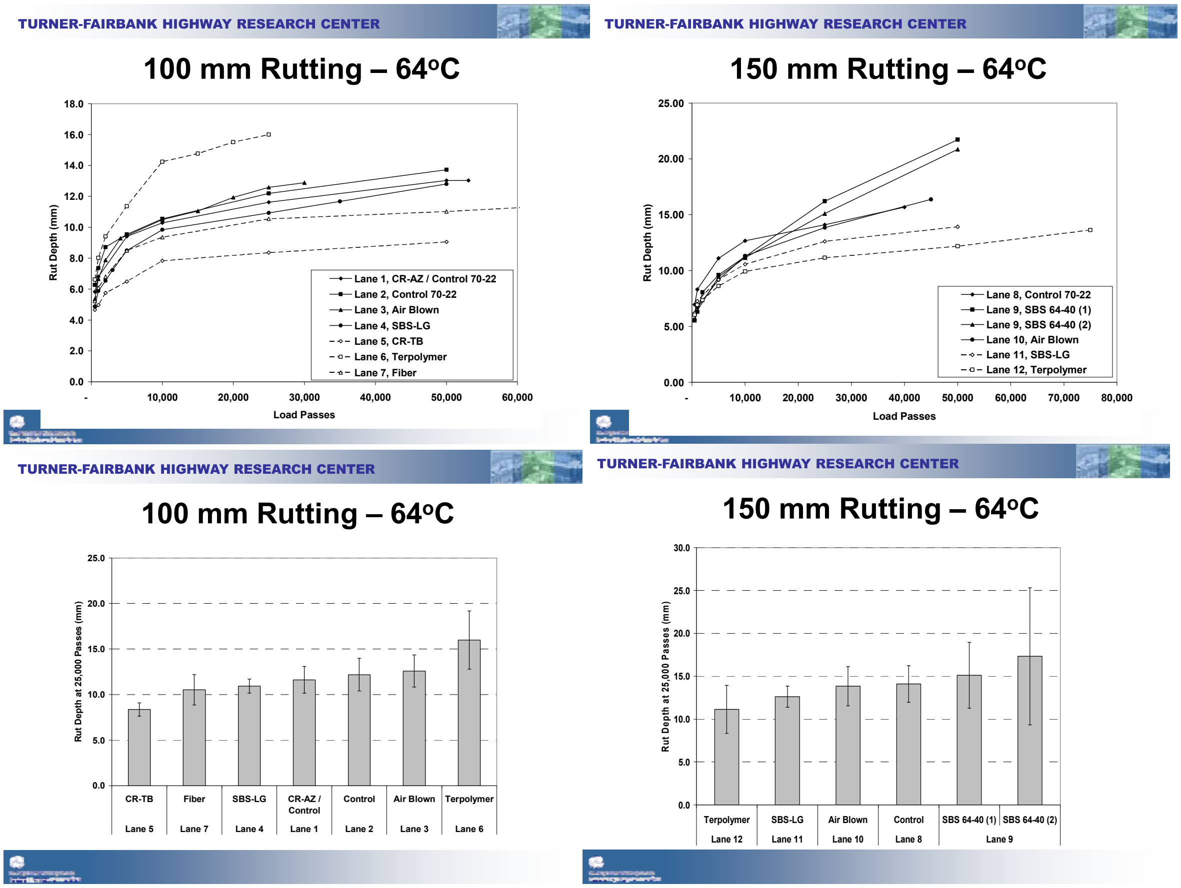


Figure V3c.2. Results of the ALF rutting experiments.

A 2 x 2 matrix comprised of two carefully selected binders and two carefully selected aggregates with significantly different mineralogical properties is being used to validate PANDA as well as the micromechanical models. In fact every product of the ARC (TAMU) will be validated based on the 2 x 2 matrix. 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 mixes produced from these materials are being subjected to the test matrix described in tables V3c.2 to V3c.4.

Table V3c.2. 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).		0.1	10 (the final value will determined based on pilot testing)	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.
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.3. 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.4. 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	

The Year 4 workplan includes three flow charts that explain how healing characterization (figure V3c.1, page 195), moisture damage (figure V3c.2, page 196) and aging characterization (figure V3c.3, page 197) are integrated into PANDA. The Year 4 work plan also describes the fact that PANDA in years 4 and 5 will be validated at three scales: laboratory mixture testing to determine engineering properties, laboratory testing to determine responses under reduced scale tracking tests, and full scale track and/or field test studies (pp. 197 – 201).

PANDA Workshop

Objective

This workshop will present the Asphalt Research Consortium's (ARC's) Pavement Analysis using Non-Linear Damage Approach (PANDA) that is currently under development by the ARC researchers at Texas A&M University. Attendees will be trained in the use of PANDA using experimental data that the participants will analyze in order to obtain the parameters required by this mechanistic model in predicting performance. The feedback from the participants in this workshop will be used to refine the model during the fifth year of the ARC project.

Location and Date

The workshop will be held at Texas A&M University on August 3 -5, 2011.

Instructors

Dr. Eyad Masad Professor emasad@civil.tamu.edu Tel.: +979 845 8308	Dr. Dallas Little Professor d-little@tamu.edu Tel.: +979 845 9963	Dr. Rashid Abu Al-Rub Assistant Professor rabualrub@civil.tamu.edu Tel.: +979 862 6603	Dr. Emad Kassem Assistant Research Scientist emad@neo.tamu.edu Tel: +979 820

Participants

A maximum of fifteen people will participate in this workshop. Those participants will be identified in consultation with the Federal Highway Administration (FHWA) to represent FHWA, academia, and research centers. Representatives from the industry and state highway agencies will be included in a follow-up workshop which will be held approximately six months following this workshop.

Workshop Topics

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

Day 1 August 3

- Description of the material constitutive model (6 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.

- Numerical implementation of the model (2 hours): this part will include description of the numerical techniques and programming of the material model in UMAT and its linkage to the Abaqus software package.

Day 2 August 4

- Identification of the model parameters (4 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.
- Development of structural models (2 hours): this session will include description of the method used to generate pavement structure models in Abaqus, loading conditions and boundary conditions.
- Discussion and feedback from participants on the topic covered during the first two days.

Day 3 August 5

- Three interactive sessions on the use of the mechanistic model (3 hours): this session will include hands-on experience with using PANDA to predict pavement performance. The training will cover the modules for inputting the model parameters, generate the structural model and predict performance. In addition, the training 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.

PANDA Software

As described in previous ARC reports, the ARC will deliver a mechanistic model in the form of a User MATerial Computational Code (UMAT) subroutine within the finite element software, Abaqus. This model will incorporate several material constitutive relationships to define the behavior (viscoelastic, viscoplastic, mechanical damage, moisture damage, fatigue damage, fracture, aging, and healing) of the asphalt composite. 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.

However, during Year 5, ARC also proposes to expand and enhance the PANDA deliverable to be in the form of a stand-alone software. The development of this software will have the following added advantages:

1. The software will be easier to use than the Abaqus package. The use of Abaqus will require some training on how to create pavement structures.
2. The software will have more flexibility in choosing different pavement structures and material properties.
3. Researchers will have the flexibility to incorporate new and improved modeling techniques for pavements.
4. Document the deliverables of the ARC in an interactive manner where the user will be able to have a hand-on experience and a better grasp of the major modeling outcomes of the ARC.
5. Initiate the first step in replacing the current empirical or semi-empirical theoretical and computational techniques for predicting the performance of pavements based on a purely mechanistic framework.

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

Table for Decision Points and Deliverables

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
V3c: Validation of PANDA (TAMU)	PANDA Workshop	Workshop on PANDA Models and Validation Results	8/11	N/A	N/A
	Draft Report	Documentation of PANDA Models and Validation	11/11	N/A	N/A
	Final Report	Documentation of PANDA Models and Validation	3/12	N/A	N/A
	UMAT Material	PANDA Implemented in Abaqus	3/12	N/A	N/A
	Software	Standalone Software to support the use of and future utility and flexibility of PANDA	3/12	N/A	N/A

Work Element V3d: Engineered Properties Testing Plan (TAMU)

The reader is referred to Work Element E1a where mixture testing status and plans are presented.

Validation Year 5

	Year 5 (4/2011-3/2012)												Team
	4	5	6	7	8	9	10	11	12	1	2	3	
(1) Field Validation													
V1a: Use and Monitoring of Warm Mix Asphalt Sections													WRI
V1b: Construction and Monitoring of additional Comparative Pavement Validation sites													WRI
(2) Accelerated Pavement Testing													
V2a: Accelerated Pavement Testing including Scale Model Load Simulation on small test track (This work element will include all accelerated pavement testing)													WRI
V2b: Construction of validation sections at the Pecos Research & Testing Center													WRI
(3) R&D Validation													
V3a: Continual Assessment of Specification													UWM
V3a-1: Evaluation of the PG-Plus practices and the motivations for selecting the "plus" tests.						D			F				
V3a-2: Detailed analysis of all PG-Plus tests being proposed or in use today, documentation of benefits and costs of these tests, and comparison with new tests													
V3a-3: Development of protocols for new binder tests and database for properties measured													
V3a-4: Development of specification criteria for new tests based on field evaluation of construction and performance			P						JP				
V3a-5: Interviews and surveys for soliciting feedback on binder tests and specifications		P							D	F			
V3b: Validation of the MEPDG Asphalt Materials Models and Early Verification of Technologies Developed by ARC using new MEPDG Sites and Selected LTPP sites													UNR/UWM/ WRI
V3b-1: Design and Build Sections										D		F	UNR
V3b-2: Additional Testing (if needed)													
V3b-3: Select LTPP Sites to Validate New Binder Testing Procedures					JP				D	F			UWM
V3b-4: Testing of Extracted Binders from LTPP Sections													
V3b-5: Review and Revisions of Materials Models													
V3b-6: Evaluate the Impact of Moisture and Aging													

Deliverable codes	**Deliverable Description**
D: Draft Report	Report delivered to FHWA for 3 week review period.
F: Final Report	Final report delivered in compliance with FHWA publication standards
M&A: Model and algorithm	Mathematical model and sample code
SW: Software	Executable software, code and user manual
JP: Journal paper	Paper submitted to conference or journal
P: Presentation	Presentation for symposium, conference or other
DP: Decision Point	Time to make a decision on two parallel paths as to which is most promising to follow througjh

Work planned
Work completed
Parallel topic

Validation Years 2 - 5	Year 2 (4/08-3/09)				Year 3 (4/09-3/10)				Year 4 (04/10-03/11)				Year 5 (04/11-03/12)				Team
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	
(1) Field Validation																	
V1a: Use and Monitoring of Warm Mix Asphalt Sections																	WRI
V1b: Construction and Monitoring of additional Comparative Pavement Validation sites																	WRI
(2) Accelerated Pavement Testing																	
V2a: Accelerated Pavement Testing including Scale Model Load Simulation on small test track																	WRI
V2b: Construction of validation sections at the Pecos Research & Testing Center																	WRI
(3) R&D Validation																	
V3a: Continual Assessment of Specification																	UWM
V3a-1: Evaluation of the PG-Plus practices and the motivations for selecting the "plus" tests.		P	D,F											D	F		
V3a-2: Detailed analysis of all PG-Plus tests being proposed or in use today, documentation of benefits and costs of these tests, and comparison with new tests				P	D												
V3a-3: Development of protocols for new binder tests and database for properties measured						JP				P							
V3a-4: Development of specification criteria for new tests based on field evaluation of construction and performance						D		P	P			JP	P		JP		
V3a-5: Interviews and surveys for soliciting feedback on binder tests and specifications									P		JP		P		D	F	
V3b: Validation of the MEPDG Asphalt Materials Models and Early Verification of Technologies Developed by ARC using new MEPDG Sites and Selected LTPP sites																	UNR/UWM
V3b-1: Design and Build Sections																D, F	
V3b-2: Additional Testing (if needed)																	
V3b-3: Select LTPP Sites to Validate New Binder Testing Procedures					DP			P		JP, DP		P		JP	D	F	
V3b-4: Testing of Extracted Binders from LTPP Sections																	
V3b-5: Review and Revisions of Materials Models																	
V3b-6: Evaluate the Impact of Moisture and Aging																	

Deliverable codes	Deliverable Description
D: Draft Report	Report delivered to FHWA for 3 week review period.
F: Final Report	Final report delivered in compliance with FHWA publication standards
M&A: Model and algorithm	Mathematical model and sample code
SW: Software	Executable software, code and user manual
JP: Journal paper	Paper submitted to conference or journal
P: Presentation	Presentation for symposium, conference or other
DP: Decision Point	Time to make a decision on two parallel paths as to which is most promising to follow througjh

Work planned
Work completed
Parallel topic

PROGRAM AREA: TECHNOLOGY DEVELOPMENT

Work Element TD1: Prioritize and Select Products for Early Development (AAT, WRI)

Six test methods were identified as early products. The six methods were identified from prior FHWA research by ARC members. Table TD1 lists the six test methods.

Table TD1. Products identified from previous research by ARC members.

Product	ARC Research Program	Format	Estimated Completion Date	ARC Partner
Simplified Continuum Damage Fatigue Analysis for the Asphalt Mixture Performance Tester	Prior	Test Method	12/31/2010	AAT
Wilhelmy Plate Test	Prior	Test Method	12/31/2010	TTI
Universal Sorption Device	Prior	Test Method	12/31/2010	TTI
Dynamic Mechanical Analysis	Prior	Test Method	12/31/2010	TTI
Automated Flocculation Titrimetric Analysis	Prior	Test Method	12/31/2010	WRI
Determination of Polymer in Asphalt	Prior	Test Method	Completed	WRI

Brief descriptions of the six test methods are listed below.

Technology Development Product Name

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

Format

Test Method

ARC Partner

Advanced Asphalt Technologies, LLC

Product Description

A test method for conducting and analyzing cyclic direct-tension fatigue tests in the Asphalt Mixture Performance Tester (AMPT) will be prepared. The test method will be based on continuum damage analysis which is a promising alternative to flexural fatigue testing. In continuum damage fatigue testing, a cylindrical specimen like that used in the AMPT is tested in cyclic direct-tension loading, while the change in stiffness with load cycles is monitored. Through continuum damage theory, a comprehensive fatigue relationship for an asphalt concrete mixture can be developed from a limited number of tests. Completed research has shown that results from continuum damage and flexural fatigue testing are very similar.

Equipment Availability and Cost

The fatigue test method would be an add-on to the currently available AMPT which costs approximately $75,000. Both current AMPT manufacturers have developed prototype hardware and software for cyclic tension fatigue testing. The additional cost for an AMPT with fatigue capability is estimated to be approximately $5,000 to $10,000.

Potential Applications

The target application is as a performance test to compliment mixture design. Once a volumetric design has been completed, its resistance to fatigue damage would be evaluated and compared to that require for the design axle load level.

Targeted Users

Engineers and experienced technicians who design asphalt concrete mixtures.

Time and Skill Requirements

Fatigue testing and analysis will require approximately 4 to 5 working days. This includes time for specimen fabrication, fatigue testing, and analysis of the data. The equipment can be operated by experienced HMA technicians. The analysis is being targeted to engineers with knowledge of pavement design and asphalt mixture characterization.

Recommended Next Steps

1. Evaluation of a wide range of mixtures with varying fatigue characteristics to further validate the procedure.
2. Ruggedness testing to refine the procedure followed by an interlaboratory study to develop precision estimates for the procedure.

Technology Development Product

Wilhelmy Plate Method

Format

Test Method

ARC Partner

TTI

Product Description

The Wilhelmy plate device is used to determine the three surface free energy components of the asphalt binder. Surface free energy of the asphalt binder dictates the durability of the adhesive bond between the asphalt binder and different aggregate surfaces in both wet and dry conditions.

The surface free energy components of the asphalt binder can be combined with the surface free energy components of the aggregates (either measured or available from a database of values as a part of the ARC material properties database) to determine the work of interfacial adhesion for different combinations of these materials in dry as well as wet conditions. These properties provide material properties input for micromechanical models and can also be used as a screening tool by which to select the most durable combinations of asphalt binder and aggregate during the mixture design process. In addition, the surface free energy of asphalt binders is an important material property input to model and predict the fatigue crack growth behavior of asphalt materials in wet and dry conditions. Studies related to the measurement of the surface free energy of asphalt binders and its application to characterize fatigue crack growth in asphalt mixtures and the fine aggregate matrix have been well documented in peer reviewed journals in the past few years as well in the final report for NCHRP project 9-37.

The procedure to determine the surface free energy components using the Wilhelmy plate device was developed in a recently completed NCHRP project 9-37 and the technology for its use was extended in Texas Department of Transportation (TxDOT) project 4524 into an automated system by which to evaluate the combination of aggregate and asphalt binder that would optimize resistance to moisture damage. However, this was done only for Texas materials.

Equipment Availability and Cost

The Wilhelmy plate device ($20,000) is available commercially from manufacturers such as Cahn Instruments and KSV Instruments and can be used to carry out the test procedure to determine the surface free energy components.

Potential Applications

Screening tool to identify aggregate-binder combinations that have potential for moisture damage. Material properties required to predict mixture behavior using advanced models.

Targeted Users

DOT, especially centralized labs, and other transportation agencies.

Time and Skill Requirements

One day including binder specimen preparation and testing. A trained laboratory technician can conduct the test.

Recommended Next Steps

As a part of the technology development, there is a need to evaluate the sensitivity and ruggedness of this test method and standardize procedures for its use with polymer modified asphalt binders and mastics.

Technology Development Product

Universal Sorption Device

Format

Test Method

ARC Partner

TTI

Product Description

The Universal Sorption Device (USD) is used to determine the three surface free energy components and specific surface area of aggregates. The surface free energy and specific surface area of the aggregate dictates the durability of the adhesive bond between the aggregate surface and different asphalt binders in both wet and dry conditions.

The surface free energy components of the aggregate can be combined with the surface free energy components of the asphalt binder to determine the work of interfacial adhesion for different combinations of these materials in dry as well as wet conditions. This methodology can be used as a screening tool by which to select the most durable combinations of asphalt binders and aggregates during the mixture design process. Studies related to the measurement of the surface free energy of aggregates and their application to the selection of material combinations that are resistant to moisture induced damage are well documented in peer reviewed journal publications.

The USD measures adsorption characteristics of aggregates in a vacuum environment and is available commercially from Rubotherm of Germany. Similar sorption test equipment that allows measurement of surface properties in an inert gas environment is also available from other manufacturers such as TA instruments.

The procedure to determine the surface free energy components and specific surface area using the USD was developed in a recently completed NCHRP project 9-37 and the technology for its use was extended in Texas Department of Transportation (TxDOT) project 4524 into an automated system by which to evaluate the combination of aggregate and asphalt binder that would optimize resistance to moisture damage. However, this was done only for Texas materials. Furthermore, Texas A&M has tested about 25 minerals to assess the mineral components that produce surface energy. This study has been highly enlightening as it identifies the major mineral sources of surface free energy as well as the impact of coating on the mineral surface that can and do impact and often compromise adhesive bond energy. Organic as well as inorganic coatings were studied. One impact of this study will be to provide a method of approximation of the surface energy based a reasonable knowledge of the mineralogical composition of the aggregate being evaluated.

Equipment Availability and Cost

Sorption device ($50,000) available from manufacturers such as Rubotherm from Germany or TA instruments.

Potential Applications

Screening tool to identify aggregate-binder combinations that have potential for moisture damage. Material properties required to predict mixture behavior using advanced models.

Targeted Users

DOT, especially centralized labs, and other transportation agencies.

Time and Skill Requirements

One day including aggregate specimen preparation and testing. A trained laboratory technician can conduct the test.

Recommended Next Steps

As a part of the technology development efforts, there is a need to evaluate the sensitivity and ruggedness of this test method.

Technology Development Product Name

Dynamic Mechanical Analysis

Format

Test Method

ARC Partner

TTI

Product Description

Aggregate particles (smaller than 1.18 mm) together with the asphalt binder constitute the fine aggregate matrix (FAM) in an asphalt mixture. The FAM can also be thought of as a combination of aggregate particles smaller than 1.18 mm and the mastic (binder and filler (particles smaller than 74 μm). The FAM holds the coarse aggregate particles together as a mixture composite. Mechanical properties of the FAM have a significant impact on the performance and durability of the full asphalt mixture. Conventional Superpave guidelines characterize asphalt binders, aggregates, and the complete asphalt mixture. These tests and specifications do not address material properties of the FAM, which represent an important intermediate length scale. The dynamic mechanical analysis (DMA) provides a tool by which to characterize the mechanical properties of the FAM.

The DMA provides rheological properties of the FAM as well as material parameters that characterize the evolution of fatigue damage. Information from the DMA can be used to design more durable asphalt mixtures as well as to provide material property inputs for constitutive models that can be used for structural design of pavements. Results from DMA testing of FAM can define the rate of crack growth damage, the potential of the FAM to heal or recover during rest periods between loads, and the potential for moisture damage within the FAM. The ability of the DMA to evaluate fracture, healing, and durability properties of the FAM is well documented in several referred (peer reviewed) journal publications during the past five years.

The analysis methodology for the DMA has been revised a number of times over the past three years in order to address the three types of damage that can be monitored during the DMA testing process. Based on these a unified methodology has been developed by which to analyze both controlled stress and controlled strain experiments and testing guidelines have been established to assure that the methodology is applicable. The evolution of the DMA testing has also produced a system that reduces the variability of the analysis to levels from which statistical inferences can be made within reasonable tolerances. Based on this approach a protocol in AASHTO format has been developed as has software that captures the testing data, analyzes the data and presents the data in the format of a crack growth index which is based on the three components of dissipated strain energy and other important materials properties of the FAM.

The test equipment is currently available in a number of laboratories in the United States.

The DMA can be carried out using equipment available from manufacturers such as Malvern Instruments, and TA Instruments, USA.

There is a need to standardize the FAM design and fabrication procedures, conduct sensitivity and ruggedness tests on the use of DMA to characterize the FAM.

Equipment Availability and Cost

1. Superpave Gyratory Compactor for preparing test samples ($20k)
2. Dynamic Mechanical Analyzer (about $70K)
3. Coring fixtures to obtain DMA specimens from gyratory specimens ($3k).

Potential Applications

This test can be used to characterize the mechanical properties of the FAM. These properties are entered into models to predict the resistance to moisture damage and fatigue cracking.

Targeted Users

1. Pavement and materials engineers/researchers;
2. State DOT technical personnel; and
3. Practitioners/lab technicians

Time and Skill Requirements

Lab technicians will be able to conduct this test. A software has been developed to help in analyzing the data. The test takes up to 2 hours and the analysis using the software takes less than 10 minutes.

Recommended Next Steps

This test method is available in AASHTO format.

Technology Development Product Name

Automated Flocculation Titrimetric (AFT) Analysis

Format

Test Method

ARC Partner

Western Research Institute

Product Description

A standard method for Automated Flocculation Titrimetry (Automated Heithaus Titrimetry) has been developed and accepted by ASTM International. The standard method is designated D6703-07. This test method describes a procedure for quantifying three Heithaus compatibility parameters that estimate the colloidal stability of asphalts, asphalt cross blends, aged asphalts, and pyrolyzed heavy oil residua. Compatibility of asphalt materials influences important physical properties such as the rheological properties of complex modulus and phase angle.

Equipment Availability and Cost

Equipment is available from Koehler Instruments, Geneq Instruments, Hoskin Scientific, PSL Systemtechnik, and others. Cost is approximately $50,000.

Potential Applications

Material compatibility may have practical importance when two different asphalt sources, even of the same grade, are mixed in a storage tank in a situation such as when a portable asphalt plant is moved from one location to another and different asphalt sources are being used. Another example may be where a contractor purchases asphalt from two different suppliers. Other variations of mixing different asphalt or crude oil sources may also have importance. The instrument and test method can also be used to calculate coking indexes in refinery operations.

Targeted Users

Refiners, State DOT’s, Suppliers, Contractors, Test laboratories.

Time and Skill Requirements

The time requirement for one test is approximately 2 hours. Larger groups of samples can improve time effectiveness. A laboratory technician with minimal training can conduct the testing.

Recommended Next Steps

None.

Technology Development Product Name

Determination of Polymer in Asphalt

Format

Test Method

ARC Partner

Western Research Institute

Product Description

This method is used to determine the polymer content of an asphalt sample and is based on Gel-Permeation Chromatography (GPC), also called Size-Exclusion Chromatography. This method is applicable to any asphalt binder or asphalt cement that can be dissolved in toluene. The equipment required for this procedure is available from commercial vendors but requires a general knowledge of column chromatography and chromatography equipment. A standard method for the determination of the polymer content of an asphalt has been prepared in AASHTO format.

The draft AASHTO format method can be delivered upon FHWA request.

Equipment Availability and Cost

Equipment is available from Waters Corporation, and others. Cost is approximately $75,000.

Potential Applications

Verification of type and quantity of polymer modifier added to an asphalt binder.

Targeted Users

Refiners, State DOT's, Suppliers, Contractors, Test laboratories.

Time and Skill Requirements

The time requirement for one test is approximately 1 hour. Larger groups of samples can improve time effectiveness. A laboratory technician with minimal training can conduct the testing.

Recommended Next Steps

This method can be utilized as-is. However, with more work the method can be advanced to determine not only polymer concentration but also polymer identity and molecular weight range. This may be particularly useful if polymer-modified pavements are going to be used as RAP.

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

Major Findings and Status

The research team has continued to review interim research products to identify potential mid-term and long-term development projects. Many of these were presented last year. Review and prioritization by the ETG's and/or FHWA is valuable and necessary to move the products forward toward general use.

Table TD3 lists the research products identified as mid-term products. Following table TD3 are brief descriptions of the research products.

Table TD3. ARC Mid-term research products.

Product	ARC Work Element	Format	Estimated Completion Date	ARC Partner
A Method for the Preparation of Specimens of Fine Aggregate Matrix of Asphalt Mixtures	M1c	Test Method	12/31/2010	TTI
Measuring intrinsic healing characteristics of asphalt binders	F1d	Test Method	12/31/2010	TTI / UT Austin
Lattice Micromechanical Model for Virtual Testing of Asphalt Concrete in Tension	F3b	Analysis Program	12/31/2011	NCSU
Cohesive Zone Modeling as an Efficient and Powerful Tool to Predict and Characterize Fracture Damage of Asphalt Mixtures Considering Mixture Microstructure, Material Inelasticity, and Moisture Damage	F3b	Performance Predicting Model	12/31/2010	University of Nebraska
Pavement Analysis Using Nonlinear Damage Approach (PANDA)	F3c	Test Method	12/31/2010	TTI
Test Methods for Determining the Parameters of Material Models in PANDA (Pavement Analysis Using Nonlinear Damage Approach)	F3c E1a	Test Method	12/31/2010	TTI
Continuum Damage Permanent Deformation Analysis for Asphalt Mixtures	E1a	Test Method	12/31/2010	TTI
Characterization of Fatigue and Healing Properties of Asphalt Mixtures Using Repeated Direct Tension Test	E1a	Test Method & Data Analysis Program	12/31/2010	TTI
Nondestructive Characterization of Tensile Viscoelastic Properties of Undamaged Asphalt Mixtures	E1a	Test Method & Data Analysis Program	Completed	TTI
Nondestructive Characterization of Field Cores of Asphalt Pavements	E1a	Test Method & Data Analysis Program	12/31/2010	TTI

Table TD3 continued. ARC Mid-term research products.

Product	ARC Work Element	Format	Estimated Completion Date	ARC Partner
Self-Consistent Micromechanics Models of Asphalt Mixtures	E1a	Analytical Model & Data Analysis Program	Completed	TTI
Nondestructive Characterization of Anisotropic Viscoelastic Properties of Undamaged Asphalt Mixtures under Compressive Loading	E1a	Test Method	Completed	TTI
Mix Design for Cold-In-Place Recycling (CIR)	E1c	Practice	12/31/2011	UNR
Mix Design for Cold Mix Asphalt	E1c	Practice	3/31/2012	UNR
Evaluation of RAP Aggregates	E2b	Practice	12/31/2010	UNR
Identification of Critical Conditions for HMA mixtures	E2c	Practice	12/31/2011	UNR
Modified Thermal Stress Restrained Specimen Test (TSRST)	E2d	Test Method	3/31/2011	UNR
HMA Thermal Stresses	E2d	Model	3/31/2012	UNR
Dynamic Model for Flexible Pavements 3D-Move	VP3a	Software	3/31/2011	UNR
Binder Bond Strength Test (BBS)	M1a	Test Method	6/31/2010	UWM
Elastic Recovery – DSR	F2a	Test Method	12/31/2010	UWM
Linear Amplitude Sweep (DSR)	F2e	Test Method	3/31/2010	UWM
Binder Yield Energy Test (BYET)	F2e	Test Method	9/30/2010	UWM
Rigden Voids for fillers	F2e	Test Method	9/30/2011	UWM
Binder Lubricity Test – DSR	E1c	Test Method	12/31/2010	UWM
Method to Quantify the Effect of RAP and RAS on Blended Binder Properties without Binder Extraction	E2b	Test Method / Software	12/31/2010	UWM
Single Edge Notch Bending	E2d	Test Method	3/31/2011	UWM
Binder Glass Transition Test	E2d	Test Method	3/31/2011	UWM
Asphalt Mixture Glass Transition Test	E2d	Test Method	3/31/2011	UWM
Planar imaging/ Aggregate Structure	E1b	Test Method/ Software	3/31/2011	UWM
Gyratory Pressure Distribution Analyzer (GPDA)	E1c	Test Method	Completed	UWM
Improved Oxygen and Thermal Transport Model of Binder Oxidation in Pavements	F1c	Methodology, Publication		TAMU
Field Validation of an Improved Oxygen and Thermal Transport Model of Binder Oxidation in Pavements	F1c	Methodology, Publication		TAMU

Table TD3 continued. ARC Mid-term research products.

Product	ARC Work Element	Format	Estimated Completion Date	ARC Partner
Validation of an improved Pavement Temperature Transport Model for use in an Oxygen and Thermal Transport Model of Binder Oxidation in Pavements	F1c	Methodology, Publication		TAMU
Pavement Air Voids Size Distribution Model for use in an Oxygen and Thermal Transport Model of Binder Oxidation in Pavements	F1c	Methodology, Publication		TAMU
Improved Understanding of Fast-Rate, Constant-Rate Binder Oxidation Kinetics Mechanism through the Effects of Inhibitors	F1c	Publication		TAMU
Improved Understanding of Fatigue Resistance Decline with Binder Oxidation	F1c	Publication		TAMU
Micromechanical Properties of Various Structural Components in Asphalt using Atomic Force Microscopy (AFM)	F2d	Test and Analysis Method	3/2011	TAMU

Brief descriptions of the ARC Mid-term research products are listed below.

Technology Development Product Name

A Method for the Preparation of Specimens of Fine Aggregate Matrix of Asphalt Mixtures

ARC Research Program

M1c

Format

AASHTO Test Method

Estimated Completion Date

December 31, 2010

ARC Partner

Texas A&M

Product Description

A new method will be developed for preparing Fine Aggregate Matrix (FAM) specimens for the DMA testing. This method aims at preparing FAM specimens that represent the composition and structure of the fine portion of the mixture. The method involves preparing loose full asphalt mixtures and sieving them into different sizes. Then, ignition oven is used to determine the binder content associated with the small size materials (passing sieve #16). The sieve # 16 is used to separate fine aggregates from the coarse aggregates. The binder content and original mixture gradation for sizes passing sieve #16 are used to prepare gyratory specimens. The DMA samples are cored out of the gyratory specimens. The test method will also include a procedure for moisture conditioning of DMA specimens.

Equipment Availability and Cost

Superpave gyratory compactor, equipment used for mixing and compaction of asphalt mixtures, and an ignition oven ($70k).

Potential Applications

This test method will be used to prepare FAM specimens for testing in the DMA. The testing results are used to predict the resistance to fatigue and moisture damage.

Targeted Users

1. Pavement and materials engineers/researchers;
2. State DOT technical personnel; and
3. Practitioners/lab technicians

Time and Skill Requirements

Lab technicians will be able to prepare specimens and test them in the DMA. The specimen preparation takes about 5 to 6 hours.

Recommended Next Steps

Develop an AASHTO procedure for DMA specimen preparation.

Technology Development Product Name

Intrinsic healing rate of asphalt binders measured using the Dynamic Shear Rheometer (DSR)

ARC Research Program

F1d

Format

Test Method

Estimated Completion Date

12/31/2012

ARC Partner

Texas A&M

Product Description

A test method to measure the rate of intrinsic healing in asphalt binders at different temperatures will be prepared. Self-healing in asphalt binders can be regarded as the reversal of micro-damage. The fracture or crack growth process in an asphalt binder entails development of a failure process zone ahead of the crack tip followed by crack opening. The process of self-healing can be regarded as a reversal in two stages, i.e. crack wetting and a regain of strength over time (intrinsic healing). Intrinsic healing is a temperature dependent material property that is impacted by the chemical make-up of the asphalt binder. The proposed test method is to measure the intrinsic healing rate of an asphalt binder using the DSR. The procedure requires measuring the G* of an asphalt binder in the form of two separate disks that are brought into contact under a very small normal load of about 0.4 Newtons. The values of G* are measured after continually increasing rest periods. The results are compared to the G* of a single specimen of the same binder and with a geometry that is similar to the composite, two-piece specimen. The ratio of the shear modulus of the two-piece specimen to that of the one-piece specimen at a specific time interval is compared to quantify intrinsic healing characteristics of the asphalt binder. The test can be conducted at multiple temperatures. The test can be carried out using most automated DSRs.

Intrinsic healing tests have been performed on approximately six binders selected for their different compositions, and the intrinsic healing properties of these binders has been seen to vary according to the predictions of a material characterization model developed under the ARC program that explains the process of healing as the convolution of a wetting process and a longer term healing process. The cohesive bond energy (computed from surface energy measurements) of the binders has been found to be strongly related to intrinsic healing as predicted by the material characterization model. Molecular morphology has also been found to be strongly related to long term healing as predicted by the material characterization model.

It is envisioned that the intrinsic healing properties of the asphalt binder can be used as an additional dimension to select asphalt binders in a manner very similar to the current specifications for rutting and fatigue cracking. Once developed, this test procedure can be used for applications other than measurement of intrinsic healing. For example, one can use a composite of aged and virgin binder to determine the blending of virgin binder with recycled binder in RAP mixtures that produces superior healing properties. In this sense, healing should be viewed as an integral part of the overall fatigue fracture process of damage and healing.

Equipment Availability and Cost

Dynamic Shear Rheometer ($50,000 – DSR is already in use for other binder tests)

Potential Applications

Screening for intrinsic healing potential of asphalt binders

Targeted Users

DOT and other transportation agencies

Time and Skill Requirements

One day including binder specimen preparation and testing.
Skill level required is similar to that for binder DSR testing.

Recommended Next Steps

Technology Development Product

Lattice Micromechanical Model for Virtual Testing of Asphalt Concrete in Tension

ARC Research Program

ARC F3b

Format

Analysis Program

Estimated Completion Date

2/28/2012

ARC Partner

North Carolina State University

Product Description

A multiscale virtual-testing methodology will be developed with the ultimate goal of linking the binder and aggregate properties to the cracking performance of asphalt concrete. The main ingredients of the proposed methodology are (a) a virtual fabrication technique that generates the microstructure of asphalt concrete specimens without the need for physical fabrication, (b) a lattice modeling approach that simulates the micromechanical behavior of cracked asphalt concrete specimens, and (c) a multiscale methodology that incorporates the effects of aggregates of widely varying sizes. A failure criterion based on continuum damage theory will be implemented to simulate gradual degradation of lattice links. A stand-alone virtual microstructure fabrication approach will automatically attain the two-dimensional (2D) internal structure of HMA from the job mix formula. To improve computational efficiency, these two approaches will be integrated through the multiscale modeling method to perform a seamless microstructural analysis of actual HMA specimens with the ultimate aim of performance evaluation and mix design optimization.

The target audience includes practitioners and researchers who want to supplement the PG binder specification and Superpave volumetric mix design with virtual cracking performance testing. The main benefit of this model is the ability to determine the cracking resistance of a mixture without having to perform laboratory tests. As a result, multiple combinations of aggregate gradation and asphalt content can be virtually tested using the model, and the results may be used to aid the Superpave volumetric mix design by optimizing the aggregate gradation and asphalt content. It is expected that the virtual test results would be accurate enough to determine the mixture’s pass/fail acceptance in terms of cracking performance.

Time and Skill Requirements

1. Understanding of the effects of mixture parameters on cracking resistance of asphalt mixture
2. Computer skills capable of the operation of common MS Windows-based software
3. 2-5 hours of run time depending on the computer speed

Recommended Next Steps

1. Verification and calibration of the lattice model using a wide range of mixtures under varying conditions
2. Development of AASHTO specification based on the lattice model and ruggedness testing of the program

Technology Development Product Name

Cohesive Zone Modeling for Fracture Damage of Asphalt Mixtures

Format

Performance Predicting Model and Test Method

ARC Partner

University of Nebraska (sub-contractor to Texas A&M University)

Product Description

A model for predicting and characterizing fracture damage of asphalt mixtures will be prepared. The technique will be based on cohesive zone approach to model initiation and propagation of physical cracks. The cohesive zone approach can effectively and accurately address inelastic fracture damage and failure of heterogeneous asphaltic composites. In addition, the cohesive zone model can be incorporated with the influence of moisture diffusion to properly model moisture induced fracture in asphalt mixtures.

We will deliver the cohesive zone model in the form of a UEL (User ELement) code subroutine within a commercial finite element software, *ABAQUS* and laboratory test methods developed to identify cohesive zone model inputs such as fracture properties. In addition, a set of documents including theory manuals which describe constitutive equations of the cohesive zone model and testing protocols to estimate or measure the cohesive zone model parameters.

Potential Applications

The cohesive zone model herein predicts crack evolution based on physically measured fracture properties in realistic length scales. Therefore, it is a clearly attractive stand-alone alternative to other ARC modeling efforts that are based on continuum damage approaches which typically characterize damage using phenomenological internal state variables. In addition, the cohesive zone model can complement other ARC modeling efforts. The UEL computational code subroutine can be easily integrated with other computational modeling approaches such as the PANDA (Pavement Analysis Using Nonlinear Damage Approach) by providing a powerful fracture engine, so that nonlinear-viscoelastic-viscoplastic responses with microfracture to complete failure of asphaltic mixtures can be modeled.

Targeted Users

Since the technology developed herein is based on mixture-level characteristics by accurately accounting for the mixture microstructure and fundamental properties of individual mixture components and their interactions, this technology can benefit pavement- and materials engineers to select mixture components in a more engineered manner and to potentially improve current volumetric mix-design concepts. Consequently, target audience of this work would be materials engineers, pavement design practitioners as well as researchers who are interested in constitutive damage modeling and fracture mechanisms of pavement materials.

Technology Development Product Name

Pavement Analysis Using Nonlinear Damage Approach (PANDA)

ARC Research Program

F3c

Format

Subroutines in the Abaqus finite element program

Estimated Completion Date

12/31/2012

ARC Partner

TTI

Product Description

The ARC will deliver a mechanistic model in the form of a User MATerial Computational Code (UMAT) subroutine within the finite element software, Abaqus. This model will incorporate several material constitutive relationships to define the behavior (viscoelastic, viscoplastic, mechanical damage, moisture damage, fatigue damage, fracture, aging, and healing) of the asphalt composite. 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 **UMAT** (i.e. 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 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 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.

(3) The third part is a set of documents that include:

- guidelines to estimate or measure the material constants associated with the constitutive equations in UMAT.
- 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 UMAT.
- description of different pavement structures (boundary conditions, method of applying repeated loading).

Equipment Availability and Cost

Subroutines will be developed as part of the Abaqus finite element package. The cost is that for the license of Abaqus.

Potential Applications

This model can be used to predict the performance of asphalt pavements.

Targeted Users

- Pavement and materials engineers/researchers;
- Consultant engineers;
- State DOT engineers

Time and Skill Requirements

Engineers will be able to input the model parameters, run the software, and make conclusion on performance. Workshops will be organized for training potential users.

Recommended Next Steps

It is recommended to extend this task to develop a stand-alone software for PANDA to it can be used without the Abaqus software.

Technology Development Product Name

Test Methods for Determining the Parameters of Material Models in PANDA (Pavement Analysis Using Nonlinear Damage Approach)

ARC Research Program

F3c and E1a

Format

AASHTO Test Procedure

Estimated Completion Date

12/31/2011

ARC Partner

TTI

Product Description

An experimental program will be developed for determining the parameters of the PANDA material model. It is envisioned that this experimental program will be in the form of creep recovery test at multiple stresses and temperatures. The tests will be conducted in uniaxial tension and triaxial compression at multiple confining stresses. The tests will allow determining the viscoelastic, viscoplastic and damage parameters of the model. It will rely on the analytical technique that was developed during the second year of the ARC project for separating viscoelastic deformation from viscoplastic deformation.

Equipment Availability and Cost

Universal testing machine with a Triaxial cell equipped to measure radial and axial strains, apply different confining stresses and operate under temperatures from 10C to 55C. (Estimate cost is about $100k).

Potential Applications

This set of testing is required for determining the parameters of the PANDA material model. The model is then used to predict the structural performance of asphalt pavements.

Targeted Users

1. Pavement and materials engineers/researchers;
2. State DOT technical personnel; and
3. Practitioners/lab technicians

Time and Skill Requirements

1. Pavement engineers and lab technicians can conduct the mechanical testing. The testing may take three to four weeks.
2. Engineers/researchers will be able to analyze the data to interpret the parameters of the PANDA material model. The analysis will take two working days.

Recommended Next Steps

Automate the method to analyze the data and write the procedure in AASHTO format.

Technology Development Product Name

Continuum Damage Permanent Deformation Analysis for Asphalt Mixtures

ARC Research Program

E1a

Format

Test Method

Estimated Completion Date

9/30/2011

ARC Partner

Texas A&M University

Product Description

A test method has been developed to conduct and analyze the permanent deformation in asphalt mixtures. This test method is based on the viscoplastic analysis of the permanent deformation properties of asphalt mixtures. A general yield surface has been developed to fulfill the whole range of material friction angles and the non-associated flow rule will apply. A microstructural parameter and a continuum damage based parameter are introduced to modify the nominal stresses in the viscoplastic models so as to consider the inherent anisotropy and load-induced anisotropy, respectively. In the permanent deformation testing, a cylindrical specimen is tested in cyclic compressive loading with varying rest period sequences, while the changing viscoplastic strain and modulus degradation along different directions with load cycles is recorded. Through the anisotropic viscoplastic damage theory, a comprehensive permanent deformation accumulation relationship is developed for an asphalt mixture. A limited number of tests will be sufficient to investigate the effect of inherent anisotropy, load-induced anisotropy and rest period healing on the permanent deformation of asphalt mixtures. With implementation of the fracture mechanics theory on the test results in the tertiary phase, the crack initiation, propagation and size distribution along different directions can be calculated during the tertiary viscoplastic deformation of asphalt mixture. Therefore, the proposed test method will be able to analyze the permanent deformation and fatigue cracking properties of asphalt mixtures under compressive loading simultaneously. The material properties that are generated with this test sequence are fully compatible with the PANDA 3-dimensional performance prediction model. The properties include the material friction angles and effective cohesive shear strength in accordance with the well-known and widely used Mohr-Coulomb formulations, anisotropic yield and plastic potential functions, anisotropic Paris' Law parameters, and anisotropic healing properties.

Equipment Availability and Cost

1. MTS machine or equivalent with temperature chamber, LVDTs and load cell; and

2. Sample rotation equipment ($50) and scanner ($100) for determining inherent anisotropy.

Potential Applications

The data produced in this destructive compressive test can be used to accurately predict or simulate the rutting behavior of asphalt mixtures. If carried to the tertiary phase, it will be able to determine the extra load induced anisotropy. Data can also be used as input to PANDA for performance predictions.

Targeted Users

Materials engineers; Consulting engineers; Pavement design engineers; Contractor's engineers; Material suppliers technical personnel; Forensic engineers; and Lab technicians.

Time and Skill Requirements

1. Lab technicians who can run compressive tests on MTS equipment will be able to run this test which can be done on a single sample in one day.
2. Engineers need to be able to use Excel macros to analyze the data and determine the viscoplasticity characteristics of an asphalt mixture. The analysis time is between 1 hour and 2 hours.

Recommended Next Steps

1. Workshops for lab technicians to instruct and give them experience in operating both MTS equipment and capturing the required data; and
2. Worships for engineers to explain the theory underlying the data processing software and to give them hands-on experience in analyzing actual data.

Technology Development Product Name

Characterization of Fatigue and Healing Properties of Asphalt Mixtures Using Repeated Direct Tension Test

ARC Research Program

E1a

Format

Test Method and Data Analysis Program

Estimated Completion Date

9/30/2011

ARC Partner

Texas A&M University

Product Description

A test method has been developed to characterize the fatigue and healing properties of asphalt mixtures under repeated direct tensile loading. The test method and data analysis program have been documented in the Quarterly Reports of the Asphalt Research Consortium (ARC) Program that is sponsored by the Federal Highway Administration (FHWA). In the fatigue test protocol, a destructive haversine tensile load is applied to the asphalt mixture specimen repeatedly at a certain frequency for 1,000 loading cycles. The vertical deformation of the specimen is recorded using three linear variable differential transformers (LVDTs). The applied stress and measured strain are used to determine the dissipated pseudo strain energy (DPSE) and the recoverable pseudo strain energy (RPSE) in the specimen. The DPSE is then separated into two components: 1) DPSE for fracture, and 2) DPSE for permanent deformation. The DPSE for fracture is used to obtain the rate of fatigue crack growth, and the RPSE is employed to determine the starting point of the crack growth that is indicated by the mean air void radius (initial crack radius). An energy balance equation is established to determine the amount of energy dissipated to drive the fatigue crack growth and to predict the mean crack radius and the number of cracks with the increase of load applications. At the end of the fatigue test, a series of 1,000-cycles with reduced rest periods between two adjacent 1,000-cycles are applied to the same specimen to study the healing properties of the asphalt mixture. The preliminary results of the healing test protocol have demonstrated that the binder type has a significant effect on the healing properties of asphalt mixtures. The data analysis program of healing test is expected to be completed by the end of 2010.

Equipment Availability and Cost

1. MTS machine or equivalent with temperature chamber, LVDTs and load cell programmable loading; and

2. Same sample as used in nondestructive characterization, no sample-to-sample variance.

Potential Applications

Determine fatigue and healing properties of asphalt mixtures as well as the effects of aging and moisture on these properties.

Targeted Users

Material engineers; Consulting engineers; Forensic engineers; Materials lab technicians; Pavement design engineers; Material suppliers; and Contractor's engineers.

Time and Skill Requirements

The complete nondestructive characterization and tensile fracture and healing test can be run on a single sample in one day.

Technician skill is the same as required to run the nondestructive tensile properties test.

Engineers will need to be able to use Excel macros (already written) to generate the fatigue and healing properties from the measured data.

Recommended Next Steps

1. Workshops for lab technicians to give hands-on experience in running destructive tensile tests and recording the data necessary to generate fatigue and healing properties; and
2. Workshops for engineers to explain the theory of crack propagation, its measurement and data collection process, and hands-on experience with analyzing real data.

Technology Development Product Name

Nondestructive Characterization of Tensile Viscoelastic Properties of Undamaged Asphalt Mixtures

ARC Research Program

E1a

Format

Test Method and Data Analysis Program

Estimated Completion Date

Completed

ARC Partner

Texas A&M University

Product Description

A test method and a data analysis program have been developed to nondestructively characterize the viscoelastic properties of undamaged asphalt mixtures under tensile loading. The test method and data analysis program have been developed within the Asphalt Research Consortium (ARC) Program sponsored by the Federal Highway Administration (FHWA); they have been detailed in the Quarterly Reports of the ARC Program. In the test protocol, a constant tensile load or a monotonically increasing tensile load is applied to an asphalt mixture specimen for a short period of time that is less than one minute. The vertical deformation and horizontal deformation are recorded by linear variable differential transformers (LVDTs). The test is repeated at three temperatures: 10, 20 and 30°C. The applied load and measured deformations at each temperature are used to calculate the stress and strains that are transformed from the time domain into the frequency domain using the Laplace transform. The transformed stress and strain functions are then utilized to determine: 1) the master curve of the magnitude of the complex modulus; 2) the master curve of the phase angle of the complex modulus; 3) the master curve of the magnitude of the complex Poisson's ratio; and 4) the master curve of the phase angle of the complex Poisson's ratio. Since the test duration is less than one minute and it takes approximately two hours to change the specimen temperature, this test method provides an efficient approach to nondestructively characterize the viscoelastic tensile properties of asphalt mixtures in a single day. This test method does not introduce any damage to the specimen so the same specimen can be tested subsequently for its fatigue, healing and other properties.

Equipment Availability and Cost

1. MTS machine or equivalent with temperature chamber, LVDTs and load cell;
2. Sample saw for parallel ends;
3. Coring machine for a sample with uniform composition;

4. Gluing jig; and
5. Universal fixture for the base of the testing sample.

Potential Applications

Tensile characterization of the properties of an undamaged asphalt mixture must precede the determination of the fatigue and healing properties of the same mixture. It will also determine the effect that aging and moisture have on these undamaged properties.

Targeted Users

Material engineers and lab technicians.

Time and Skill Requirements

1. Materials engineers: fitting the lab data with the master curve functions for modulus, Poisson's ratios and their phase angles; and
2. Lab technicians: data for a complete tensile master curve for a mixture can be determine in one day.

Recommended Next Steps

Laboratory workshops for engineers followed by instruction and practical exercises on how to fit master curve functions to lab data and how to trouble-shoot faulty measurements.

Technology Development Product Name

Nondestructive Characterization of Field Cores of Asphalt Pavements

ARC Research Program

E1a

Format

Test Method and Data Analysis Program

Estimated Completion Date

9/30/2011

ARC Partner

Texas A&M University

Product Description

A test method has been developed to nondestructively characterize the properties of field cores taken from the asphalt layer of an asphalt pavement. The test method has been documented in the Quarterly Reports of the Asphalt Research Consortium (ARC) Program that is sponsored by the Federal Highway Administration (FHWA). In the test protocol, each field core is trimmed into construction lifts, and each construction lift is cut to a prismatic sample. A monotonically increasing tensile load is applied to the prismatic sample whose vertical deformation is recorded by linear variable differential transformers (LVDTs). The loading rate and loading time are carefully controlled in order to limit the vertical strain within a certain level so that the specimen is not further damaged by the laboratory testing. The same test is repeated at three temperatures, 10°C, 20°C and 30°C, in order to construct the master curve of the magnitude and phase angle of the complex modulus using the time-temperature superposition principle. The tested field cores have shown stiffness gradient with the pavement depth because the asphalt layer is not aged uniformly in the field. An analytical method has been developed to characterize the stiffness gradient with pavement depth of the field specimen. When this test method and analysis is perfected, it will provide an independent means of determining the effect of field aging on as-built asphalt mixtures.

Equipment Availability and Cost

1. MTS machine or equivalent with temperature chamber, LVDTs, load cell and end caps;
2. Parallel saw to prepare prismatic samples from field cores; and
3. Gluing jig.

Potential Applications

Determine the properties of mixtures that have been exposed in service and measure the effects of aging on mixture properties.

Targeted Users

Material engineers; Consultants; Forensic engineers; and Lab technicians.

Time and Skill Requirements

1. Lab technicians: complete characterization testing can be completed in one day for each core; and
2. Engineers: ability to use analytical program to extract the modulus gradient information from the test data.

Recommended Next Steps

1. Workshops for lab technicians to instruct them in all of the steps of sample coring, sawing, gluing, mounting and testing; and
2. Workshops for engineers to explain the effects of field expose on field samples and hands-on exercises on analyzing test data and to determine the effects of in service exposure.

Technology Development Product Name

Self-Consistent Micromechanics Models of Asphalt Mixtures

ARC Research Program

E1a

Format

Analytical Model and Data Analysis Program

Estimated Completion Date

6/30/2011

ARC Partner

Texas A&M University

Product Description

Inverse and forward self-consistent micromechanics models have been developed using micromechanics theory for composite materials to predict the properties of an asphalt mixture and its components. Both micromechanics models are developed within the Asphalt Research Consortium (ARC) Program that is sponsored by the Federal Highway Administration (FHWA). The inverse micromechanics model takes as input the volumetric composition of the mixture and the measured frequency-dependent bulk and shear properties of a mixture and a binder and extracts from them the bulk and shear properties of the aggregate. The forward micromechanics model takes as input the frequency-dependent bulk and shear properties of the aggregate and binder and produces the frequency-dependent properties of the mixture. These models are programmed in MATLAB using the System Identification Method and are applied to the analysis of the frequency-dependent magnitudes of the viscoelastic properties of an asphalt mixture at different aging periods. It has been proved that the inverse model and the forward model are in fact the inverse of each other and that the inferred aggregate properties are realistic. These models proved a technique to catalog the properties of aggregates and use them in a computerized determination of the combinations of binders, aggregates and air to produce desired properties of asphalt mixtures.

Equipment Availability and Cost

Measurement of the properties of aggregates, binders and mixtures separately and arranged in computerized catalog databases proceeds the use of the self-consistent micromechanics model.

Electronic access to the materials catalog data base and a computer to exercise the micromechanics model.

Cost of personal computer.

Potential Applications

1. Optimum design of asphalt concrete mixtures to have desired mechanical properties;
2. Forensic investigations of premature pavement failures; and
3. Material selection from among available candidate binders and aggregates to delay effects of aging and moisture damage.

Targeted Users

Mix design engineers; Consultants, forensic engineers; and Materials engineers, contractor's engineers for warranty jobs.

Time and Skill Requirements

1. Computer operation skills and understanding of the process of mixture design;
2. Computer operations to determine the properties of mixture components from the measured properties of mixtures sampled from distressed pavements; and
3. Computer operations to run the model with a variety of candidate materials to determine the appropriate combination(s).

Recommended Next Steps

1. Workshops for potential users to acquaint them with the use of this tool for all these purposes. Workshops should have small attendance and much personal attention from instructors; and
2. Generation of materials data bases that can be used by the workshop participants.

Technology Development Product Name

Nondestructive Characterization of Anisotropic Viscoelastic Properties of Undamaged Asphalt Mixtures under Compressive Loading

ARC Research Program

E1a

Format

Test Method

Estimated Completion Date

Completed

ARC Partner

Texas A&M University

Product Description

A test method has been developed within the Asphalt Research Consortium (ARC) Program to nondestructively characterize the anisotropic viscoelastic properties of undamaged asphalt mixtures under compressive loading. This test method includes three nondestructive test scenarios: 1) uniaxial compressive creep test, 2) uniaxial tensile creep test, and 3) indirect tensile creep test. The elastic-viscoelastic correspondence principle is used to determine the frequency-dependent magnitude and phase angle of six complex material properties, including: 1) compressive complex modulus in the vertical direction (compaction direction), 2) compressive complex Poisson's ratio in the vertical direction, 3) compressive complex modulus in the horizontal plane that is perpendicular to the compaction direction, 4) compressive complex Poisson's ratio in the horizontal plane, 5) tensile complex modulus, and 6) tensile complex Poisson's ratio. Each of these three test scenarios takes approximately one minute and is repeated at three temperatures (10°C, 20°C and 30°C) in order to construct master curves of the magnitude and phase angle of each complex property. This test method offers an efficient approach to nondestructively characterize the undamaged anisotropic viscoelastic properties of asphalt mixtures under compressive loading. The test results have demonstrated the significant difference between properties in the vertical direction and the properties in the horizontal plane. The measured anisotropic properties of the asphalt mixture will be taken as input into a finite element program to predict the pavement performance. Since this test does not introduce any damage to the specimens, the same specimens will be tested destructively for its viscoplasticity, fatigue, healing and other properties.

Equipment Availability and Cost

1. MTS and UTM machines or equivalent and temperature chamber, LVDTs and load cells;
2. Indirect tension loading fixture for 6-in long sample; and

3. Gluing jib for tensile creep test.

Potential Applications

The undamaged compressive properties must be known in order to determine the damaged properties of viscoplasticity and tertiary fracture. This has direct application to the prediction of rutting and tertiary fracture.

Targeted Users

Materials engineers; Pavement design engineers; Consulting engineers; Forensic engineers; Lab technicians; Material suppliers technical personnel; and Contractor's engineers.

Time and Skill Requirements

Lab technicians who can operate both MTS and UTM equipment have all of the required skill. The complete set of tests can be run on a simple sample in one day.

Engineers need to be able to use Excel macros (already written) to analyze the data and generate the directional mixture properties. Analysis time is between 30 minutes and 2 hours.

Recommended Next Steps

1. Workshops for lab technicians to instruct and give them experience in operating both MTS and UTM equipment and capturing the required data; and
2. Worships for engineers to explain the theory underlying the data processing software and to give them hands-on experience in analyzing actual data.

Technology Development Product

Mix Design for Cold-In-Place Recycling (CIR)

ARC Research Program

ARC-E1c

Format

Practice

Estimated Completion Date

12-31-2011

ARC Partner

University of Nevada, Reno

Product Description

The use of cold in place recycling (CIR) of asphalt has been gaining popularity due to its low cost and effectiveness in retarding reflective cracking. The CIR process consists of pulverizing the top 2 – 3 inches of the old HMA layer, stabilizing it with asphalt emulsion and laying it down in place. The CIR layer is then overlaid with a surface treatment when used on low volume roads or with an HMA overlay when used on heavy volume roads. The in-place re-use of the old HMA layer offers economic advantage over the option of reconstruction the entire pavement. In addition, the low binder content of the CIR layer results in a highly flexible layer that offers improved resistance to reflective cracking.

However, there is not a standard mix design method that is consistent for the design CIR mixtures. This practice will offer a mix design method for CIR that is consistent with the Superpave technology and that can be used to define the optimum combination of moisture content, emulsion content, and any additive that maybe required. The mix design process will use the standard equipment used in the Superpave volumetric mix design.

Equipment Availability and Cost

Commercial grade equipment is available at the cost of $30,000 - $40,000

Potential Applications

Mix Design Process

Targeted Users

State Highway Agencies, Research Laboratories, Commercial Laboratories, and Materials Suppliers and Producers

Time and Skill Requirements

Design can be conducted within 3-5 days and will require technician level skills to conduct.

Recommended Next Steps

Submit to AASHTO

Technology Development Product

Mix Design for Cold Mix Asphalt

ARC Research Program

E1c

Format

Practice

Estimated Completion Date

3-31-2012

ARC Partner

University of Nevada, Reno

Product Description

The use of cold mix asphalt offers few advantages in terms of cost, long construction season, and ease of construction. Cold mix asphalt consists of producing a mixture of asphalt emulsion and mineral aggregate that can be used as a surface course on a flexible pavement. The production of cold mix asphalt uses significantly less energy than the production of hot mix asphalt, and therefore, it is significantly less expensive. The construction of cold asphalt mix asphalt can be achieved year round regardless of the ambient temperatures. In addition, cold mix asphalt is produced and constructed at significantly lower emissions than hot mix asphalt, thereby making it very attractive with respect to workers safety and environmental pollution.

However, there is not a standard mix design method for the design of cold mix asphalt. This practice will offer a mix design method for cold mix asphalt that is consistent with the Superpave technology and that can be used to define the optimum combination of moisture content, emulsion content, and any additive that maybe required. The mix design process will use the standard equipment used in the Superpave volumetric mix design.

Equipment Availability and Cost

Commercial grade equipment is available at the cost of $30,000 - $40,000

Potential Applications

Mix Design Process

Targeted Users

State Highway Agencies, Research Laboratories, Commercial Laboratories, and Materials Suppliers and Producers

Time and Skill Requirements

Design can be conducted within 3-5 days and will require technician level skills to conduct.

Recommended Next Steps

Submit to AASHTO

Technology Development Product

Evaluation of RAP Aggregates

ARC Research Program

E2b

Format

Practice

Estimated Completion Date

4-30-2011

ARC Partner

University of Nevada, Reno

Product Description

As reclaimed asphalt pavement (RAP) usage becomes more common throughout the industry, the differences in handling RAP materials as compared to virgin aggregates are becoming more significant. These differences include RAP aggregate properties, such as specific gravity, absorption, and aggregate gradation, along with other aggregate properties of the virgin and RAP blends. In recent years, there have been many recommendations regarding the measurement and usage of these RAP properties. However, there has not been a consistent recommendation for assessing the RAP aggregate properties. Both the solvent extraction and the ignition oven methods can be used to recover RAP aggregates for specific gravity testing and for determining other properties of the aggregate blend. The solvent extraction method may leave a residue of asphalt on the aggregate while the ignition oven method may cause aggregate degradation. This practice will recommend the most effective methods for extracting RAP aggregates based on their impact on the various properties of the RAP aggregates and the volumetric calculations for the Superpave mix design. The practice utilizes the equipment being currently used in the Superpave volumetric mix design method.

Equipment Availability and Cost

Commercial grade equipment is available at the cost of $30,000 - $40,000

Potential Applications

Mix Design Process

Targeted Users

State Highway Agencies, Research Laboratories, Commercial Laboratories, and Materials Suppliers and Producers

Time and Skill Requirements

Tests can be conducted within 3-5 days and will require technician level skills to conduct.

Recommended Next Steps

Submit to AASHTO or ASTM

Technology Development Product

Identification of Critical Conditions for HMA mixtures

ARC Research Program

E2c

Format

Practice

Estimated Completion Date

12-31-2011

ARC Partner

University of Nevada, Reno

Product Description

Field performance data from the WesTrack project and other pavements indicate that every HMA mix has a critical temperature and a critical loading rate beyond which the mixture will become highly unstable that must be identified during the design process. Once these two critical conditions are identified, they must be checked against the expected field conditions where the HMA mix will be placed. Furthermore, it is believed that the critical conditions of an HMA mix can be significantly influenced through changes in binder content, binder properties, and aggregates gradation. This process will allow the mix design engineer to design excellent performing HMA mixtures for mainline traffic and traffic on off-ramps and at intersections with changes that can be accommodated in the production process without major interruptions, such as slightly modify the binder properties or slightly reduce the binder content as the construction approaches the intersection. The final product will be in the form of a recommended practice to identify the critical condition of an HMA mix at the mix design stage to avoid accelerated rutting failures of HMA pavements. An interim report (Characteristics of Dynamic Triaxial Testing of Asphalt Mixtures) has been completed which summarizes the state of stresses under the various loading conditions that were calculated using the pavement analysis software 3D-Move.

Equipment Availability and Cost

Commercial grade equipment is available at the cost of $70,000- $80,000.

Potential Applications

Mix Design Process and Mix Performance Evaluation.

Targeted Users

State Highway Agencies and Research Laboratories.

Time and Skill Requirements

Test can be conducted within 48 hours and will require technician level skills to operate.

Recommended Next Steps

Conduct Round Robin Testing

Technology Development Product

Modified Thermal Stress Restrained Specimen Test

ARC Research Program

E2d

Format

Test Method

Estimated Completion Date

9-30-2011

ARC Partner

University of Nevada, Reno

Product Description

The thermal stress restrained specimen test (TSRST) is currently being modified to account/incorporate for the following factors:

- A cylindrical test sample obtained from a Superpave Gyratory compacted specimen
- Accommodate variable cooling and warning rates to better simulate field conditions
- Improve repeatability of the measured fracture temperature and fracture stress
- Provide input that can be directly incorporated into the thermal stresses model

The UNR researchers are currently conducting laboratory experiments to assess the impact of sample size and variable cooling and warning rates on the response of the TSRST. The applicability of the modifications has been evaluated against the original TSRST with a beam sample and a constant cooling rate. In addition, the measurements from the modified TSRST have been compared with the low temperature properties of the binders used in the evaluated mixtures. The final version of the TSRST test will be practical to use with the current Superpave mix design method and will produce mix properties that are directly incorporated into the Thermal Stress Model currently being developed.

Equipment Availability and Cost

Commercial grade equipment is available at the cost of $60,000- $70,000.

Potential Applications

Mix performance evaluation and generate input to analysis/performance models

Targeted Users

State Highway Agencies, Research Laboratories, and Commercial Laboratories

Time and Skill Requirements

Test can be conducted within 48 hours and will require technician level skills to operate.

Recommended Next Steps

Conduct Round Robin Testing

Technology Development Product

HMA Thermal Stresses

ARC Research Program

E2d

Format

Model

Estimated Completion Date

3-31-2012

ARC Partner

University of Nevada, Reno

Product Description

Thermal cracking of HMA mixtures is caused by the non-polar oily or neutral fractions of the binder becoming a rigid solid at low temperature. Glass is a common example of such an amorphous super-cooled liquid and thus the analogy to glass is responsible for the term “glass transition temperature” of asphalts which is the temperature at which the liquid component of the asphalt freezes to a solid. Any attempt to deform the frozen structure results in fracture.

Field performance data indicate that HMA mixtures in the intermountain region of the U.S. experience severe thermal cracking distresses that are not well covered by the current technology. The intermountain region experiences significant hardening of the asphalt binder coupled with extreme thermal cycling, and highly absorptive aggregate leading to thermal cracks that are six inches wide.

The final product will be in the form of a thermal cracking model that can effectively simulate the long-term properties of HMA mixtures in the intermountain region and assess the impact of such properties on the resistance of HMA mixtures to thermal cracking.

Equipment Availability and Cost

Commercial grade equipment is available at the cost of $60,000- $70,000.

Potential Applications

Mix Design Process and Mix Performance Evaluation

Targeted Users

State Highway Agencies, Research Laboratories, and Commercial Laboratories

Time and Skill Requirements

Modeling can be completed within 24 hours and will require engineering level skills.

Recommended Next Steps

Submit to AASHTO

Technology Development Product

Dynamic Model for Flexible Pavements: 3D-Move

ARC Research Program

VP3a

Format

Software

Estimated Completion Date

3-31-2011

ARC Partner

University of Nevada, Reno

Product Description

The loads generated by the moving vehicle are dynamic in nature, and they invoke a dynamic response from the pavement structure which is greatly impacted by the inertia of the pavement structure and the viscoelastic behavior of the hot mix asphalt (HMA) layer. The normal and shear dynamic stresses that are generated at the tire-pavement interface control the pavement response in terms of the stresses, strains, and deformations that are generated throughout the pavement structure. The tensile strains generated at the bottom of the HMA layer control the fatigue performance of the HMA pavement. The compressive stresses and strains generated throughout the various pavement layers greatly influence the rutting performance of the HMA pavement. The shear stresses and strains generated within the HMA layer greatly control the shoving performance of the HMA pavement at intersections, on off-ramps, and at facilities that service slow moving heavy loads such as seaports and airports. The final product will be in the form of a pavement analysis software that incorporates the viscoelastic properties of the HMA layer with the non-circular/non-uniform two dimensional pressure distributions at the tire-pavement interface along with vehicle speed. The model will also be capable of predicting pavement performance in terms of rutting and fatigue.

Equipment Availability and Cost

Computer hardware at the cost of $2,000.

Potential Applications

Mix Performance Evaluation.

Targeted Users

State Highway Agencies and Research Laboratories.

Time and Skill Requirements

Modeling can be completed within 24 hours and will require engineering level skills.

Recommended Next Steps

Submit to AASHTO.

Technology Development Product Name

Bitumen Bond Strength (BBS) Test.

Format

Test Method.

ARC Partner

University of Wisconsin – Madison, Modified Asphalt Research Center (UWMARC).

Product Description

The Bitumen Bond Strength (BBS) test is a simple, quick and repeatable approach for evaluating adhesion properties of asphalt-aggregate systems. The test method can measure the effect of moisture in the asphalt-aggregate interface. The BBS is a significantly modified version of the Pneumatic Adhesion Tensile Testing Instrument (PATTI). The main components of the BBS equipment are: portable pneumatic adhesion tester, pressure hose, piston, reaction plate and a metal pull-out stub. The pull-out stub has a rough surface that can prevent asphalt debonding from the stub surface by providing mechanical interlock and larger contact area between the asphalt binder and stub. To start the test, the piston is placed over the pull-out stub and the reaction plate is screwed on it. Then, a pressure hose is used to introduce compressed air to the piston. During the test, a pulling force is applied on the specimen by the metal stub. Failure occurs when the applied stress exceeds the cohesive strength of the binder or the bond strength of the binder-aggregate interface (i.e., adhesion). The BBS test can differentiate the effects of conditioning time, conditioning solution, and modification of binders. These factors significantly affect the pull-off tensile strength of asphalt-aggregate systems.

Equipment Availability and Cost

Pneumatic Adhesion Tensile Testing Instrument (PATTI) costs approximately $8,000. The specially designed pull-out stubs cost $50 each.

Potential Applications

Practical method to evaluate the bond strength between asphalt and aggregate in dry and moisture conditions. Evaluate the effect of anti-stripping or other modifications on the moisture susceptibility of asphalt-aggregate systems.

Targeted Users

State DOT’s, Research Institutions, Asphalt Producers, and Test Laboratories for QC/QA.

Time and Skill Requirements

Time to conduct the dry BBS testing is approximately 4 hours (includes sample preparation). Moisture conditioning time needs to be added if testing wet specimens. A technician with minimal training can perform the test.

Recommended Next Steps

Verification of the BBS as a surrogate test for surface energy measurements and comparison with mixture testing using the standard Tensile Strength Ratio (TSR) method.

Technology Development Product Name

Elastic Recovery in the DSR test

Format

Test Method

ARC Partner

University of Wisconsin – Madison, Modified Asphalt Research Center (UWMARC)

Product Description

A test procedure to measure the elastic recovery in the Dynamic Shear Rheometer (DSR). The current protocol measures the elastic recovery in a ductility bath which has the disadvantages of poor repeatability, manual data collection, and time consuming. The test can be performed on any DSR and it uses standard 8 mm parallel plate geometry. The procedure for measuring the elastic recovery in the DSR consists of two steps: a constant shear strain rate is applied for two minutes followed by a zero constant stress for an hour. The main difference from the current protocols can be seen in the last step where instead of cutting the sample a constant zero shear stress is applied. The elastic recovery in the ductility bath and elastic recovery in the DSR correlates very well. Moreover statistical analysis showed that very good correlation is obtained for reduced relaxation times. It is recommended to use 30 minutes relaxation time instead of 60 minutes.

Equipment Availability and Cost

Dynamic Shear Rheometer (DSR) costs between $50,000-80,000 depending upon the manufacture.

Potential Applications

Determine elastic recovery of asphalt binders. Replace highly variable results from elastic recovery tests with ductility bath.

Targeted Users

Asphalt Producers, State DOT’s, and Contractors.

Time and Skill Requirements

Testing time is approximately 2 hours. Standard DSR training is required. A technician with minimal training can perform the test.

Recommended Next Steps

Draft standard specification for testing method.

Technology Development Product Name

Linear Amplitude Sweep (LAS) Test

Format

Test Method

ARC Partner

University of Wisconsin – Madison, Modified Asphalt Research Center (UWMARC)

Product Description

The Linear Amplitude Sweep (LAS) test method quantifies fatigue damage accumulation of asphalt binders with a short-duration procedure that can be easily implemented into current practice. The results from the test are analyzed using the framework of Viscoelastic Continuum Damage (VECD) to derive a relation between number of cycles to failure and strain. Thus, from a single test one can account for both traffic loading (i.e., number of cycles to failure) and pavement structure (i.e., strain), which are known to affect fatigue resistance of pavements. It has been shown that LAS fatigue performance of asphalt binders can be correlated to mixture performance in the laboratory and to field fatigue performance.

The test procedure is run in the Dynamic Shear Rheometer (DSR) with standard 8 mm parallel plate geometry. The procedure consists of two tests. The first is a frequency sweep to obtain an undamaged material response. The second, which can be run directly following the frequency sweep, consists of cyclic loading at a constant frequency of 10 Hz, with systematically, linearly increasing strain amplitudes. Each strain step consists of 100 cycles of loading. Loading begins with 0.1% strain to obtain an undamaged material response. Loading proceeds with a 1% strain step followed by strain steps increasing in 1% increments up to 30% applied strain.

Equipment Availability and Cost

Dynamic Shear Rheometer (DSR) costs between $50,000-80,000 depending upon the manufacture.

Potential Applications

Determine binder contribution to mixture fatigue. Product can be used to rank asphalt binders based on fatigue damage resistance. It can be used to determine the effect of modification on the fatigue performance of asphalt binders. Contractors can be used procedure for selecting appropriate material based on fatigue cracking.

Targeted Users

Asphalt Producers, State DOT’s, Contractors, Research Institutions, and Test Laboratories for QC/QA

Time and Skill Requirements

Total testing time with conditioning is approximately 30 minutes. Standard DSR training is required.

Recommended Next Steps

Finalize procedure and propose limits based on correlations to field Long Term Pavement Performance (LTPP) performance.

Technology Development Product Name

Binder Yield Energy (BYET) Test

Format

Test Method

ARC Partner

University of Wisconsin – Madison, Modified Asphalt Research Center (UWMARC)

Product Description

The Binder Yield Energy Test (BYET) method measures the asphalt binders' resistance to yield-type failure under monotonic constant shear-rate loading. The BYET method is conducted using the Dynamic Shear Rheometer at the intermediate temperature performance grade (PG Grade) of the asphalt binder. The test method can be used with material aged using AASHTO T 240 (RTFOT) and/or AASHTO R 28 (PAV) to simulate the estimated aging for in-service asphalt pavements. It uses the 8-mm parallel plate geometry with a 2-mm gap setting and samples prepared consistent with Test Method AASHTO T 315 (ASTM D 7175-05) (DSR). The sample is monotonically sheared using a constant shear rate until peak shear strength is achieved and the sample has yielded. This test method is intended to evaluate the amount of energy required to cause yielding in the asphalt binder. The "yield energy" of the material can be used to identify the relative performance of different materials, and the stress-strain response curve can be useful in identifying the presence of polymer modifiers in the material. Some polymer modified binders are capable of accumulating considerable amount of damage in the post peak region of the stress-strain curve. Therefore, the parameter BYE20 which measures the area underneath stress-strain curve up to 2000% strain is used. The 2000% strain was selected because this strain level is beyond peak stress for all the tested binders and the effect of the double peak can be captured by this parameter. The binder stiffness is taken into account by normalizing the energy BYE20 to the stiffness (G*) to obtained normalized parameters: BYEpeak/G* and BYE20/G*.

Equipment Availability and Cost

Dynamic Shear Rheometer (DSR) costs between $50,000-80,000 depending upon the manufacture.

Potential Applications

Determine binder contribution to fatigue. Determine modification type in asphalt binder

Targeted Users

Asphalt Producers, State DOT's, and Contractors.

Time and Skill Requirements

Testing time is approximately 1 hour. Standard DSR training is required. A technician with minimal training can perform the test.

Recommended Next Steps

To be determined based on ETG feedback.

Technology Development Product Name

Rigden Voids Test

Format

Test Method

ARC Partner

University of Wisconsin – Madison, Modified Asphalt Research Center (UWMARC)

Product Description

The Rigden voids test determines the voids in a dry and compacted filler sample. The test is conducted using a Rigden apparatus; hence the name "Rigden" voids. Knowing the voids in a compacted sample allows for determination of the percent volume of free asphalt a filler can carry. The void content is estimated by compacting dry fillers using specified mold size and compaction effort. Research has shown that Rigden voids significantly affects the stiffening effect of fillers on binders. Furthermore, research has demonstrated this stiffening effect is reflected in both mastic and mixture workability and rutting performance.

Equipment Availability and Cost

Rigden Apparatus cost approximately $3000.

Potential Applications

Improve HMA rutting and workability performance by controlling Rigden voids.

Targeted Users

Aggregate producers and state highway agencies.

Time and Skill Requirements

Testing time is approximately 1 hour. A technician with minimal training can perform the test.

Recommended Next Steps

Develop specification and define relation to HMA performance.

Technology Development Product Name

Asphalt Lubricity Test

Format

Test Method

ARC Partner

University of Wisconsin – Madison, Modified Asphalt Research Center (UWMARC)

Product Description

The conventional laboratory method for evaluation of asphalt binder workability has been unable to demonstrate an ability to exhibit a measured reduction in viscosity due to the presence of warm mix additives consistent with enhanced mixture workability observed in the laboratory and field. Thus indicating that viscosity reduction is not the only mechanism by which warm mix additives allow for compaction at reduced temperatures. It is believed that some additives enhance mixture workability through improving the lubricating effects of asphalt binders through reduction in the internal friction of the material.

A standard test in the oil industry, ASTM D-5183: Standard Test Method for Determination of the Coefficient of Friction of Lubricants Using the Four Ball Wear Test Machine has been adapted to allow for the test to be conducted in the Dynamic Shear Rheometer (DSR). The apparatus consists of three lower balls which are clamped in a cup; a fourth ball held in a chuck is loaded against them, a sufficient amount of lubricant is added to produce a film between the chuck and clamped assembly. The chuck is rotated in one direction with resistance provided by the fixed balls in the cup below. During the test torque and normal force are monitored under a constant speed and the coefficient of friction of the asphalt binder is calculated. The test is conducted in the temperature range of conventional HMA/WMA compaction.

Equipment Availability and Cost

Standard Superpave testing equipment with the addition of four ball testing fixture. Cost of prototype fixture is approximately $5000.

Potential Applications

The test has potential use in mix design to optimize the use of WMA additives such that mixture workability is achieved in the desired temperature range.

Targeted Users

Research Laboratories and contractors.

Time and Skill Requirements

Testing time is approximately 2 hours. Standard Superpave testing equipment training is needed (DSR). Specific training on test procedure and analysis of data.

Recommended Next Steps

Establish repeatability and sensitivity to test parameters to allow for procedure development. Draft standard test method. Implement procedure to investigate use of lubricity to classify WMA additives.

Technology Development Product Name

Test Method to Quantify the Effect of RAP and RAS on Blended Binder Properties without Binder Extraction

Format

Test Method

ARC Partner

University of Wisconsin – Madison, Modified Asphalt Research Center (UWMARC)

Product Description

A testing procedure that quantifies the effect of RAP and RAS on the fresh binder properties at all critical pavement temperatures has been prepared. The approach minimizes labor and eliminates the need for binder extraction. In the testing procedure mortar and binder samples are tested in the Bending Beam Rheometer (BBR) and Dynamic Shear Rheometer (DSR) to quantify the effect of RAP and RAS binder on the fresh binder continuous grade profile, allowing for an estimation of mixture binder properties at critical pavement temperatures. The testing procedure produces a RAP/RAS binder-fresh binder continuous grade improvement rate, that is, the rate of change of the fresh binder continuous grade per percent fresh binder replaced by RAP/RAS binder. This allows users to estimate the performance grade of the mixture binder given any amount of RAP and RAS binder replacement within the mixture. The RAP and RAS binder analysis procedure was verified by testing artificial RAP materials and was found to be capable of estimating the RAP binder-fresh binder continuous grade to within 2.4 degrees Celsius at low and intermediate temperatures and under three degrees Celsius at high temperature of the known binder grade. The procedure was also extended to RAP and RAS blends and was found to be capable of producing a fresh binder-RAP/RAS binder relationship that allows users the ability to adjust (optimize) RAP or RAS binder replacement and determine the mixture continuous grade (PG). The utility of this application is evident; current specifications regarding inclusion limits of RAP and RAS into new HMA can easily be evaluated to check the validity of the PG change recommendation.

Equipment Availability and Cost

Standard Superpave testing equipment with the addition of the ignition oven test

Potential Applications

High percentage RAP and RAS mixture performance grade optimization and establishing more reasonable mixture specifications as they pertain to allowable RAP and RAS materials.

Targeted Users

State DOT’s, Contractors, and Research Institutions.

Time and Skill Requirements

Standard Superpave testing equipment training (BBR, DSR, etc.).

Recommended Next Steps

Increase sample sizes (in RAP/RAS source) and finalize sample preparation procedure. Draft AASHTO standard specification for testing method.

Technology Development Product Name

Single-Edge Notch Bending (SENB)

Format

Test Method

ARC Partner

University of Wisconsin – Madison, Modified Asphalt Research Center (UWMARC)

Product Description

The Single Edge Notch Bending (SENB) test measures the fracture properties of asphalt binders and mastic at low temperatures. The SENB test follows ASTM E399 and assumes that Linear Elastic Fracture Mechanics (LEFM) conditions are true. Asphalt binders samples prepared using the Bending Beam Rheometer (BBR) geometry with a notch on it are tested in three-point bending using displacement controlled mode. Load-displacement curves and fracture mechanics concepts are used to estimate both fracture energy (G_f) and fracture toughness (K_{IC}).

Preliminary results indicate that this test method is capable of differentiate good and poor low temperature performance of both asphalt binders and mastics. Furthermore, the effect of modification on the thermal cracking performance of asphalt binders can be evaluated with this method.

Equipment Availability and Cost

Modification of the Superpave Bending Beam Rheometer (BBR) to apply load using displacement control. The cost is approximately divided into BBR ($40,000) and Motor Step-Loading Frame ($12,000).

Potential Applications

Asphalt binders and mastics characterization at low temperatures. Asphalt binder grading based on fracture mechanics. Test method can be used to estimate the low temperature strength of BBR mixture beams. Product can be used for ranking of asphalt materials based on fracture toughness and to estimate the ductile to brittle transition of asphalt binders. Effect of modification on low temperature cracking of asphalt binders.

Targeted Users

Asphalt Producers, State DOT's, Contractors, Research Institutions, and Test Laboratories for QC/QA.

Time and Skill Requirements

The time required for testing one specimen is 2 hours approximately. This includes sample preparation and sample conditioning at specified temperature for 1 hour. A larger set of experiments will significantly improve the time required for SENB testing. A technician with minimal training can perform the test.

Recommended Next Steps

Draft AASHTO test method. Validation with fracture mechanics-based mixture testing and field performance measured in MnROAD sections. Comparisons with test methods currently used by transportation agencies.

Technology Development Product

Binder Glass Transition Test

Format

Test Method

ARC Partner

University of Wisconsin – Madison, Modified Asphalt Research Center (UWMARC)

Product Description

The glass transition temperature (T_g) and the coefficients of thermal expansion/contraction above and below T_g of asphalt binders are measured by means of a dilatometric test system. The apparatus monitors the dilatometric properties of binders while the samples are subjected to a prescribed temperature program. The specific volume vs. temperature data obtained from test can be used to fit a non-linear model that contains the glass transition temperature and the thermal coefficients of contraction/expansion above and below T_g as parameters. Very precise capillary tubes are used to measure volume changes in the sample during the test. The system is automated with precise pressure sensors that continuously measure the change of alcohol height, which is proportional to changes in specific volume of the binder. Furthermore, the dilatometric cells made of aluminum are sealed with military-specified o-rings to minimize the effect of rubber contraction on the test results.

Equipment Availability and Cost

Total estimated cost of equipment and assembly is approximately $2,500. The system is comprised of insulated chamber ($100), dilatometric cell ($1000), pressure sensor ($250), capillary tube ($100), and a cooling system with solenoid valve ($200). Liquid nitrogen is currently been used as cooling agent. A tank of nitrogen costs $70 (for 5 tests).

Potential Applications

Recent results show that the T_g has a very close relationship to the fracture properties and brittleness. The proximity of the pavement service temperature to the T_g is believed to be an important overlooked factor in predicting low temperature performance. Procedure can be used to accurately estimate coefficient of thermal expansion/contraction for design purposes.

Targeted Users

Asphalt research institutes

Time and Skill Requirements

Testing time is approximately 4 hrs for 1°C/min of cooling rate. The T_g test procedure is very straight forward and relatively simple, but the delicate equipment involved require the utmost care and patience in testing.

Recommended Next Steps

Draft standard for test method. The current usage of liquid Nitrogen as cooling agent is costly and inconvenient. Attempts will be made to replace the cooling system with an electric chiller system.

Technology Development Product

Asphalt Mixture Glass Transition Test

Format

Test Method

ARC Partner

University of Wisconsin – Madison, Modified Asphalt Research Center (UWMARC)

Product Description

A new procedure for testing the thermal expansion and contraction coefficients as well as the glass transition temperature (T_g) for asphalt mixtures is currently been developed, in which beam samples are fabricated gluing rectangular prisms cut from gyratory compacted cylinders.

The T_g system for asphalt mixtures measures the change in specimen length by means of two LVDTs as function of temperature. The same non-linear model used for asphalt binders can be used for mixtures to estimate T_g and the coefficients of thermal expansion/contraction above and below T_g. The experimental data collected with this method will be used to modify current models and to provide typical/default values of T_g and contraction coefficients that can be used to predict thermal cracking.

Equipment Availability and Cost

Total estimated cost of equipment and assembly is approximately $3,500. The cost breakdown is the same as for the asphalt binder T_g but adding the cost of two LVDTs ($600) and two polymer invar rods ($50).

Potential Applications

The proximity of the pavement service temperature to the T_g is believed to be an important overlooked factor in predicting low temperature performance of pavements. Furthermore, the mixture coefficient of thermal expansion is an important factor for the prediction of thermal stress buildup. Results have shown that other than the binder T_g, the mixture T_g is affected by mixture volumetrics and aggregate structure. Thus, direct measurement of the mixture T_g, is very convenient.

Targeted Users

Asphalt research institutes

Time and Skill Requirements

The test takes approximately 4 hrs (based on cooling rate of 1°C/min). Compared to the binder T_g, the mixture T_g test is much simpler and significantly less delicate. The test mechanism is straight forward, resulting in good accuracy and minimal potential problems.

Recommended Next Steps

Finalize test procedure and propose limits based on correlations to field performance. Thermal cracking sensitivity analysis will be conducted to determine which of the glass transition parameters are statistically important for thermal cracking, which ones need to be measured, and what is the effect of using estimated rather than measured values.

Technology Development Product Name

Standard Practice for Determining Aggregate Structure in Asphalt Mixes by Means of Planar Imaging

Format

Test Method / Software

ARC Partner

University of Wisconsin – Madison, Modified Asphalt Research Center (UWMARC)

Product Description

The Image Processing and Analysis System (iPas) has been developed to allow for the processing and analysis of planar images of asphalt mixes. This software can be used for the characterization of the internal aggregate structure. In addition to iPas, a standard practice has been developed to summarize the guidelines used in digital image analysis of asphalt mixtures. Research has shown that internal structure of asphalt mixtures may dictate the mechanical performance of the mix. A number of studies have been conducted to confirm this, yet each uses a different method of capturing, processing, and analyzing images of the asphalt mixes, many of which are cumbersome and therefore have not become widely accepted. User confidence, or lack thereof, also prevents several methods from widespread adoption. iPas allows for a systematic and repeatable means of determining internal structure of asphalt mixes from planar images. The new system not only caters to users of nearly any level of experience, but also provides feedback matching processed image information with known laboratory volumetrics to ensure the user that the image is appropriately processed before moving on the analysis phase.

Equipment Availability and Cost

Standard flatbed scanner ($50)

Potential Applications

Ease and improved resolution of internal structure characterization of asphalt mixes that may aid in determining the contribution of a given structure to mechanical performance. It can be used to determine number of contact points and degree of segregation in the asphalt mixture. The orientation of the aggregates can also be estimated to determine level and method of compaction.

Targeted Users

State DOT’s, Research Laboratories, and Contractors.

Time and Skill Requirements

Basic computer skills and asphalt mixture design knowledge. Analysis time varies upon resolution of the image. It usually takes about 30 min to process one image.

Recommended Next Steps

Analysis of broad range of images to define relation to HMA performance

Technology Development Product Name

Gyratory Pressure Distribution Analyzer

Format

Test Method

ARC Partner

University of Wisconsin – Madison, Modified Asphalt Research Center (UWMARC)

Product Description

The test method measures cyclic forces on the surface of an asphalt mixture at a minimum of three points located at 120°. Forces are monitored with time during each gyration through use of a separate device inserted into the mold with the material specimen. Asphalt mixtures are to be prepared per Superpave procedures as specified in AASHTO MP-2. The device is inserted into the SGC mold on top of the mixture prior to compaction. The reactive force and its effective location with respect to the material sample centerline (eccentricity) imparted by the material specimen are measured during compaction. These combined measurements (force x distance) may also be represented as a tilting moment and are used to calculate the resistive effort of the mix. The relationship between resistive effort and mixture densification is used to evaluate mixture workability and stability.

Equipment Availability and Cost

Super Pave Gyratory Compactor and Gyratory Pressure Distribution Analyzer (GPDA) required. The GPDA is currently being marketed by Troxler and sells for approximately $8000.

Potential Applications

This technology has most use as a mix design tool. Aggregate gradation, asphalt binder grades, and types of modification can be optimized by establishing a mixture that exhibits workability during construction and adequate aggregate interlock for in-service stability. The GPDA also has potential use as a QC tool by specifying a level of resistive effort for a given gyration.

Targeted Users

Research Laboratories, Contractors, and State Agencies.

Time and Skill Requirements

Testing time is approximately 1 hour. Standard Superpave mix design training. Specific training related to use of the GPDA and analysis of the data collected is also required.

Recommended Next Steps

Establish precision and bias statement for incorporation into draft ASTM Standard that is currently under review. Compare GPDA indices with new SGC equipment that implements external measurement of shear to estimate tilting moment.

Technology Development Product Name

Improved Oxygen and Thermal Transport Model of Binder Oxidation in Pavements

Format

Methodology, Publication

ARC Partner

TAMU

Product Description

An improved oxygen and thermal transport model of binder oxidation in pavements will be developed. Improvements will include both fast-rate and constant-rate binder oxidation kinetics; an air void size distribution model based upon CT imaging determinations of air voids; consideration of limiting cases of oxygen levels in the air voids (provided either by convective flow or by diffusion through the pores only); and an improved pavement temperature model (each of these elements is described in a separate product description.) The improved model will use input data (pavement location for use in determining environmental data that impacts temperature over time, pavement air voids structure, binder kinetics parameters) to calculate binder oxidation and hardening in pavements as a function of time an depth. These results can be used with mixture models to estimate changes in mixture properties such as fatigue resistance that occur due to binder oxidation.

Equipment Availability and Cost

Potential Applications

The model will provide essential information for an improved pavement design method. Current methods provide only empirical estimates of binder oxidation in pavements that are quite imprecise and in addition overlook some important effects of binder oxidation on mixture properties and performance.

Targeted Users

Pavement design and maintenance engineers

Time and Skill Requirements

Recommended Next Steps

Ongoing validation using field locations across the country.

Technology Development Product Name

Field Validation of an Improved Oxygen and Thermal Transport Model of Binder Oxidation in Pavements

Format

Methodology, Field Data, Publication

ARC Partner

TAMU

Product Description

Validation of the pavement oxidation model will be conducted with field cores taken over time from a number of pavements. Planned test sites are the WRI test sections in several locations in the central part of the U.S. and Canada. Validation will include measuring the binder oxidation kinetics parameters (both fast-rate and constant-rate parameters, provided original binder is available), core total air voids and pore size distribution, and binder oxidation levels of binder recovered from cores at several times in each pavement's service life. An initial validation with a number of cores taken from Texas pavements has been completed.

Equipment Availability and Cost

Potential Applications

A verified model will provide essential information for an improved pavement design method. Current methods provide only empirical estimates of binder oxidation in pavements that are quite imprecise and in addition overlook some important effects of binder oxidation on mixture properties and performance.

Targeted Users

Time and Skill Requirements

Recommended Next Steps

Obtain cores for the WRI and other test (or other pavement) sections.

Technology Development Product Name

Validation of an improved Pavement Temperature Transport Model for use in an Oxygen and Thermal Transport Model of Binder Oxidation in Pavements

Format

Methodology, Publication

ARC Partner

TAMU

Product Description

An improved pavement temperature model will be validated by comparing predictions (as a function of time and depth) to measurements (available in the LTPP data base) at locations across the U.S.

Equipment Availability and Cost

Potential Applications

Targeted Users

Time and Skill Requirements

Recommended Next Steps

Validation with additional sites.

Technology Development Product Name

Pavement Air Voids Size Distribution Model for use in an Oxygen and Thermal Transport Model of Binder Oxidation in Pavements

Format

Methodology, Publication

ARC Partner

TAMU

Product Description

Using a distribution of air void pore sizes, instead of a single average size, in the oxygen and thermal transport model for binder oxidation in pavements, will provide more accurate estimates of binder oxidative aging in pavements. The methodology will determine a distribution of air void pore sizes from CT imaging techniques which will be used to calculate upper and lower limits on binder oxidation rate estimates for two limiting cases: convective air flow through interconnected pores in the pavement versus diffusive flow only. In reality, probably both mechanisms contribute to supplying oxygen to pavement pores.

Equipment Availability and Cost

Potential Applications

This product will allow improved modeling of binder oxidation in pavements, essential for accurate prediction of pavement performance over time and in the presence of deterioration due to oxidative embrittlement of binders.

Targeted Users

Time and Skill Requirements

Recommended Next Steps

Validation with additional pavement sites.

Technology Development Product Name

Improved Understanding of Fast-Rate, Constant-Rate Binder Oxidation Kinetics Mechanism through the Effects of Inhibitors

Format

Publication

ARC Partner

TAMU

Product Description

This product will provide both fast-rate and constant-rate binder oxidation kinetics parameters for use in pavement oxidation models. Previously, it has been assumed that the slower, constant-rate reaction mechanism has been the primary oxidation process over the life of the pavement. Field data and modeling has shown that the shorter lasting, but faster rate initial reaction process can have a significant impact on binder oxidation in pavements, especially in colder climates, and must be understood in order to make improved performance predictions. Measuring both fast-rate and constant-rate kinetics parameters will provide the information needed for pavement modeling, but measuring each individual asphalt material is prohibitively time consuming. The goal of this work is to deliver a more fundamental understanding of the reaction mechanisms, or at least relationships between the fast-rate and constant-rate reaction processes, that will lead to a sufficiently complete kinetics picture for each binder but with a greatly reduced measurement effort.

Equipment Availability and Cost

Potential Applications

Targeted Users

Time and Skill Requirements

This is a long-term effort. Understanding reaction mechanisms or at least relationships between fast-rate and constant-rate mechanisms is an effort with unknown probability of success, yet the reward from a successful effort will be significant. A minimum of one year is required to determine if such a venture is likely to be successful. Then another year likely will be needed to finish the product.

Recommended Next Steps

Measure the effect of oxidation inhibitors on both fast-rate and constant-rate reaction kinetics.

Technology Development Product Name

Improved Understanding of Fatigue Resistance Decline with Binder Oxidation

Format

Publication

ARC Partner

TAMU

Product Description

This effort will deliver quantitative measurement of mixture fatigue resistance as it is affected by binder oxidation for a number of ARC binders and mixtures. Previous work has shown that the fatigue resistance of a mixture declines with binder oxidation, but how the rate of this decline is related to mixture design parameters is unknown. This is fundamental experimental work that will complement theoretical modeling of mixture properties.

Equipment Availability and Cost

Potential Applications

Targeted Users

Time and Skill Requirements

Recommended Next Steps

To measure fatigue resistance in WRI test section cores taken at several times in the pavements' lives and in laboratory prepared mixtures having different mixture parameters.

Technology Development Product Name

Micromechanical Properties of Various Structural Components in Asphalt using Atomic Force Microscopy (AFM)

ARC Research Program

F2d

Format

Test and Analysis Method

Estimated Completion Date

3/2011

ARC Partner

TAMU/TTI

Product Description

The purpose of this test and analysis method is to characterize the micromechanical properties of various structural components in asphalt using Atomic Force Microscopy (AFM) and to quantify mechanical, viscoelastic properties of the phase components of asphalt binders before and after various degrees of oxidative aging. Nano-indentation experiments have been performed under work element F2d on a micro-grid of asphalt. TAMU has been successful in determining micromechanical properties such as stiffness, adhesion and elastic/plastic behavior. TAMU has noted a substantial difference in these mechanical properties between unaged and aged binders. The binders tested to date are AAB, AAD and ABD from the Materials Reference Library (MRL) of the Strategic Highway Research Program (SHRP). These binders were chosen based on the variation in crude source, chemical composition and elemental analysis that represent.

This product will be a test method in AASHTO recommended practice format to used nano-indentation to quantify viscoelastic properties of the phases of the asphalt binder as well as the composite asphalt binder before and after aging. These properties will ultimately be used to predict the fracture, hardening, fatigue, permanent deformation and fracture healing potential of asphalt binders and their performance in asphalt mixtures. The recommended standard practice will address the testing methodology and the methods by which to extract the viscoelastic properties as well as the utility of using these viscoelatic properties to screen for performance potential in terms of facture, fatigue, permanent deformation and compatibility with aggregate of all size fractions within the asphalt mixture.

Equipment Availability and Cost

An AFM capable of performing this function can be purchased for approximately $35,000 and is available from Agilent Technologies among other manufacturers.

Potential Applications

This methodology should be used as a screening tool for asphalt binder fracture, fatigue, and permanent deformation potential and development of adhesive (with aggregate) and cohesive bond energy in a mixture and thus compatibility with a selected aggregate as well as moisture susceptibility.

Targeted Users

Central laboratories of the FHWA and state DOTs as well as consultancies will be likely to immediately benefit.

Time and Skill Requirements

Use of the AFM requires a dedicated technician, knowledgeable in the science and use of the AFM. The testing protocol will be sufficiently specific, however, to make this a reasonable and beneficial effort.

Recommended Next Steps

Complete the testing protocol and develop methods of analysis to define viscoelastic properties.

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

Year 5 Work Plan

Work on mid-term and long-term products will continue.

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 developed since 2007. The website was maintained throughout year 4 of the Consortium. Useful and asphalt related links were added to the ARC website under the "Links" webpage. The final copies of the year 4 work plan, all the quarterly progress reports, the ARC newsletters, and any other technical reports have been uploaded to the website.

The following references were added and periodically updated:

- List of Publications and Conference Proceedings was added to the ARC website under the "Publications" webpage. A link to the *Abstract* was also provided for each publication.
- List of Presentations and Posters was added to the ARC website under the "Outreach" webpage. A link to the *Presentation* or *Abstract* was also provided for each reference.
- List of Theses and White Papers was added to the ARC website under the "Outreach" webpage. A link was also provided for each reference.

A web Tracker (i.e. visitor/site tracker) was added to the ARC website. The "StatCounter" was added to provide hit counters, visitor tracking and website stats. A link "View My Site Visitors Stats" to access the site visitors' statistics such as the number of page loads, unique visitors and returning visitors, was added at the bottom of each of the ARC WebPages.

A new webpage "Software" was created to release and download ARC related software. The various versions of the *3D-Move Analysis* software were uploaded to the ARC website. A registration web site having the following characteristics was created:

- Users are required to register before downloading the software.
- Once the user has completed the registration form, the software download Web page appears. From here, users can click a link to download and install the 3D-Move software on their computer.
- A database stores a list of users who have downloaded the software. Note that this database is physically separate from the master ARC database.
- The project manager is notified when the software is downloaded.

The software download application was modified so that existing registered users could enter their e-mail to download the software, rather than having to complete all of the registration information again.

Additionally, an internet based forum "3D-Move Discussion Group" has been created and added to the ARC website to provide guidance and feedback to 3D-Move registered users. The forum has been maintained throughout year 4 of the Consortium.

An ARC forum discussion was also created and added to the ARC site for internal information exchange purposes. The forum was created to help generating and gathering ETG topics through discussions without generating and managing dozens of e-mails. The forum includes two sections:

- a public comment/question section on the website content and research
- a section only accessible to ARC/FHWA for the purpose of information/document sharing and discussion.

Year Five Work Plan

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

Table for Decision Points & Deliverables

Date	**Deliverable**	**Description**
07/31/11	Final Report	Upload quarterly progress report and newsletter
11/30/11	Final Report	Upload newsletter
10/31/11	Final Report	Upload quarterly progress report
01/31/12	Final Report	Upload quarterly progress report and newsletter
03/31/12	Final Report	Upload newsletter
04/30/12	Final Report	Upload quarterly progress report

Work element TT1b: Communications (UNR)

Major Findings & Status

Three newsletters were published in year 4 of the Consortium. The newsletters were electronically distributed to the industry and were published on the Consortium Website.

Year Five Work Plan

Three ARC newsletters will be published.

Table for Decision Points & Deliverables

Date	Deliverable	Description
07/31/11	Final Report	Newsletter will be published
11/30/11	Final Report	Newsletter will be published
03/31/12	Final Report	Newsletter will be published

Work element TT1c: Prepare Presentations and Publications (All)

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.

Year Five Work Plan

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

Work Element TT1d: Development of Materials Database (UNR)

Major Findings and Status

During year 4, significant testing of the ARC materials database occurred providing the opportunity to improve usability and to locate and fix bugs. Using the information gathered from the database training workshop participants, some new software functionality needed to be added. In addition, some software features required redesign in order to improve usability or meet specific organizational goals. Some of these changes were relatively simple, while others required structural changes to the database, procedures that operate on the underlying database, and user interface elements. The following list summarizes the changes that were made and implemented to the database:

- Enhancement and implementation of user interface to include bulk editing of property measures (i.e. multi-dimensional properties).
- Implementation of the enhanced material filtering.
- Implementation of validation sites with the concept of a test run so that materials used in a validation site can be traced back to their origin.
- Completed the infrastructure for the enhanced role-based authentication system. The user interface elements for role-based system are complete for several forms and development is in progress for the remaining forms.
- Numerous enhancements to the form to manage material properties.

- Created a new form called "Property Sorting and Copying" to aid the data administrator in controlling how properties are applied to materials and displayed on the measure editing forms.
- Completed the form to enter contractors responsible for validation sites.
- Completed the form to enter contacts information.

Because of the redesign efforts, development of the Help system was temporarily suspended. Because changes were required to selected database tables and fields, along with changes to user interface elements, changes will also be required for the corresponding Help system elements.

A database teleconference training for ARC database users was conducted on February 25, 2011. The training provided participants with a summary of the software and technologies used to create the database, a high-level overview of the database structure and the user interface, and a detailed demonstration of the user interface for the software and best practices for its use.

<u>Year Five Work Plan</u>

In addition to the continuous testing of the beta-version of the database the year 5 will include the following work-items:

1. Finalize the implementation of the validation sites.
2. Finalize the implementation of the file management subsystem.
3. Complete the help system and documentation based on the latest changes.
4. Complete the user/super user system for the remaining forms and user interface elements.
5. Design the system that will be seen by the general public to access the data created by the consortium researchers.
6. Conduct a workshop to the database "super users" and "sub users" to evaluate the latest version of the database system. The overall objective of the workshop is to train users on how to effectively use the materials database and validation section and to evaluate the ease of use of the database system. It is anticipated that the workshop will take place in Reno, Nevada around mid of April, 2011.
7. Develop the training materials for the anticipated workshop.
8. Identify work-items that would arise from the workshop.
9. Upload data to the ARC database.
10. Manage the ARC database.

Table for Decision Points & Deliverables

Date	Deliverable	Description
04/15/11	Workshop	Training for "super users" and "sub users" on how to use the materials database and validation section and to evaluate the potential errors, bugs and the ease of use of the database system..

Work element TT1e: Development of Research Database (UNR)

Major Findings & Status

The final version of the year 4 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 contacts information for the ARC members are listed in the Home and Contact sections of the ARC Website.

Technical reports and Journal papers are published 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.

Year Five Work Plan

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

Work element TT1f: Workshops and Training (UNR lead)

Major Findings & Status

A teleconference database training session was provided on February 25, 2011 for the ARC "super users" and "sub users" of the materials database. The training session 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.

Year Five Work Plan

A workshop session will be held in year 5 for the materials database in Reno, Nevada. A workshop for PANDA software will be conducted in Year 5.

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

Technology Transfer Year 5

	Year 5 (4/2011-3/2012)												Team
	4	5	6	7	8	9	10	11	12	1	2	3	
(1) Outreach and Databases													
TT1a: Development and Maintenance of Consortium Website	■	■	■	■	■	■	■	■	■	■	■	■	UNR
TT1b: Communications	■	■	■	■	■	■	■	■	■	■	■	■	UNR
TT1c: Prepare presentations and publications	■	■	■	■	■	■	■	■	■	■	■	■	UNR
TT1d: Development of Materials Database													UNR
TT1d-1: Identify the overall Features of the Web Application													
TT1d-2: Identify Materials Properties to Include in the Materials	■	■	■	■	■	■	■	■	■	■	■	■	
TT1d-3: Define the Structure of the Database													
TT1d-4: Create and Populate the Database	■	■	■	■	■	■	■	■	■	■	■	■	
TT1e: Development of Research Database													UNR
TT1e-1: Identify the Information to Include in the Research Database													
TT1e-2: Define the Structure of the Database													
TT1e-3: Create and Populate the Database	■	■	■	■	■	■	■	■	■	■	■	■	
TT1f: Workshops and Training	■	■	■	■	■	■	■	■	■	■	■	■	UNR

Deliverable codes	**Deliverable Description**
D: Draft Report	Report delivered to FHWA for 3 week review period.
F: Final Report	Final report delivered in compliance with FHWA publication standards
M&A: Model and algorithm	Mathematical model and sample code
SW: Software	Executable software, code and user manual
JP: Journal paper	Paper submitted to conference or journal
P: Presentation	Presentation for symposium, conference or other
DP: Decision Point	Time to make a decision on two parallel paths as to which is most promising to follow througjh

■ Work planned
Work completed
Parallel topic

Technology Transfer	Year 2 (4/08-3/09)				Year 3 (4/09-3/10)				Year 4 (04/10-03/11)				Year 5 (04/11-03/12)				Team
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	
(1) Outreach and Databases																	
TT1a: Development and Maintenance of Consortium Website																	UNR
TT1b: Communications																	UNR
TT1c: Prepare presentations and publications																	ALL
TT1d: Development of Materials Database																	UNR
TT1d-1: Identify the overall Features of the Web Application																	
TT1d-2: Identify Materials Properties to Include in the Materials Database																	
TT1d-3: Define the Structure of the Database																	
TT1d-4: Create and Populate the Database							SW, v. β	SW									
TT1e: Development of Research Database																	UNR
TT1e-1: Identify the Information to Include in the Research Database																	
TT1e-2: Define the Structure of the Database																	
TT1e-3: Create and Populate the Database																	
TT1f: Workshops and Training																	UNR

Deliverable codes	Deliverable Description
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Work planned
Work completed
Parallel topic