Western Research INSTITUTE

Asphalt Research Consortium

Quarterly Technical Progress Report
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INTRODUCTION

This document is the Quarterly Report for the period of January 1 to March 31, 2012 for the Federal Highway Administration (FHWA) Contract DTFH61-07-H-00009, the Asphalt Research Consortium (ARC). The Consortium is coordinated by Western Research Institute with partners Texas A&M University, the University of Wisconsin-Madison, the University of Nevada Reno, and Advanced Asphalt Technologies.

The Quarterly Report is grouped into seven areas, Moisture Damage, Fatigue, Engineered Paving Materials, Vehicle-Pavement Interaction, Validation, Technology Development, and Technology Transfer. The format of the report is based upon the Research Work Plan that is grouped by Work Element and Subtask. At this point in the project, much of the planned work is completed or near completion, therefore, many of the Subtasks and some Work Elements have coalesced into a larger product (as planned) and current activity is reported there. There is a Table of Deliverables at the end of each Program Area that is updated each quarter. The table gives a brief description of each deliverable and an expected date of delivery.

This Quarterly Report summarizes the work accomplishments, data, and analysis for the various Work Elements and Subtasks. This report is being presented in a summary form. The Quarter of January 1 to March 31, 2012 is fourth quarter of the Year 5 contract year. Reviewers may want to reference the previous Annual Work Plans and many other documents that are posted on the ARC website, www.ARC.unr.edu. The more detailed information about the research such as approaches to test method development, data collection, and analyses will be reported in research publications as part of the deliverables.

SUPPORT OF FHWA AND DOT STRATEGIC GOALS

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

GENERAL CONSORTIUM ACTIVITIES

PROGRESS THIS QUARTER

Several ARC members attended and made presentations at the 91st Annual TRB Meeting in Washington DC during the week of January 22, 2012. ARC members also participated on TRB committees.

Dr. Jean-Pascal Planche from WRI attended the Annual Association of Modified Asphalt Producers (AMAP) meeting in Albuquerque, New Mexico on February 7 – 8, 2012.

Several ARC members attended and made presentations at the Binder, Mix & Construction, and Fundamental Properties & Advanced Models ETG meetings in Baton Rouge, Louisiana during the week of March 19 – 23, 2012.

ARC members attended and made presentation at the Annual Association of Asphalt Paving Technologists (AAPT) meeting in Austin, Texas on April 1 – 4, 2012.

WORK PLANNED FOR NEXT QUARTER

Several ARC members are planning to attend and make presentations at the Eurasphalt and Eurobitume Congress in Istanbul, Turkey on June 13 – 15, 2012.

PROGRAM AREA: MOISTURE DAMAGE

CATEGORY M1: ADHESION

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

<u>Work Done This Quarter</u>

The research team focused on developing a draft standard for the Sessile Drop Method to measure contact angle for the following conditions: (a) asphalt binder as substrate (b) aggregate as substrate and asphalt binder as liquid (figure M1a.1). Measurements of contact angle of binder as substrate and different liquids (e.g., water) can be used to determine the surface free energy of the asphalt. This property is key in determining moisture susceptibility, wettability, and adhesive potential of the binder. The contact angle between the asphalt binder and the aggregate allows for direct measurement of the wettability of the asphalt binder on the aggregate. For example, as indicated in figure M1a.1 the asphalt binder PG 58-22 +PPA (i.e., lower contact angle) has better wettability than the PG 64-22 binder for the same granite aggregate.

PG 64-22 on Granite **PG 58-22 +PPA on Granite**

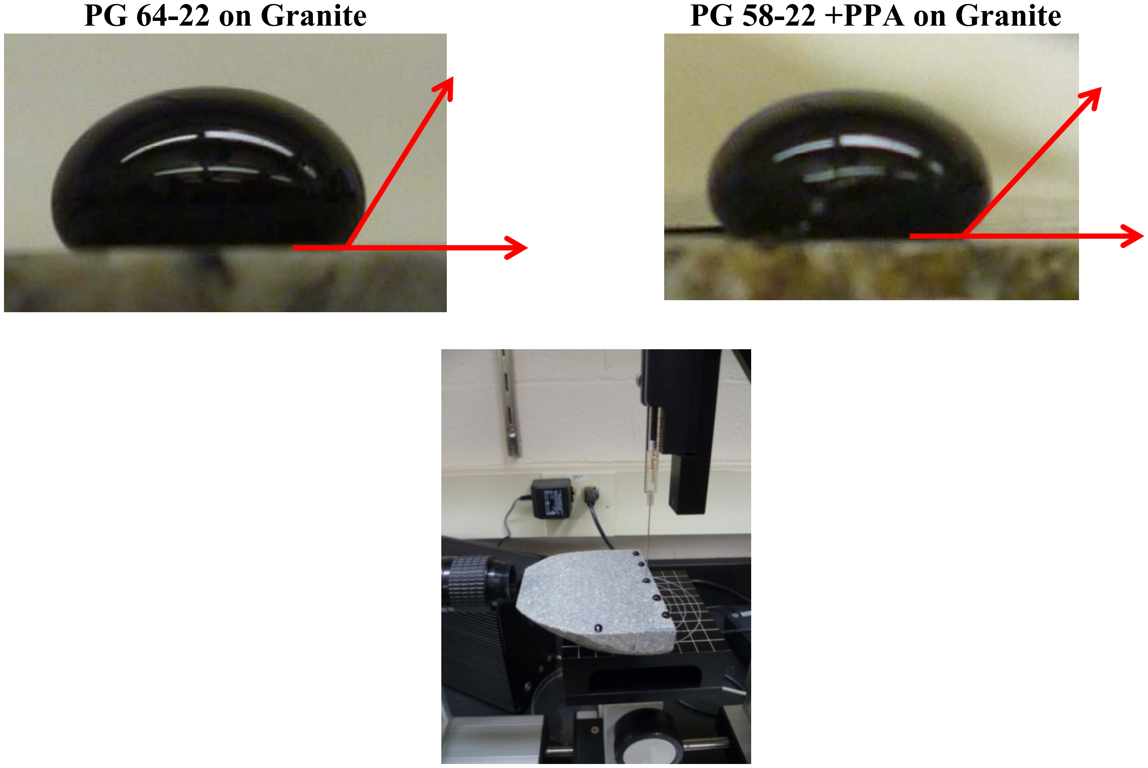


Figure M1a.1. Photograph. Contact angle of asphalt binder on granite aggregate.

Significant Results

Table M1a.1 shows preliminary results for the binder-aggregate contact angle procedure. The asphalt binders were conditioned in water for extended periods of time: 0, 3, 6, and 9 months.

Table M1a.1. Contact angle between asphalt conditioned in water and aggregate.

Sample	Average (°)	CV (%)
Original- unconditioned	77	23.7
Conditioned 3 months	112	15.6
Conditioned 6 months	103	18.4
Conditioned 9 months	128	3.5

Significant differences are observed between the wettability of the original unconditioned binders and the binders conditioned in water for long periods of time. However, further work needs to be completed to improve repeatability of the test focusing on controlling the size of the binder drop.

Work also started on using the contact angle measurements as an indicator for coating of aggregates and as a tool to evaluate the effects of Warm Mix Additives. Testing of binders contact angle before and after foaming started this quarter and is expected to continue next quarter. These activities will be part of E1c-1 and E1c-2 activities.

Work Planned Next Quarter

The research team will work on finalizing the standard procedure for contact angle and on improving the sample preparation procedure for asphalt-aggregate samples. New measurements for determining effects of foaming and other types of WMA additives will be conducted.

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)

Work Done This Quarter

The main goal of this subtask is to provide material property inputs required in other work elements as required. Any data obtained from this subtask will be included in the material properties database. In the last quarter surface free energy of some aggregates and asphalt binders that are being used to develop test methods were measured.

Significant Results

None.

Significant Problems, Issues and Potential Impact on Progress

None.

Work Planned Next Quarter

Work on this subtask will be conducted in conjunction with and as required by other work elements.

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

Work Done This Quarter

Work reported under subtask M2a-2 (Work of Cohesion) is also directly relevant to this subtask.

Significant Results

See subtask M2a-2.

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

Work Done This Quarter

This work element was completed and findings were reported in previous quarterly reports. There was no activity this quarter.

Work Planned Next Quarter

None.

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

Work Done This Quarter

This work element was completed and findings were reported in previous quarterly reports. There was no activity this quarter.

Work Planned Next Quarter

None.

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)

Note about Work Element M2a: Per the Year 5 work plan, the objectives of this work element will be accomplished in other tasks.

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

Abstract

Work conducted on these subtasks during this quarter was related to the specific deliverable of an "AFM-based micro/nano-scale cyclic direct tension test." This test procedure provides a method to directly measure fracture energy in a compression/tension test as a function of temperature and rate and to resolve the total fracture energy into reversible and dissipative components. This quarter we have demonstrated this new procedure in preliminary testing. Like the rheological parameters, fracture energy has two components, is rate and temperature dependent, and is not amenable to description as a single independent value. Attempts to quantify fracture energy without specifying the fracture rate and temperature are essentially meaningless.

In preliminary work using this new AFM-based direct tension test we show fracture energy versus fracture rate as a series of plots collected at three temperatures. The result is a plot resembling rheological data that has not been shifted onto a master curve. Both the reversible and the dissipated portions of the total fracture energy are shown quantitatively as a function of separation rate and temperature in the plot. We are currently working on shift procedures needed to generate a master curve-type presentation of fracture energy (i.e. strain energy release rate).

The development of this test method represents a significant step forward in work toward the ultimate goal of understanding and predicting asphalt fracture. With this tool the asphalt research community will be able to quantitatively measure the effect upon fracture energy (i.e. strain energy release rate) of service and production variables such as oxidative aging, crude source, filler gradation, polymers, various additives, RAP, mix temperature, environmental conditions, etc. We believe that this tool could have as significant an impact upon the understanding of fracture as the introduction of the rheometer has had upon the understanding of permanent deformation.

Work conducted this quarter represents significant progress toward three of the four deliverables associated with these two subtasks. At the time of this writing, an AFM-based cyclic direct tension test has been demonstrated. Some additional work will be conducted to refine and improve this new test method. We estimate work on this deliverable to be ~85% completed.

This new test will allow us to directly measure fracture energy in terms of surface energy and viscoplastic components, and will thus be instrumental in completing the deliverable related to supplying these quantities as inputs needed for various performance models. We estimate work on this deliverable to be ~60% completed.

The test procedure also provides information related to ductile-brittle properties of the test asphalt, also with respect to temperature and separation rate. We believe that test data can be interpreted to provide a quantifiable ductility parameter that is applicable to asphalt binders. The development of the AFM cyclic direct tension test represents ~80% completion of this deliverable.

No progress on the fourth deliverable (a method to determine surface roughness of aggregate based on AFM) is reported this quarter. Work in previous quarters has shown that our plan to probe fractured aggregate surfaces (as would be encountered in an actual mix) rather than an artificially polished surface (not particularly relevant to an actual mix) is impractical due to the extreme depth and angularity of the fractured surface when viewed at AFM scale. We have modified the original test to eliminate fractured-surface samples and have obtained new samples representative of four common aggregate types. This deliverable is ~35% complete at this time.

Work Done This Quarter

Preliminary experiments conducted last quarter indicated that variable rate AFM force displacement measurements can provide a method to quantitatively evaluate the dissipative component of the overall work of adhesion for an asphalt/substrate adhesive joint. Work conducted this quarter continued and refined experiments begun last quarter. This quarter experimental work was directed toward the quantitative determination of the dissipative (i.e. non-reversible) contribution to the overall fracture energy (i.e. work of adhesion) for an asphalt adhesive joint. This dissipative component can result in fracture energies that are significantly greater than those predicted based only upon the thermodynamic (i.e. reversible) work of adhesion. Changes in the dissipative component relative to the fracture rate are responsible for the rate dependence of the fracture energy of asphalt adhesive joints when measured by mechanical testing methods (Packham, 1996).

In an AFM pull-off experiment the force required to separate the tip from the surface provides a measure of the surface energy of the fractured material (Drelich, 2004). The surface energy of the fractured material is responsible for the thermodynamic or reversible portion of the work expended in creating a fracture or crack. This reversible component is thus a measure of the surface energy associated with the new surface area created as a result of the fracture. Because it results from surface energy, the reversible work remains essentially constant across the range of conditions tested. Surface energy is not rate dependent and should change by only a few mJ/m^2 relative to the temperatures used in this testing.

Contact mechanics models have been developed to relate the mechanical work required to separate two surfaces to the ‘chemical work’ related to the creation of new surface (e.g. Chadhury, 1996). Commonly used contact mechanics models include models developed by Hertz (Hertz model) Johnson, Kendall, and Roberts (JKR model) and Derjaguin, Muller and

Toporov (DMT model). These models differ mainly in how they treat attractive forces in and near the contact patch, and each is applicable to some specific set of conditions. All of the models assume some equilibrium condition, and therefore, none is exactly appropriate for our viscoelastic system (Attard, 2007; Hui, 1998). For this work we used the DMT contact mechanics model to approximate the reversible component of the fracture energy. While not strictly appropriate for our system, this model is typically applied to the case of contact between small rigid spheres, and is relatively simple to apply. The spherical tip that we use in our testing meets the criteria for a 'small sphere'. However, the rigidity of the system decreases as the system temperature increases so that the rigidity requirement is not strictly met, particularly at the highest test temperature.

When the DMT model is used with the measured pull-off-force to quantify the reversible component of the measured fracture energy a value consistent with the expected surface energy for an asphaltic material is obtained. Considering the relative imprecision of the AFM pull-off force measurement, a fairly small number of samples, and the fact that the DMT model is not exactly applicable, we only expect a reasonably close value from the AFM measurements. The value, as measured with the AFM, was relatively constant across the range of temperatures and separation rates used in the experiments. It was also in reasonably good agreement with asphalt surface energy values obtained by more conventional contact angle techniques.

In an AFM pull-off experiment, the integrated area bounded by the retraction curve and the zero-force axis represents the overall work of adhesion (or fracture energy in the present case) (Cappella, 1999). Experiments conducted this quarter show rate dependence for the overall work of adhesion as measured for an asphalt/glass adhesive contact using AFM force displacement measurements. Since surface energy is not rate dependent, the rate dependence of the measured work of adhesion must be attributed to the non-reversible or dissipative component of the fracture energy. Unlike the reversible work, the dissipative component is strongly rate and temperature dependant.

A modified form of the Griffith fracture criterion introduced by Irwin gives the overall fracture energy as the sum of surface energy and dissipative terms. This concept is now commonly applied to the analysis of adhesive contacts, and for the case of essentially cohesive failure (where the fracture occurs within the adhesive rather than at the adhesive/substrate interface) fracture can be described by this simple expression (Charrault, 2009)

$$G = 2\gamma + Gp$$

or similarly,

$$G = 2\gamma\big(1 + \Phi(\nu)\big)$$

Where G is the overall fracture energy expended in the creation of one unit area of new surface (also referred to as the strain energy release rate), γ is the surface energy of the fractured material, and *Gp* is the dissipated energy or, alternatively where $\Phi(\nu)$ is a dissipative function with respect to separation rate. It can be implicitly understood that G, 2γ, and *Gp* are all related to the same fracture, and thus, to the same amount of new surface created as a result of the fracture. That is, each of these terms can be associated with the creation of the same specific amount of new surface, for any particular fracture test.

Thus, according to Irwin's modification of the Griffith fracture criteria, the energy dissipated in the creation of one unit of new surface can be determined by simply subtracting the measured surface energy component (2γ) from the measured overall fracture energy.

$$Gp = G - 2\gamma$$

The result can then be normalized in with respect to the reversible energy so that the relative magnitude of the dissipative term, with respect to separation rate, can be compared across the temperature range used in the testing as well as for variations related to crude source and/or chemistry, aging, etc.

$$\frac{G - 2\gamma}{2\gamma}$$

For this quarter we report the results of our first set of experiments conducted to quantify the energy expended in the fracture of an asphalt adhesive joint as a function of temperature and separation rate and to break this overall fracture energy into its thermodynamic and dissipative components. We then generate what is essentially a 'fracture energy master curve' for an asphalt adhesive.

Significant Results

Figure M2a-2.1 shows fracture energy versus relative separation velocity when an adhesive joint between a glass bead AFM tip and an asphalt surface is fractured at three temperatures. For the experiment reported, a glass bead with a 10-µm diameter was 'glued' to a glass microscope slide using a thin (~860-nm) film of aged SHRP core asphalt AAA-1 as the adhesive. The glass bead is mounted on an AFM cantilever spring with a nominal spring constant (as reported by the manufacturer) of 14-N/m. For each data point, an adhesive joint was first created, at the test temperature, by bringing the glass bead into contact with the asphalt surface and applying a predefined contact pressure for a period of one minute. The AFM feedback electronics were used to establish and control the contact pressure by maintaining a constant cantilever deflection during the 'loading cycle' when the adhesive joint was formed. This technique allowed us to create adhesive joints that exhibited reasonably consistent contact areas as evidenced by good repeatability of the measured work of adhesion when the joints were fractured in a standardized manner.

After an adhesive joint was established, as described above, the joint was subsequently fractured at a controlled rate and both the force and the work associated with the fracture were measured and recorded. Each data point was collected at a new randomly selected location on the asphalt surface. The reported values for pull-off force and total work represent the average of the several points (typically 6 or 7) that were collected at these several locations for each temperature/rate combination.

The controlled fracture of the adhesive joint was executed by first locking the AFM feedback loop and then pulling the sample away from the probe tip by retracting the nano-positioning stage upon which the sample was mounted. The fracture rate was controlled by controlling the rate of the nano-stage retraction. The maximum measured deflection of the cantilever spring as the asphalt surface was pulled away from the glass bead multiplied by the cantilever spring constant provides a measure of the force required to separate the glass bead from the surface. Using the DMT contact mechanics model, as should be reasonable for the small rigid spherical tip used in our system (Barthel, 2008), we can then calculate the thermodynamic (reversible) work associated with the fracture.

$$w = Fpo/2\pi R$$

Where w is the reversible work, Fpo is the pull-off force, and R is the radius of the spherical tip. For a cohesive fracture, $w = 2\gamma$, i.e. the reversible work is two times the surface energy of the new surface generated by the fracture, since two surfaces are created.

While not exactly repeatable, the measured pull-off force is remarkably consistent across the range of rates and temperatures used in the experiments. The relatively constant pull-off force is related to the surface energy of the asphalt adhesive, a material property, which varies modestly (~5-mJ/m^2) over the temperature range used in the experiments, but does not vary with respect to separation rate. The DMT model predicts a surface energy for this asphalt of ~35.5 ±1 mJ/m^2 at room temperature. Over the range of temperatures used in the testing the DMT model predicts an average surface energy of ~33±6 mJ/m^2.

The rather large variation in the predicted surface energy indicates that this single model is not appropriate for the entire temperature range used in the experiments (Grierson, 2005). However, the surface energies predicted from the data using the DMT model are reasonable for the surface energy of an organic compound and are also in reasonably good agreement with published values for asphalt surface energy as derived using more standard contact angle methods. With additional work we expect to improve the precision of the measurement of the reversible portion of the fracture energy, but this is not the focus of the current research. For our current purpose we will assume a surface energy of ~35-mJ/m^2. This value obviously cannot be exactly correct across the temperature range used in the testing, but it does provide a useful estimate of the reversible or thermodynamic contribution to the total fracture energy, and it also provides a reasonable baseline to show the relative importance of the dissipative energy component.

Data was collected from these experiments essentially as AFM force displacement curves. In these data, the area enclosed by the withdrawal curve and the zero-force axis represents the total work expended in separating the contact, and the maximum cantilever deflection times the cantilever spring constant represents the force required to separate the contact. Both the work and the force relate to the same fracture, and thus to the same amount of new surface or fracture area. From the pull-off force we can approximate the reversible portion (2γ) of the total work using a suitable contact model as shown above. Using the relationship $G = 2\gamma*(1+\Phi(v))$ we can then establish the dimensionless dissipation function $\Phi(v)$. Figure M2a-2.1 shows $2\gamma*(1+\Phi(v))$ plotted with respect to the log of the separation rate.

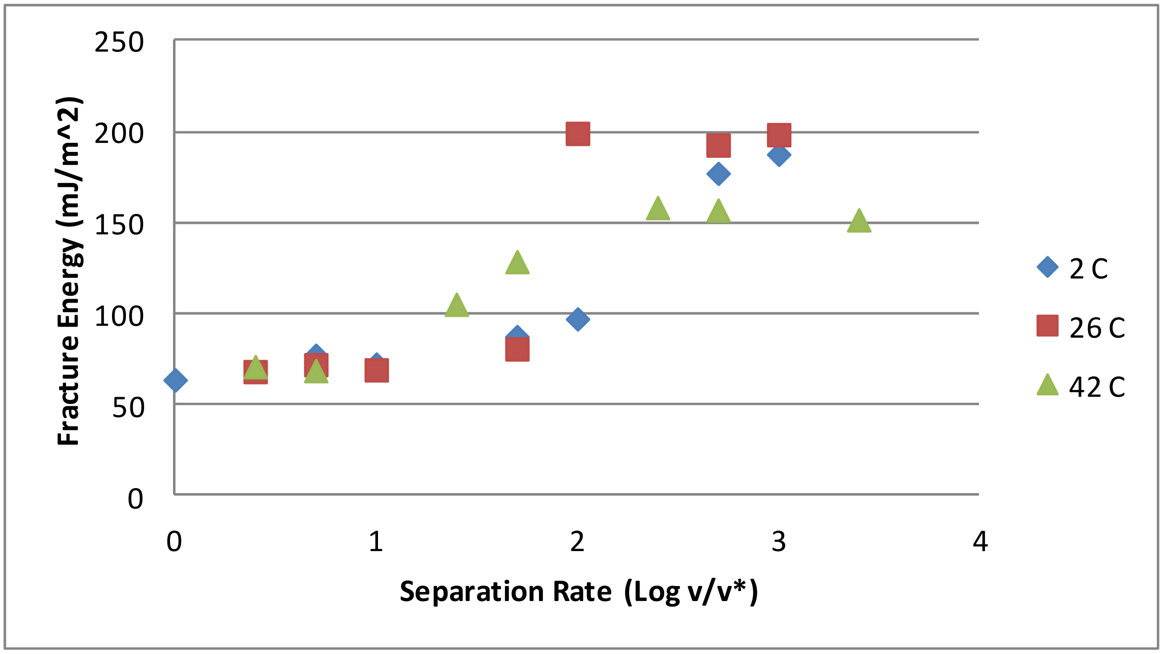


Figure M2a-2.1. Fracture energy vs. separation rate at three temperatures for an adhesive joint made with SHRP core asphalt AAA-1between glass substrates.

Under the same applied load the probe tip obviously will sink more deeply into the warmer (softer) sample. Therefore, with other conditions constant, the contact area, and the measured forces related to this area, will increase with increasing temperature. In order to compare data collected at different temperatures, it is necessary to normalize the data with respect to contact area.

We account for the change in the contact area relative to temperature by arbitrarily assigning an area of 1 unit squared to the contact area that results when our standard load is applied at the coldest test temperature. At 2° C both the force and the work associated with the fracture remained relatively constant for the lowest separation rates, indicating that reversible work accounts for the majority of the fracture energy (i.e. $\Phi(v) \approx 0$). We assume that the dissipative contribution to the fracture energy is negligible at the slowest rates at all of the test temperatures, and that the surface energy of the asphalt changes little over this temperature range. With these assumptions we can then normalize all of our data with respect to the one unit of contact area related to the pull-off at 2° C. This technique allows us to sidestep the sticky problem of determining the actual contact area while still allowing us to directly compare data collected at different temperatures.

The two assumptions used in the normalization of the fracture data are both reasonable and imperfect. We know, for example, that the surface energy is not constant across the temperature range used in the testing. An additional surface energy-temperature ($\gamma(t)$) function can be added to increase the accuracy of the normalization. Additional points could be collected at even lower separation rates to assure that $\Phi(v) \approx 0$. We are currently working on some improvements with respect to the interpretation and presentation of these data. However, while still subject to some improvement, the technique as developed so far provides a clear path to the realization of what is essentially a time/temperature master curve of fracture energy (i.e. stain energy release rate), and a method for quantifying both the reversible and the dissipative portions of this energy.

Significant Problems, Issues and Potential Impact on Progress

One of our two AFMs is currently inoperable due to electronics problems. We are in the process of resolving this issue. This problem may result in some rearrangement of our plan, but it should not impact the overall progress of these subtasks.

Work Planned Next Quarter

For the next quarter tests are planned to measure fracture energy as a function of rate and temperature for three SHRP core asphalts (AAA-1, AAD-1, and AAM-1). Improvements with respect to the interpretation and presentation of these fracture data are currently underway. We will also begin to investigate the effect of aging on fracture energy. Fracture test data will be analyzed for the purpose of developing a ductility or ductile/brittle parameter. Some work will continue toward adapting available contact mechanics models toward the goal of providing a quantitative measure of the actual contact area associated with the various temperatures used in the testing. Polished samples representative of four common aggregate types will be prepared for imaging in the following quarter.

References

Attard, P., 2007, Measurement and interpretation of elastic and viscoelastic properties with the atomic force microscope. *Journal of Physics: Condensed Matter*, 19, 473201, 33pp.

Barthel, E., 2008, Adhesive elastic contact – JKR and more. *Journal of Physics D: Applied Physics*, 41, 163001 (40pp).

Cappella, B., and G. Dietler, 1999, Force-distance curves by atomic force microscopy. *Surface Science Reports*, 34, 1-104.

Charrault, E., C. Gauthier, P. Marie, and R. Schirrer, 2009, Experimental and Theoretical Analysis of a Dynamic JKR Contact. *Langmuir*, 25(10), 5847-5854.

Chaudhury, M. K., T. Weaver, C. Y. Hui, and E. J. Kramer, 1996, Adhesive contact of a cylindrical lens and a flat sheet. *Journal of Applied Physics*, 80 (1), 30-37.

Drelich, J., G.W. Tormoen, and E.R. Beach, 2004, Determination of solid surface tension from particle-substrate pull-off forces measured with the atomic force microscope. *Journal of Colloid and Interface Science*, 280 (2), 484-487.

Grierson, D.s., E. E. Flater, and R. W. Carpick, 2005, Accounting for the JKR-DMT transition in adhesion and friction measurements with atomic force microscopy. *Journal of Adhesion Science and Technology*, 19 (3-5), 291-311.

Hui, C. Y., J. M. Barney, and E. J. Kramer, 1998, Contact Mechanics and the Adhesion of Viscoelastic Spheres. *Langmuir*, 14, 6570-6578.

Packham, D. E., 1996, Work of adhesion: contact angles and contact mechanics. *International Journal of Adhesion and Adhesives*, 16, 121-128.

Work Element M2b: Impact of Moisture Diffusion in Asphalt Mixtures

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

Work Done This Quarter

There was no activity this quarter.

Work Planned Next Quarter

We have accomplished significant portions of this work element including measurement of diffusion through binders and fine aggregate matrix. Further work will be conducted if prioritized based on the requirements from other work elements.

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

The remaining activity is reported under Work Element M1a.

CATEGORY M3: AGGREGATE SURFACE

Work Element M3a: Aggregate Surface Characterization (TAMU)

This work element was completed and findings were reported in previous quarterly reports. There was no activity this quarter.

CATEGORY M4: MODELING

Work Element M4a: Micromechanics Model (TAMU, UNL)

Subtask M4a-1: Model Development

<u>Work Done This Quarter</u>

Using research outcomes, we have submitted one journal article (title: computational microstructure modeling to estimate progressive moisture damage behavior of asphaltic paving mixtures) to the International Journal for Numerical and Analytical Methods in Geomechanics. The paper is under review.

<u>Significant Problems, Issues and Potential Impact on Progress</u>

None.

<u>Work Planned Next Quarter</u>

In the next quarter we will update the final report based on feedback/comments from the Texas A&M University.

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

This work element is addressed under Work Element F1b-1 and E1a.

Work Element M4c: Unified Continuum Model (TAMU)

<u>Work Done This Quarter</u>

The work done this quarter concentrated on completing the development of a thermodynamic-based moisture-induced damage model. The model takes into consideration the effects of the presence of the moisture in the solid part and the flow of the moisture inside the cracks and voids. Relative humidity effect was considered as the reason of diffusion inside the solid part and its degradation. Emphasis is placed on the consideration of the pore-water pressure that accelerates crack evolution and propagation due to presence of moisture and washing away of the mastic due to flow of moisture through the asphalt cracks and void both as a result of fast traffic loading. In addition, both energetic and dissipative processes are clearly distinguished through this thermodynamic framework. The moisture conditioning protocol and test types are assigned to be done for calibration and validation of the model through ARC moisture-damage experiments done at North Carolina State University.

Moreover, three-dimensional (3D) micromechanical moisture-damage simulations have been completed. Several simulations on the 3D micromechanical model have been done in order to investigate the effect of moisture conditioning time, moisture content, material properties parameters, strain rate, and temperature at both tension and compression. The results completely show the crack propagation and damage concentration after moisture conditioning the specimens. These simulations can be used to conduct virtual moisture-damage simulation experiments.

Significant Results

None

Significant Problems, Issues and Potential Impact on Progress

None

Work Planned Next Quarter

The next quarter work will be focused on completing the damage models by assuming proper Helmholtz free energy via the thermodynamic framework. This thermodynamic framework is necessary in order to correctly consider the different moisture-induced damage mechanisms and the coupling between them. Moreover, work will continue on by producing virtual specimens based on the ARC mixtures using X-ray CT and the finite element method. In addition, the calibration and validation of the model at the continuum scale will start by focusing on the results of the first mixture in tension from the ARC testing.

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

Work on individual components such as test methods and micromechanics models required in the system is complete. The components will be put together in the form of a methodology towards the end of this project.

TABLE OF DECISION POINTS AND DELIVERABLES FOR MOISTURE DAMAGE

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
M1a-5: Propose a novel testing protocol (UWM)	Draft Report	Development and Implementation of the Bitumen Bond Strength test for Moisture Damage Characterization	1/10	8/11 Complete	Additional analysis/verification on the BBS test is included: operator sensitivity data, validation with TSR mixture testing and comparison with contact angle measurements. Report has been consolidated as one chapter and suggested to be included in TAMU report for moisture damage.
	Final Report	Report in 508 format on the use of the Bitumen Bond Strength test for Moisture Damage Characterization	1/11	6/12	Received comments from FHWA peer review of Report "L". Suggested revisions are being implemented in final report.
M1b-2: Work of Adhesion at Nano-Scale using AFM (WRI)	Test Method	A method to determine surface roughness of aggregate and fines based on AFM	12/30/11	1/30/13	Development of measurement technique has taken longer than initially expected
M1b-3: Identify mechanisms of competition between water and organic molecules for aggregate surface (TAMU)	Draft Report	Final report documenting the testing protocol and findings of experiments on asphalt-aggregate interactions	10/31/10	Complete	To be included in the comprehensive report on moisture damage from Texas A&M University.
	Final Report		4/30/12		
M1c: Quantifying Moisture Damage Using DMA (TAMU)	AASHTO procedure	AASHTO procedure for preparing Fine Aggregate Matrix (FAM) specimens for the DMA testing	9/30/10	Complete	N/A
	Draft Report	Use of the method to characterize various mixtures with comparison to field performance	12/31/10	Complete	
	Final Report		3/31/11	6/30/11	Report to be made 508 compliant
M2a-2: Work of Cohesion at Nano-Scale using AFM (WRI)	Test Method	A method to determine ductile-brittle properties via AFM measurements	12/30/11	4/30/13	This product is an adaptation of the AFM cyclic direct tension test and will be completed in succession.

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
M2a-2: Work of Cohesion at Nano-Scale using AFM (WRI)	Performance Model Input Data	Fracture energy in terms of surface energy and viscoplastic components	4/30/13		
M2a-2: Work of Cohesion at Nano-Scale using AFM (WRI)	Test Method	AFM-based micro/nano-scale cyclic direct tension test	3/30/13		
M2b-1: Measurement of diffusion of water through thin films of asphalt binders and FAM (TAMU)	Draft Report	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.	6/30/10	Complete	
	Final Report		9/30/11	12/31/11	The dissertation was completed at TAMU and needs editing for 508 format
M3a: Aggregate Surface Characteristics (TAMU)	Research report	Report on methods and experimental findings and utility of methodology and findings	6/30/10	Complete	To be included in the comprehensive report on moisture damage from Texas A&M University.
	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)	Draft Report	Numerical micromechanical model of moisture-induced damage in asphalt mixtures. This report will include the algorithm and modeling method.	Sep-11	Complete	
	Final Report		Sep-11	Mar-12	
M4a: Micromechanics Model Development (Moisture Damage) (UNL)	Models and Algorithm	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.	3/31/11	Complete	Models will be included in final report.
	Draft report		06/30/11	12/11	More time needed to finish extra simulations and documenting final report
	Final report		12/31/11	8/14/12	
M4a: Lattice Micromechanics Model (NCSU)	Draft Report	Documenting development of lattice micromechanical model	2/14/12	12/12	N/A
	Final Report	Documenting development of lattice micromechanical model	8/14/12	12/12	
M4a: Model to Bridge Continuum Damage and Fracture (NCSU)	Draft Report	Documenting development of continuum damage-to-fracture model	N/A	12/12	N/A
	Final Report	Documenting development of continuum damage-to-fracture model	2/14/12	12/12	

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
M4c: Unified Continuum Model (TAMU)	Models and Algorithm	Algorithm for including moisture damage in the model	6/30/11	12/31/12	Model needs to be updated based on calibration with experimental measurements
	Draft Report	Draft Report on the moisture-damage modeling	9/30/11	12/31/12	
	Final Report (M5, M4c, F1b-1, F1c, F1d-8, F3c, and V3c)	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	03/31/12	3/31/13	Work is progressing in the validation based on ARC experiments.
M5: Moisture Damage Prediction System (All)	Protocol	Protocol for implementation of component selection	6/30/11	Complete	To be included in the comprehensive report on moisture damage from Texas A&M University.
	Experimental method	Experimental method for measuring moisture damage resistance of full mixture	9/30/11	Complete	
	Draft Report (M5, M4c, F1b-1, F1c, F1d-8, F3c, and V3c)	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		
	Final Report (M5, M4c, F1b-1, F1c, F1d-8, F3c, and V3c)		3/31/12	3/31/13	Preparation of a comprehensive report.

	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 PATTI and modified DSR tests													
M1a-3	Evaluate the moisture damage of asphalt mixtures													
M1a-4	Correlate moisture damage between DSR, PATTI, 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 PATTI and 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, PATTI, and mix tests						P		P									
M1a-5	Propose a Novel Testing Protocol				P				P				JP					
M1a-6	Standard Testing Procedure and Recommendation for Specifications										P					D	F	
M1b	**Work of Adhesion**																	
M1b-1	Adhesion using Micro calorimeter and SFE						JP											**TAMU**
M1b-2	Evaluating adhesion at nano scale using AFM							JP										**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										**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								**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)

Work Done This Quarter

This task was completed in the last quarter.

Significant Results

The results demonstrated that a multiplicative relationship exists between the ideal and practical work of fracture. The relationship between these two quantities depends on binder compliance, loading rate, and temperature. This work has validated that the ideal work of fracture, which is calculated from surface energy, is a fundamental property than can be used to rank asphalt-aggregate systems based on their resistance to fracture under dry and wet conditions.

Significant Problems, Issues and Potential Impact on Progress

None

Work Planned Next Quarter

This subtask is completed.

Work Element F1b: Viscoelastic Properties (Year 1 start)

Subtask F1b-1: Viscoelastic Properties under Cyclic Loading (UT and TAMU)

Work Done This Quarter

During the previous quarter we documented an approach to measure and model the interaction nonlinearity in asphalt binders using the DSR in the form of a journal paper. The paper was submitted to the Journal of Mechanics of Time Dependent Materials for publication. This paper also includes the model verification under different loading histories other than those used to obtain the model parameters. We also continued our study on the laboratory measurement of the bulk modulus of asphalt binder. In order to avoid the effect of raising time and measure the glassy behavior of asphalt binders, we modified the loading history to a ramp displacement and a constant hold. This loading history and the equation obtained from solving the boundary value problem for the poker chip test geometry will allow the measurement of time dependency of Poisson’s ratio and bulk modulus of asphalt binders:

$$\sigma_z(t) = \int_0^t \left[\frac{4}{3}\mu(t-\xi) + K(t-\xi) \right] \frac{\partial \varepsilon_z(\xi)}{\partial \xi}\, d\xi. \quad (1)$$

where $\sigma_z(t)$ is the axial stress in the poker-chip geometry specimen, $\varepsilon_z(t)$ is the applied strain, $K(t)$ is the bulk modulus, and $\mu(t)$ is the shear relaxation modulus. Therefore, to obtain the bulk modulus from the poker-chip test, the shear modulus of the asphalt binder was also measured at the same temperature. This was done using a Dynamic Shear Rheometer (DSR) with a cone and plate geometry. The cone and plate geometry was used to achieve a uniform stress and strain distribution within the specimen. The poker chip geometry was also used with Instron ElectroPuls E1000 test instrument to measure the properties of the binder in the tension-compression mode of loading. The tests were conducted on two ARC asphalt binders (B001 and B002) at 20ºC. These binders were RTFO-aged to simulate the short-term aging. Numerical approaches are being used to solve the Volterra integral equation (Eq. 1), with an unknown quantity $K(t)$ within the integral.

Significant Results

None at this time.

Significant Problems, Issues and Potential Impact on Progress

None.

Work Planned Next Quarter

In the next quarter we plan to finish the analysis related to the measurement of bulk modulus and document the findings in a technical paper. This paper will not only present a method to measure the bulk modulus of asphalt binder, but also addresses the issues such as linearity and edge effects.

The work accomplished thus far in this task focused on the linear and nonlinear viscoelastic properties of the asphalt binder in a multi-axial stress state. This information is important in designing test methods for asphalt binders and conducting computational micromechanics of the asphalt at a mastic or mortar length scale. This understanding needs to be extended and applied to higher length scales.

The importance of characterizing damage evolution in a multi-axial stress state is further highlighted by several recent studies that have demonstrated that damage initiates under a multi-axial stress state near the surface of the pavement (Ozer et al. 2011; Wang and Al-Qadi 2010; Wang et al. 2011). However, in terms of material properties, these studies have typically used a Mohr-Coloumb type of shear failure criterion to obtain a relative estimate for the most critical location where damage initiates within the pavement structure. There is a need to determine and model the material characteristics at multi-axial stress states in order (i) to complement the studies on near surface cracking, (ii) to improve the constitutive models used in computational methods for material characterization, and (iii) to evaluate the response of different materials when subjected to a stress state that is representative of the stress state that the material experiences within a pavement structure. The importance of characterizing material properties subjected to a multi-axial stress state has also been highlighted in other studies (Erkens 2002).

In particular, during this quarter we will use the Arcan apparatus to determine the linear viscoelastic properties as well as damage evolution in asphalt mortars or FAM specimens. Figure F1b-1.1 illustrates a typical cyclic load test on a mortar specimen using the apparatus.

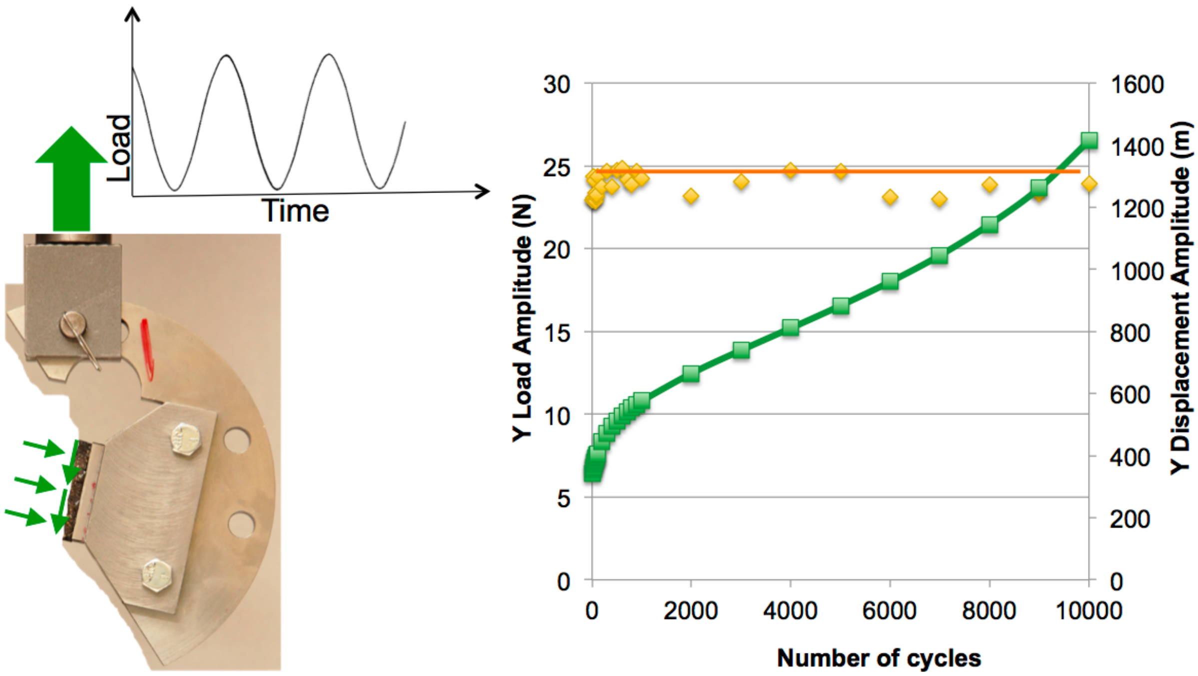


Figure F1b-1.1. Test geometries used to measure the shear and bulk properties of asphalt binders.

<u>References</u>

Erkens, S., 2002, "Asphalt Concrete Response - Determination, Modelling and Prediction." Ph.D. Dissertation, Delft, The Netherlands: Technical University of Delft.

Ozer, Hasan, Imad Al-Qadi, and Carlos Duarte, 2011, Effects of Nonuniform and Three-Dimensional Contact Stresses on Near-Surface Cracking. *Transportation Research Record: Journal of the Transportation Research Board* 2210: 97–105.

Wang, Guangming, R. Roque, and Dennis Morian, 2011, Evaluation of Near-Sruface Stress States in Asphalt Concrete Pavement. *Transportation Research Record: Journal of the Transportation Research Board* 2227: 119–128.

Wang, Hao, and Imad Al-Qadi, 2010, Near-Surface Pavement Failure Under Multiaxial Stress State in Thick Asphalt Pavement. *Transportation Research Record: Journal of the Transportation Research Board* 2154: 91–99.

Subtask F1b-2: Separation of Nonlinear Viscoelastic Deformation from Fracture Energy under Repeated and Monotonic Loading (TAMU)

Work Done This Quarter

The reader is referred to Work Elements F2c and E1a.

Work Planned Next Quarter

The reader is referred to Work Elements F2c and E1a.

Work Element F1c: Aging

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

Work Done This Quarter

No work this quarter

Significant Results

N/A

Significant Problems, Issues and Potential Impact on Progress

There are no problems or issues.

Work Planned Next Quarter

Review of the literature and work on other research projects is ongoing.

Subtask F1c-2: Develop Experimental Design (TAMU)

Work Done This Quarter

No work this quarter.

Significant Results

None.

Significant Problems, Issues and Potential Impact on Progress

The planned experiments using ARC core binders have been completed.

Work Planned Next Quarter

Analysis of date (see F1c-4) and report preparation.

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

Work Done This Quarter

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

A key element of the development process is validation with pavement cores. This quarter we received ARC cores for testing binder oxidation rates for comparison to model calculations. Specimens that have been received are from the Arizona test sites and were cored December 2010. Mixture fatigue testing has been completed and now binder extraction and recovery is proceeding. Additional cores, taken at different times and if available, will be needed to establish binder oxidation over time to compare with the model calculations.

Significant Results

N/A

Significant Problems, Issues and Potential Impact on Progress

There are no problems or issues

Work Planned Next Quarter

A key element of the proposed work is validation with pavement cores. Work in the final quarters of the project will continue with validation, to the extent appropriate pavement cores are available. Work also is proceeding on a final report on aging modeling and on incorporating the model into PANDA.

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

Work Done This Quarter

The reader is referred to Work Elements F1b-2 and F2c.

Significant Results

The reader is referred to Work Elements F2c and E1a.

Significant Problems, Issues and Potential Impact on Progress

The reader is referred to Work Elements F2c and E1a.

Work Planned Next Quarter

The reader is referred to Work Elements F1b-2 and F2c.

Subtask F1c-5: Polymer Modified Asphalt Materials (TAMU)

Work Done This Quarter

No additional work on this subtask was conducted this quarter.

Work Planned Next Quarter

The effort to establish polymer degradation kinetics due to oxidation has been reviewed and appears to be an intractable problem.

Work Element F1d: Healing (TAMU)

Subtask F1d-1: Critical review of the literature
Subtask F1d-2: Material selection
Subtask F1d-3: Experiment design
Subtask F1d-4: Test methods to measure properties related to healing
Subtask F1d-5a: Testing of materials and validating healing model
Subtask F1d-5b: Thermodynamic model for healing in asphalt binders

Work Done This Quarter

In the previous quarters, we reported a test and analytical procedure to characterize the overall healing in asphalt composites (fine aggregate matrix) using a dynamic shear rheometer (DSR). In the last quarter we have continued the development of this test procedure with two goals. The first goal was to reduce the total number of specimens required to obtain the characteristic healing function. The second goal was to extend and validate the procedure using FAM specimens in tension-compression mode. By achieving these two goals, we will be able to extend the test protocol to full asphalt mixtures (for possible implementation using AMPT) as well as develop an understanding of the damage evolution and healing process in the two modes of cyclic loading (tension and shear). In the last quarter we have also started the process of uploading the results of the tests completed thus far to the ARC database of material properties.

Significant Results

None to report at this time.

Significant Problems, Issues and Potential Impact on Progress

None.

Work Planned Next Quarter

We will continue the development of the simplified test procedure using fewer test replicates as well as testing of specimens in the tension-compression mode.

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

Work Done This Quarter

The final draft was submitted in 508 format, which also includes findings from work elements F2e and F2a in the previous quarter. This quarter a document containing captions for figures to allow for interpretation by visually impaired was prepared and submitted to FHWA. Based on new information gathered in work element F2e, study for including healing as part of binder fatigue testing is under consideration. In addition recent data collected in work element E2b for diffusion of fresh binders in aged binders is being considered to understand healing mechanisms. The findings of this subtask showed that healing is much faster when temperature is increased compared to rest period time. This could be the result of faster molecular diffusion at higher temperatures.

Significant Problems, Issues and Potential Impact on Progress

None.

Work Planned Next Quarter

Revise final report (if necessary).

Cited References

None

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

Work Done This Quarter

The emphasis of this subtask is to integrate the results from Subtasks M1b-2 and M2a-2, and other pertinent past experimental work where physico-chemical properties including chemical potentials and phase separation phenomena can be used in the asphalt microstructure model discussed in Work Element F3a. The data generated from these analyses is discussed and incorporated into the chemo-mechanical models of asphalt and asphalt mastic structures in Work Element F3a.

Significant Results

See Work Element F3a.

Significant Problems, Issues and Potential Impact on Progress

None

Work Planned Next Quarter

Activity is in Subtask is included in the discussion in Work Element F3a.

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

Work Done This Quarter

In this quarter, a general continuum damage-healing mechanics framework has been developed, which has appeared in Darabi et al. (2012). This framework extends the well-known effective (undamaged) configuration in continuum damage mechanics to an effective-healed natural configuration. This framework, which is also presented within a systematic thermodynamic formulation, can be used to properly couple healing and damage mechanics. In this quarter, special emphasis is placed on validating the derived healing evolution law based on the ALF data. Figure F1d-8.1 schematically presents the concept of the proposed healing natural configuration.

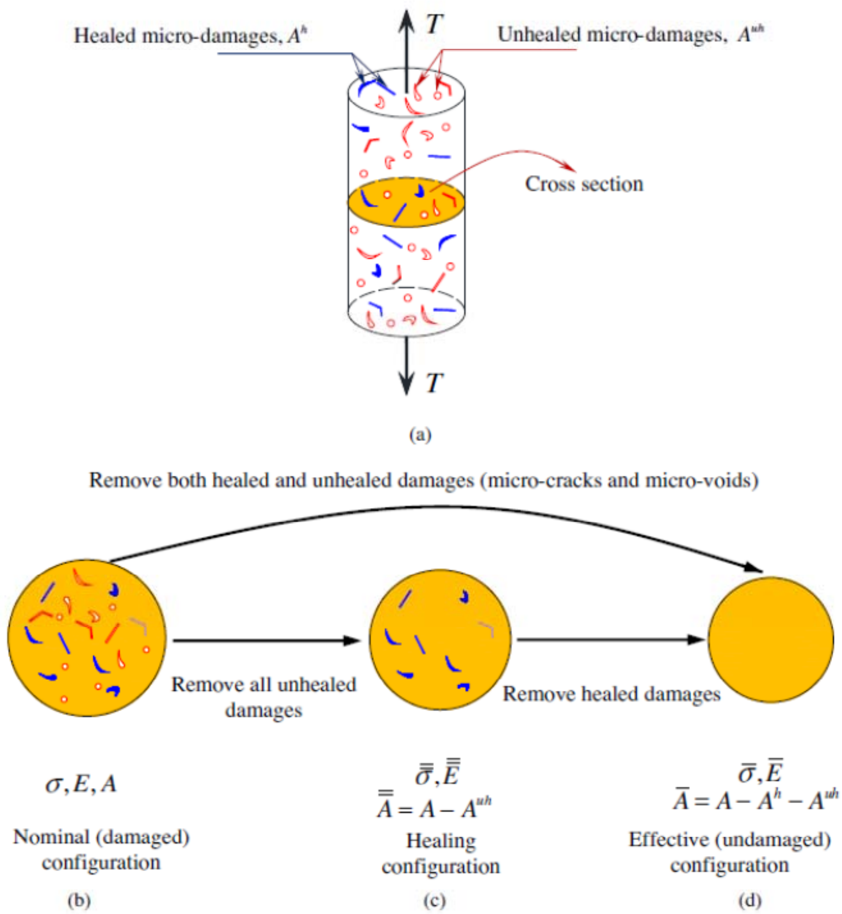
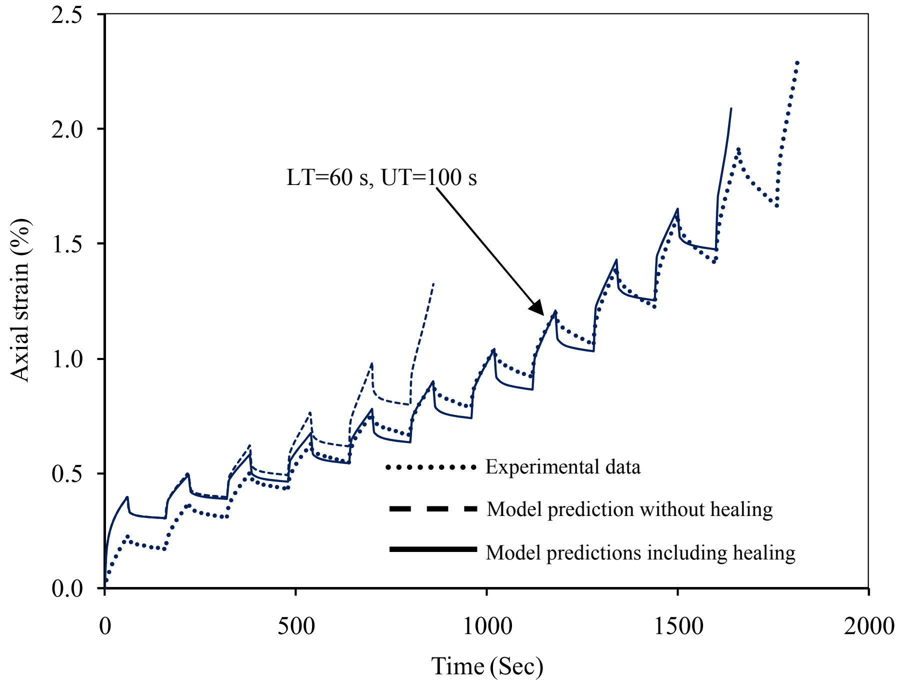


Figure F1d-8.1. Schematic representation of: (a) the damaged partially healed cylinder in tension; (b) the nominal configuration; (c) the healing configuration; and (d) the effective configuration.

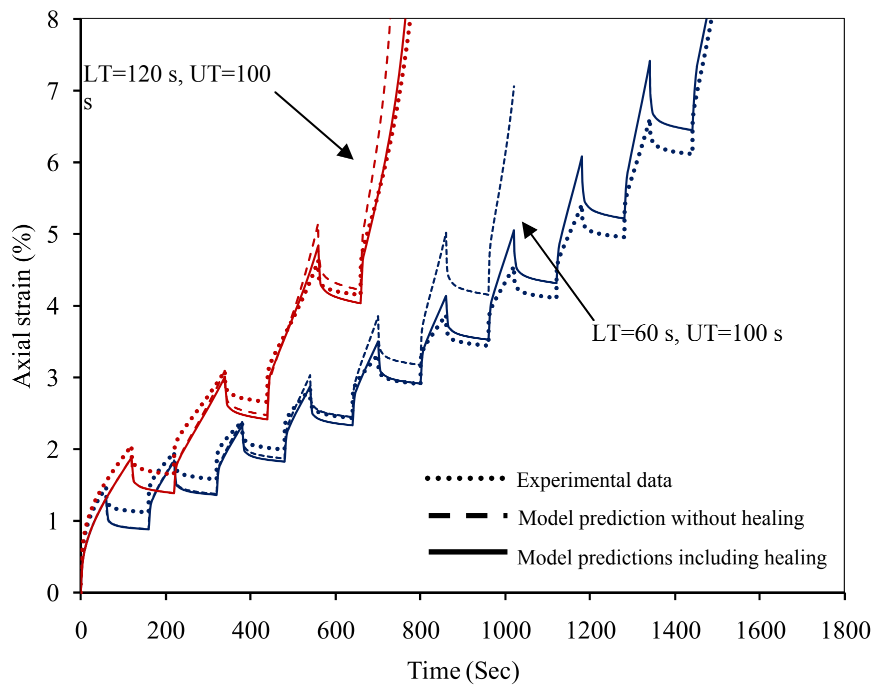
Based on the proposed healing natural configuration, a physically-based healing variable is defined as the density of healed micro-damage. The stress tensor in the nominal (damaged) configuration is then related to the stress tensor in the healing configuration as a function of the damage density ϕ and the healing variable h , such that:

$$\sigma_{ij} = \left[1 - \phi\left(1 - h\right)\right]\bar{\sigma}_{ij} \tag{1}$$

where $\bar{\boldsymbol{\sigma}}$ and $\boldsymbol{\sigma}$ are stress tensors in the healing and damaged configuration, respectively. An evolution function is proposed for the micro-damage healing model. The proposed healing evolution function is implemented in the PANDA and validated against the Nottingham and ALF experimental data on repeated creep-recovery with the rest periods between the loading cycles. Figure F1d-8.2 shows examples of the model predictions using the micro-damage healing model.



(a)



(b)

Figure F1d-8.2. Model predictions and experimental measurements for the repeated creep-recovery test in compression at $T = 20^{o}C$ for different loading times and unloading times. (a) in tension, (b) in compression.

Model predictions are compared with different experimental measurements. It is shown that the model can capture the experimental results well.

Significant Results

The significant results from the developed continuum damage-healing frameworks have been detailed in Darabi et al. (2012a, 2012b).

Significant Problems, Issues and Potential Impact on Progress

None

Work Planned Next Quarter

The main focus of the coming quarter is on further validation of the micro-damage healing model against available experimental data. Moreover, special emphasis will be placed on the development of a simplified approach for calibrating the micro-damage healing model based on simple experimental procedure. As soon the data from the ARC testing plan is ready, calibration and validation based on this data will be started.

Cited References

Darabi, M. K., R. K. Abu Al-Rub, and D.N. Little, 2012a, A continuum damage mechanics framework for modeling micro-damage healing. *International Journal of Solids and Structures*, 49 (3-4): 492-513; http://dx.doi.org/10.1016/j.ijsolstr.2011.10.017

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

CATEGORY F2: TEST METHOD DEVELOPMENT

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

Work Done This Quarter

The final draft was submitted in 508 format, which also includes findings from work elements F2e and F1d-6 in the previous quarter. This quarter a document containing captions for figures to allow for interpretation by visually impaired was prepared and submitted to FHWA.

Significant Problems, Issues and Potential Impact on Progress

None.

Work Planned Next Quarter

Revise final report (if necessary).

Cited References

None

Work Element F2b: Mastic Testing Protocol (TAMU)

Work Done This Quarter

The reader is referred to Work Elements F2c and E1a.

Significant Results

The reader is referred to Work Elements F2c and E1a.

Significant Problems, Issues and Potential Impact on Progress

The reader is referred to Work Elements F2c and E1a.

Work Planned Next Quarter

The reader is referred to Work Elements F2c and E1a.

Work Element F2c: Mixture Testing Protocol (TAMU)

Work Done This Quarter

One technical paper entitled "Characterizing Permanent Deformation and Fracture of Asphalt Mixtures Using Compressive Dynamic Modulus Tests" was accepted for publication in the ASCE Journal of Materials in Civil Engineering. Another technical paper entitled "Mechanistic Modeling of Fracture in Asphalt Mixtures under Compressive Loading" was submitted in response to an invitation of contributing an invited journal paper to the Special Issue "Mechanics and Models of Pavement Materials" of the ASCE's Journal of Materials in Civil Engineering.

Two technical presentations were made at the 91st Transportation Research Board (TRB) Annual Meeting in Washington, D.C., January 2012. The first presentation was entitled "Characterization of Inherent Anisotropy in Asphalt Mixtures" and was made in Section 581 "Strength Characteristics of Hot-Mix Asphalt: Testing and Modeling, Part 1." The second presentation, entitled "Characterizing Permanent Deformation and Fracture of Asphalt Mixtures Using Compressive Dynamic Modulus Tests", was made in Section 637 "Strength Characteristics of Hot-Mix Asphalt: Testing and Modeling, Part 2."

Two major achievements were made in this quarter: 1) data analyses were conducted on asphalt mixtures fabricated with AAD and AAM binders to determine the material properties of strength, model parameters of the viscoplastic yield surface function and the viscoplastic potential function; and 2) more laboratory tests based on the proposed testing protocol in previous ARC quarterly reports were performed on asphalt mixtures fabricated with ARC Nustar binder and Valero binder, the data of which can be used to determine the viscoelastic, viscoplastic and viscofracture properties of the material. Details of the achievements made in this quarter are summarized as follows.

1) Determination of Viscoplastic Material Properties

The determined viscoplastic model's parameters included the slope and the intercept of viscoplastic yield surface (α and κ_0), the slope of the viscoplastic potential function (β) and the yield strength ratio of extension to compression (d). All of these parameters were used in the constitutive models for characterizing viscoplasticity that were coded into the PANDA program. Thus, it is very crucial to determine these parameters accurately and efficiently. In addition, these model parameters were shown to be theoretically related to the engineered material properties such as cohesive shear strength (C) and internal friction angle (φ) as well as the modified vector magnitude (Δ') that was proposed in previous quarterly reports to characterize the inherent anisotropy of the asphalt mixture due to aggregates' preferential orientation. The theoretical relationships between the viscoplastic parameters and the engineered material properties were verified through laboratory tests in this quarter.

Prior to strength tests, lateral surface scanning tests were performed on each asphalt mixture to determine the modified vector magnitude (Δ'). Then uniaxial compressive strength tests (confining pressure $\sigma_3 = 0$) and triaxial compressive strength tests at two different confining pressures ($\sigma_3 = 103.5$kPa and 207kPa, respectively) were conducted on the asphalt mixtures with varying binders (AAM, AAD), air void contents (4%, 7%) and aging periods (unaged, 6 month 60°C continuous aged). All of the strength tests were performed at a constant strain rate (330 microstrains per second) and a constant temperature (40°C). A method of determining the yield stress of a viscoplastic material was developed based on the pseudo strain concept that was proposed in the previous quarterly reports. The yield stresses (σ_1) at different confining pressures were determined for every asphalt mixture.

In the triaxial condition, the viscoplastic yield surface used in PANDA without considering the strain hardening effect was converted to:

$$(\sigma_1 - \sigma_3) - \alpha \frac{(\sigma_1 + 2\sigma_3)}{3} - \kappa_0 = 0 \quad \text{(F2c.1)}$$

Using the Mohr-Column yield criterion, the yield surface becomes:

$$\frac{(\sigma_1 - \sigma_3)}{2} - \frac{(\sigma_1 + \sigma_3)}{2} \sin\varphi - C\cos\varphi = 0 \quad \text{(F2c.2)}$$

Applying the strength testing data to equations F2c.1 and F2c.2 produced the model parameters (α and κ_0) and material properties (C and φ) which are summarized in table F2c.1. In the triaxial condition, the relationship between α, κ_0 and C, φ were derived as follows:

$$\alpha = \frac{6\sin\varphi}{3-\sin\varphi} \tag{F2c.3}$$

$$\kappa_0 = \frac{6C\cdot\cos\varphi}{3-\sin\varphi} \tag{F2c.4}$$

The yield strength ratio of extension to compression was related to the internal friction angle:

$$d = \frac{3-\sin\varphi}{3+\sin\varphi} \tag{F2c.5}$$

In addition, the slope of viscoplastic potential function was derived as:

$$\beta = \frac{ma+2nb}{3(nb-ma)} \tag{F2c.6}$$

where

$$\begin{cases} a = \dfrac{3+\Delta'}{1-\Delta'} \\ b = \dfrac{3+\Delta'}{1+\Delta'} \end{cases} \tag{F2c.7}$$

$$\begin{cases} m = \dfrac{5}{6} - \dfrac{1}{2d} - \dfrac{\beta}{9} \\ n = \dfrac{1}{3} - \dfrac{1}{2d} - \dfrac{\beta}{9} \end{cases} \tag{F2c.8}$$

By using the measured Δ' and φ, the values of d and β were also calculated for different asphalt mixtures, and the results are collected in table F2c.1 as well.

Table F2c.1. Summary of viscoplastic material properties.

Binder	Aging	Air Voids	C	φ	α	κ_0	d	Δ'	β
	months	%	kPa	degrees	--	kPa	--	--	--
AAD	0	4	260	29	1.16	543	0.720	0.273	0.37
		7	121	38	1.56	239	0.658	0.247	0.67
	6	4	353	34	1.35	739	0.685	0.418	0.44
		7	250	37	1.49	502	0.667	0.379	0.59
AAM	0	4	247	35	1.42	504	0.677	0.308	0.54
		7	162	30	1.21	340	0.711	0.260	0.41
	6	4	419	29	1.15	884	0.719	0.387	0.29
		7	259	34	1.33	544	0.688	0.430	0.40

Furthermore, once the cohesive shear strength and internal friction angle were determined from the strength tests, α and κ_0 were predicted according to equations F2c. 3 and F2c.4, respectively. The predicted α and κ_0 were then compared with the measured α and κ_0 (as shown in table F2c.1) that were determined from the strength tests based on equation F2c.1. Figure F2c.1 compared the predicted α with the measured α while figure F2c.2 shows the comparison between the predicted κ_0 and the measured κ_0. The comparisons demonstrated a perfect match between the predicted values and the measured values for a variety of asphalt mixtures with different binders, air void contents and aging periods, which verified the theoretical relationships between the viscoplastic model's parameters and the engineered material properties as shown in equations F2c.3 and F2c.4.

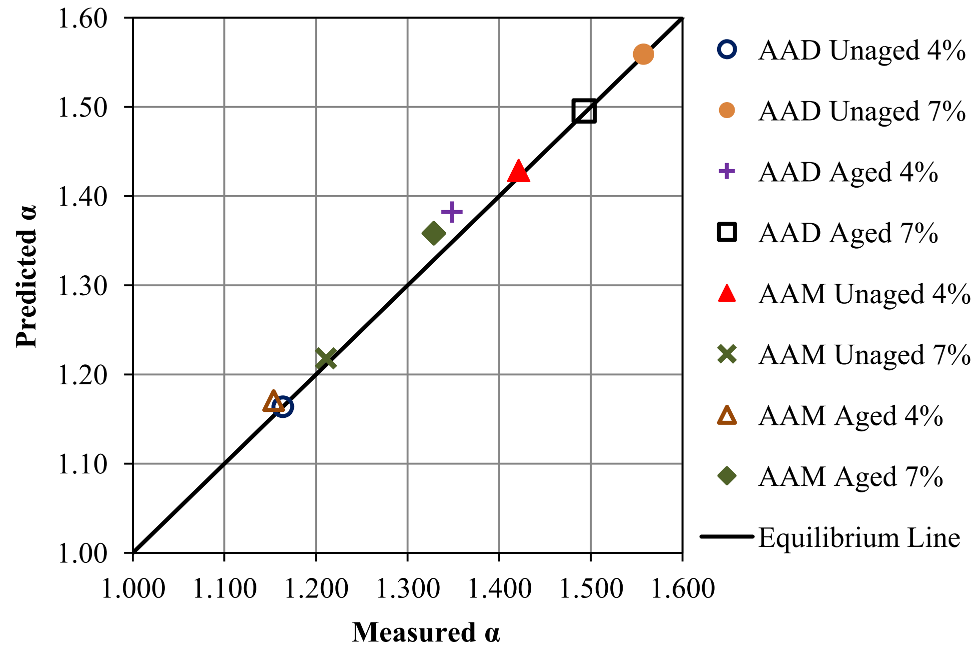


Figure F2c.1. Comparison between the measured α from strength tests and the predicted α based on internal friction angle.

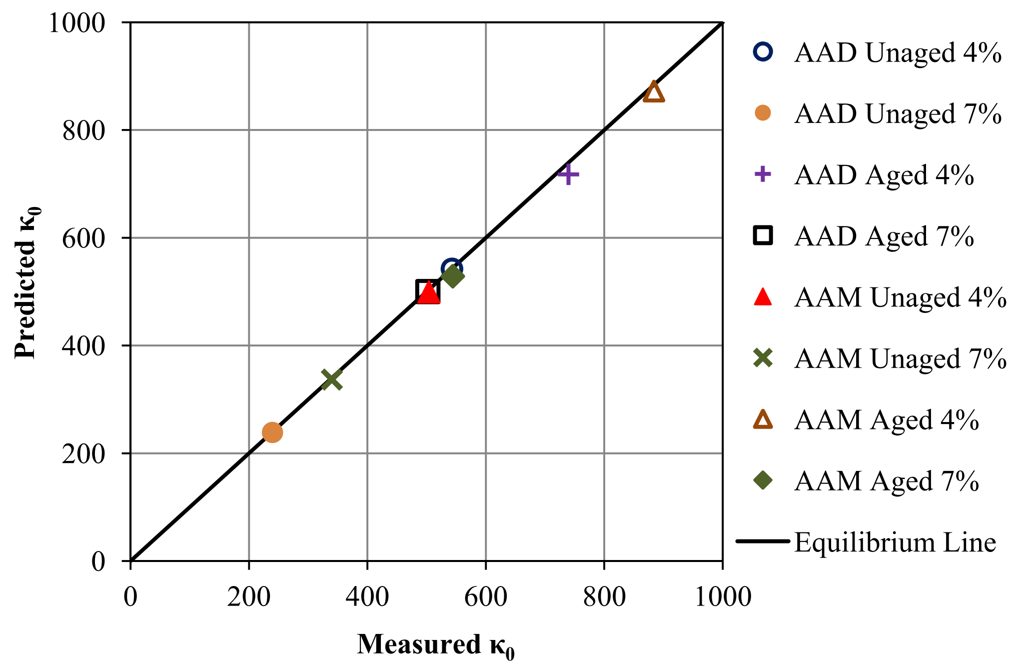


Figure F2c.2. Comparison between the measured κ_0 from strength tests and the predicted κ_0 based on cohesion and internal friction angle.

2) Laboratory Testing on ARC Asphalt Mixtures

To characterize the engineered material properties of the ARC materials, more laboratory tests based on the previously proposed testing protocol including nondestructive tests and destructive tests were performed on asphalt mixtures fabricated with different ARC binders, air void contents and aging periods. The summary of the testing progress are summarized in . F2c.2 as follows.

Table F2c.2. Testing progress on ARC materials.

	Binder	**Air Voids**	**Aging**		**Test Properties**	**Test Name**	**Progress**
		%	months				
ARC Material Tested	Nustar	4	0	**Testing Protocol**	Non-destructive	Lateral Surface Scanning Test	Done
			3				
			6			Compressive Creep Test	Done
		7	0				
			3			Dynamic Modulus Test	Done
			6				
	Valero	4	0		Destructive	Dynamic Modulus Test	Done
			3				
			6			Uniaxial Compressive Strength Test	Done
		7	0				
			3			Triaxial Compressive Strength Test	Ongoing
			6				

<u>Significant Results</u>

The viscoplastic parameters for the PANDA program was effectively and accurately determined for asphalt mixtures with AAD and AAM binders and the relationships between the viscoplastic parameters and the engineered material properties theoretically derived in previous quarterly reports were verified using laboratory testing. In addition, more laboratory tests based on previously proposed testing protocol including nondestructive tests and destructive tests were performed on asphalt mixtures fabricated with different ARC binders, air void contents and aging periods.

<u>Significant Problems, Issues and Potential Impact on Progress</u>

The universal testing machine (UTM) in the McNew Lab of Texas Transportation Institute had a problem in providing hydraulic power and is currently under repair.

<u>Work Planned in Next Quarter</u>

The triaxial strength tests will be completed on the asphalt mixtures with ARC materials in the next quarter and an abundance of data analysis will be performed to acquire the anisotropic, viscoelastic, viscoplastic and viscofracture material properties of the asphalt mixtures with ARC materials.

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

<u>Major Findings</u>

Task 1

In light of the phase structure and measured properties that were identified in previous studies [1-2], an investigation is currently underway regarding the role of these phase structures with different stiffness in terms of the fracture properties of the asphalt binder. For example, numerical analysis demonstrates that the interface of phases with different stiffness can result in a localized region of high stress that may be susceptible to failure [3]. Therefore, one may expect that an excessive presence of the relatively stiffer bee structure or a larger difference in stiffness of the bee structure relative to the stiffness of the continuous phase can render the asphalt binder more prone to fracture. The first step of this investigation involved using atomic force microscopy (AFM) to determine the changes on microstructure and microrheology due to the synthetic modification of asphalt via plastomer and elastomer (SBS) polymer modification. Based on previous research [4] which shows that polymer modification mitigates the loss of cohesive bond energy due to oxidative aging (and thus improves the fracture properties of the binder), one would expect the "susceptible phase interface" hypothesis to be supported by a reduction in "bee structures" in an aged, polymer-modified sample. Figure F2d.1 shows the results of a recent experiment to test the "susceptible phase interface" hypothesis, in which an aged, unmodified binder was imaged and compared to aged, elastomer- and plastomer-modified asphalts of the same PG grade.

The findings yield evidence of no "bee structures" after polymer modification, which seems to support the "susceptible phase interface" hypothesis. It should be noted, however, that other researchers [5] have identified "bee structures" in lesser quantities after polymer modification. More imaging of similar asphalts and polymer-modified asphalts (PMAs) will be essential to make a firm conclusion regarding the presence of the "bee structures" after polymer modification, but in the meantime, researchers involved in this study would like to offer a potential reason for the observed discrepancy of results. It has been documented as part of this research and previously [1] that thin-film specimens oxidize rapidly, and trial testing has shown that omitting steps to prevent rapid oxidation can result in similar and indistinguishable results for unaged asphalts, aged asphalts, and polymer-modified asphalts. Additional research [6] also indicates that extended (or rapid thin-film) oxidation can cause polymers to degrade and could potentially explain the appearance or re-emergence of "bee structures' after polymer modification that has been observed by other researchers [5]. Since such preventative methods are not always described in the literature of other AFM papers, it is not clear whether rapid oxidation was prevented in these cases or whether different outcomes relative to "bee structures" are possible depending upon the nature of the base bitumen, the nature and content of the polymer, and the bitumen-polymer compatibility. Differences in the type and dosage of polymers also may explain these differences.

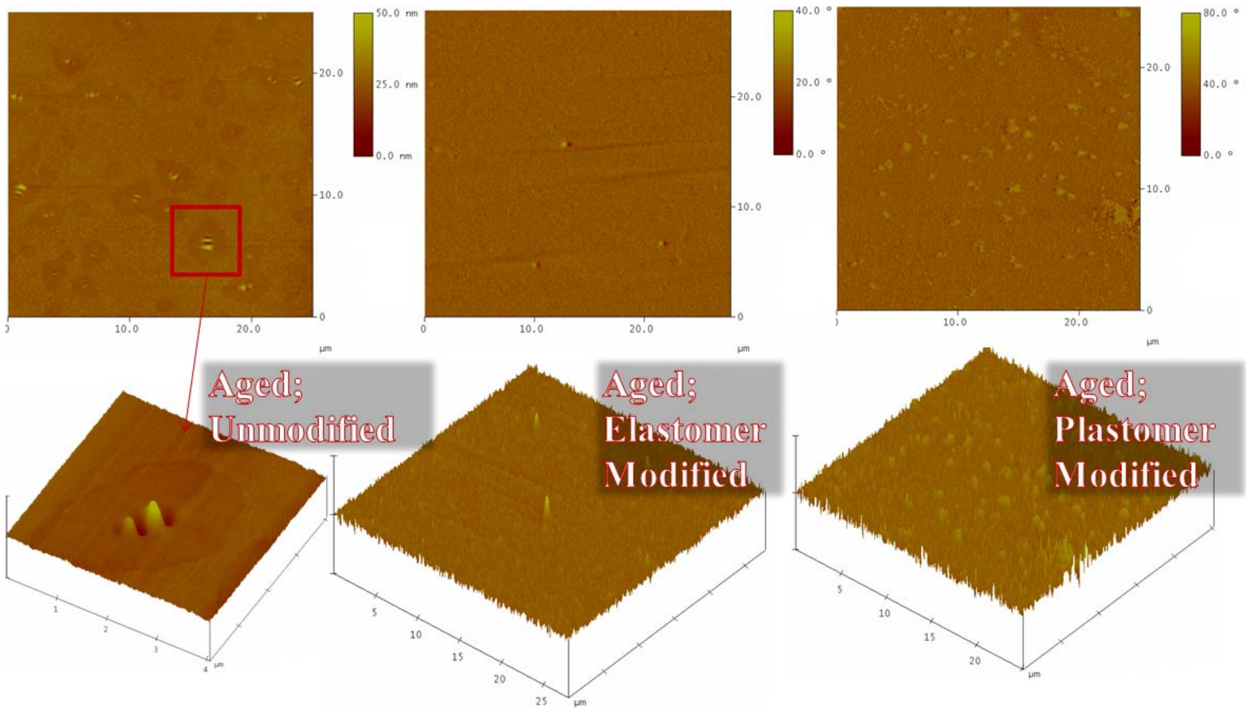


Figure F2d.1. Effects of polymer modification on asphalt aging (25 μm by 25 μm AFM topography/phase images).

Task 2

As part of the finite element analysis of the AFM indentation of asphalt binder, an axisymmetric two dimensional finite element model was developed. The geometry used in this model was based on the specifications provided by the manufacturer. The images revealed that the AFM tips used in this study were irregularly shaped. Although, it was generally assumed that the tip was composed of a spherical tip with a conical body, the actual images showed asymmetric tip shape. This was shown in figure F2d.2, where, the tip exhibited a pyramidal shaped structure. Despite the pyramid shaped structure of the tip, due to the sharp cone angle one can assume a general conical shape for numerical study purposes. As a result, in this numerical study the tip was assumed to have a conical body with a spherical tip with a radius of 5 nm. Figure F2d.3 shows a magnified view of the geometry developed for the finite element study.

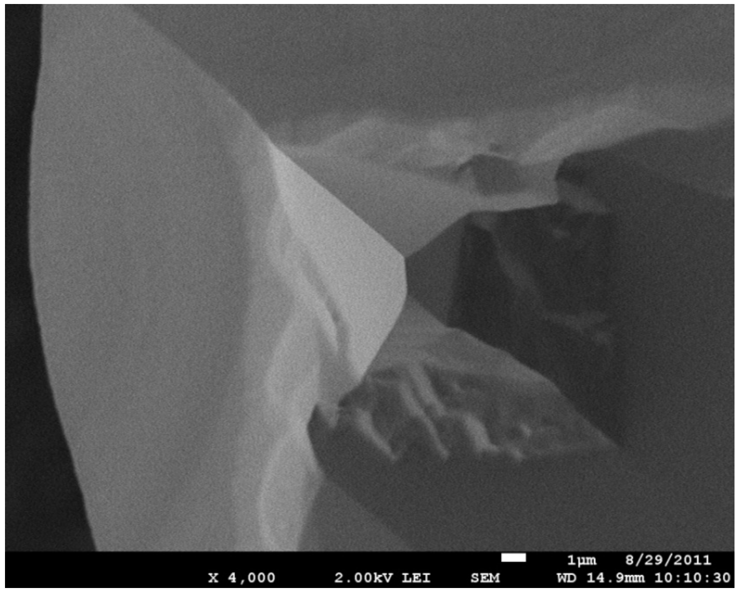


Figure F2d.2. Scanning electron microscope image of AFM tip used in this study.

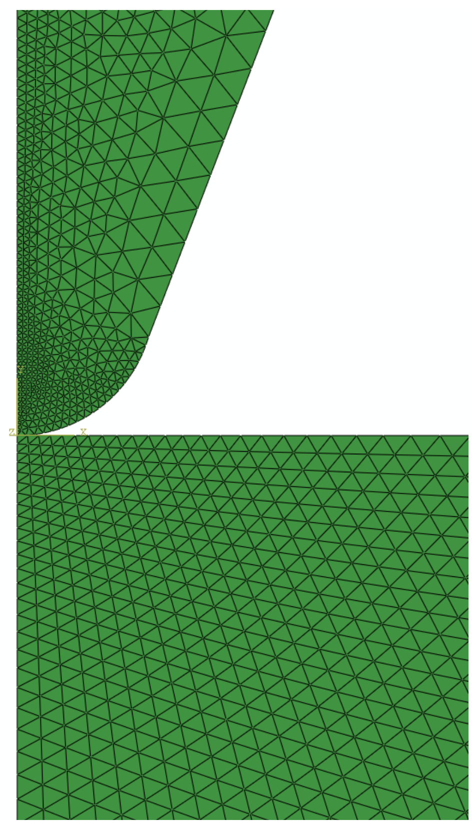


Figure F2d.3. Magnified view of geometry used for finite element study.

Various analytical linear elastic solutions for nanoindentation problems exist in the literature [6-8]. The linear elastic indentation finite element results compared closer to the Hertz spherical solution as opposed to the Sneddon conical solution. This may have been due to the fact that although the body of the tip is cone shaped, the general assumed shape of the tip of the indenter is spherical. Finite element models with linear elastic material models are restricted to a certain level of deformation. Due to this reason, a low load value of approximately 5nN was used. Different tip radii were also used, and the results indicated that a higher level of indentation depth is achieved with a lower tip radius. This can be expected, since reducing the tip radius causes the tip shape to become more conical. A separate analysis was also performed using an entirely spherical tip geometry without a conical body. The finite element results with this geometry were compared to Hertz solution, and the results indicated for low deformation the Hertz solution provides highly accurate results. However, as with increasing deformation when the small deformation assumption no longer holds, the finite element results begin to deviate as expected.

Viscoelastic creep indentation analysis was also performed using a linear viscoelastic material model and the geometry shown above. The work of Fischer-Cripps [9] provides us with viscoelastic solutions to various tip shapes. The results show the creep indentation results compare well to the spherical tip creep indentation solution provided by Fischer-Cripps. A three element Voigt spring and dashpot model was used and the sensitivity of the different material parameters was examined. The finite element results compared well to the analytical. A change in instantaneous modulus resulted in a change in the initial deformation. Whereas, increasing or decreasing any of the other two material model constants affected the time dependent behavior. Figure F2d.4 shows the change indentation depth with varying second term in the Voigt spring and dashpot model (E2), detailed in [9].

Surface forces were also incorporated into a separate finite element model with identical geometry. However, this step is still in progress. An appropriate force-distance relationship is currently being developed and will be used to accurately quantify the effect of the surface forces on the indentation simulations.

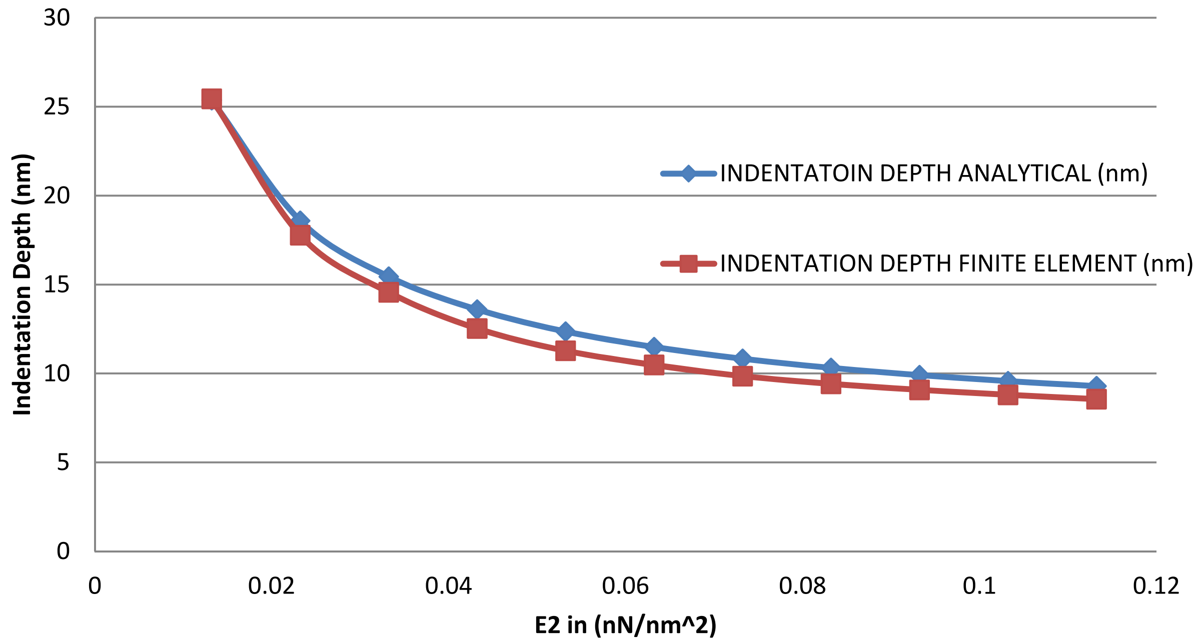


Figure F2d.4. Indentation depth as a function of E2.

<u>Summary and Conclusions</u>

Task 1

The presented findings present two types of binder modification, e.g. natural (aging) and synthetic (polymer) modification, in terms of the effects that these processes have on the microstructure of the binder and how those effects impact the performance characteristics of hot mix asphalt (HMA). Based on a combination of these findings and prior AFM research results, an interpretation of changes in asphalt microstructural phases due to natural and synthetic modification processes is shown in figure F2d.5. The depicted asphalt microstructure has a multi-phase system (continuous and dispersed phases) before and after aging and after polymer modification. While the dispersed phase exists after aging, it generally becomes more dominant and comprises a new sub-phase, which is commonly referred to in the literature as the "bee structure" phase. The "bee structure" phase has a highly irregular topographical microstructure and smaller stiffness values than its comprising dispersed phase; furthermore, recent findings [2] suggest that composite modulus values at the micro scale are greater than modulus values at the macro scale, indicating an interfacial weakening at the micro scale that is currently unidentified. These characteristics are the basis for the "susceptible phase interface" hypothesis which investigates the "bee structures" as the possible source of lost desirable strength properties of the binder.

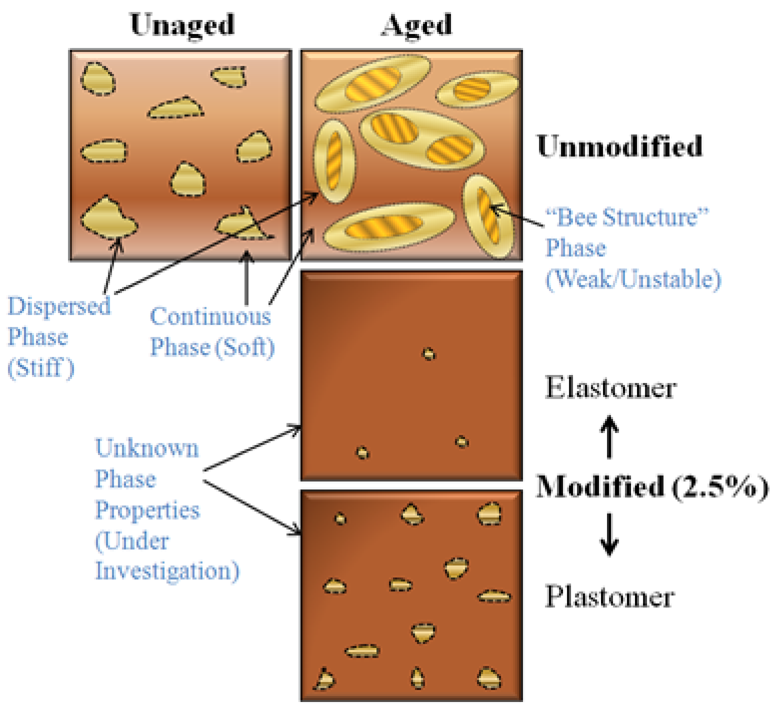


Figure F2d.5. Effects of modification processes on asphalt microstructure.

There appears to be consistency in the literature that multiple phases exist in the asphalt microstructure, and that aging typically results in an increased percentage of the "bee structure" phase. There are discrepancies, however, regarding whether or not the "bee structure" phase exists prior to aging or after polymer modification. This study evaluated the effects of discrete polymer modification, i.e. less than 5% by weight of asphalt, on the asphalt phases that are depicted in the literature [1, 5, and 12]. While the current findings show no evidence of the "bee structure" phase prior to aging or after polymer modification, which support the "susceptible phase interface" hypothesis, additional research will be necessary to resolve discrepancies with other research findings [5]. The investigated behavior will be further studied and characterized in terms of material properties, such as cohesive bond energy, which can be linked directly to fatigue fracture properties of HMA.

Task 2

The finite element results suggest that for if the tip shape is to be generalized as a sphere with a conical body, the Hertz indentation results are good approximation, especially at low levels of deformation. The SEM images of the actual tips used in the experimentation suggest that the tip profile is irregular and has no axis of symmetry. Due to this irregularity the researcher has to make a generalization about the tip shape for numerical analysis purposes. The indentation depth is highly dependent on the tip shape, and therefore must always be considered when analyzing AFM results. Without precise knowledge of the tip shape the data may be misinterpreted. The viscoelastic solutions provided in the literature appear to be adequate in analyzing creep behavior of linear viscoelastic materials, in this case asphalt. Sensitivity analysis showed there was very little disagreement between the analytical solution provided in Fischer-Cripps and the finite element model. The difference can be attributed to the finite element analysis considering large deformations. Surface forces will affect these results and are currently being developed as part of this finite element model.

Current Status/Next Steps

Task 1

Additional testing of PG 64-22 binder with 2.5% SBS (elastomer) and PG 64-22 with 2.5% 7686 (plastomer) is will be performed as needed to validate the results presented in this report. Furthermore, the second step required to test the "susceptible phase interface" hypothesis is currently being evaluated and involves measuring the surface energy of asphalt using AFM. As highlighted in this report, asphalt microstructure undergoes significant changes due to natural and synthetic modification processes. Furthermore, a decrease in asphalt cohesive bond energy with aging typically results in a reduced amount of work required (due to load or temperature) to propogate a crack in asphalt. These microstructural changes and characteristics are the basis for exploring parameters related to bond energy at the micro and nano scales. For instance, if a particular micro phase can be identified as having lower bond energy, then researchers can use this information to improve prediction models and enhance the properties of asphalt via existing and new synthetic modification processes. It will essentially provide a major step towards linking micro and nano properties of asphalt to the in-field performance of HMA. The key difference in previous methods [11-12] and the proposed protocol to measure surface energy is that AFM will be used to measure surface energies of individual phases as opposed to random or grid-based surface energy measurements of the binder.

The next step following the evaluation of the "susceptible phase interface" hypothesis is the SARA [**S**aturates, napthene **A**romatics, Polar Aromatics (**R**esins), and **A**sphaltenes] analyses. SARA analyses will be performed using AFM to assess the impact of the different molecular asphalt components on the microstructure and microrheology of asphalt. The SARA analyses serves to validate and expand on previous results presented for this work element as well as previous research performed by Pauli et al. [13]. The SARA samples have been prepared and will be tested using AFM beginning in late May/early June 2012.

Task 2

The next step in the finite element framework will include developing and finalizing the incorporation of surface van der Waals forces into the model. The effect of these surface forces will then be quantified and will be compared to the current model, which does not contain surface effects. Permanent deformation will be considered using a plasticity material model. The extent of plastic deformation will be analyzed in as a function of the forces applied during the indentation tests undertaken in this work. The effect of time dependent behavior in addition to permanent deformation or plasticity will then be examined. Through this a more accurate understanding of asphalt binder material behavior will be obtained. Furthermore, the binder will be modeled as a composite using the data obtained during the experimental phase of this work, and will be examined through the techniques mentioned above.

Issues Identified During the Previous Year and Their Implications on Deliverables

The AFM scanner and head electronics box (HEB) are currently being evaluated for repair by the manufacturer, which has resulted in a slight interruption in testing; however, the delay is not expected to impact the scheduled deliverables for Year Six.

Cited References

[1] Allen, R. G., Little, D. N., and Bhasin, A. (In Press). "Structural Characterization of Micromechanical Properties in Asphalt using Atomic Force Microscopy." *J. Mat. Civ. Eng.*

[2] Allen, R. G., Little, D. N., and Bhasin, A. (Under Review). "Identification of Composite Relaxation Modulus of Asphalt Binder using AFM Nanoindentation." *J. Mat. Civ. Eng.*

[3] Kringos N., Schmets A., Pauli T., and Scarpas T. (2009). "A Finite Element Based Chemo-Mechanical Model to Simulate Healing of Bitumen." *Proceeding of the International Workshop on Chemo-mechanics of Bituminous Materials*, Delft, Netherlands.

[4] Bhasin, A., Howson, J., Masad, E., and Little, D. N. (2007). "Effect of Modification Processes on
Bond Energy of Asphalt Binders." *J. Transp. Research Board,* 1998(04), 29-37.

[5] Wu, S., Pang, L., Mo, L., Chen, Y., and Zhu, G. (2009). "Influence of Aging on the Evolution of Structure, Morphology and Rheology of Base and SBS Modified Bitumen." Construction and Building Materials, 23 1005-1010.

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

[7] Sneddon IN (1965). "Relation between load and penetration in axisymmetric Boussinesq problem for punch of arbitrary profile." Int J Eng Sci, 3:47–57.

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

[9] A. C. Fischer-Cripps (2004). "A simple phenomenological approach to nanoindentation creep," Materials Science and Engineering A, 385, pp. 74-82.

[10] Ruan, Y., Davidson, R. R., and Glover, C. J. (2003). "Oxidation and Viscosity Hardening of Polymer-Modified Asphalts." Energy & Fuels, 17 991-998.

[11] Little, D. N., and Bhasin, A. (2006). "Using Surface Energy Measurements to Select Materials for Asphalt Pavement." Rep. No. NCHRP Project 9-37, Transp. Research Board of the National Academies, Washington, D.C.

[12] Pauli, A. T., Grimes, W., Huang, S. C., and Robertson, R. E. (2003). "Surface Energy Studies of SHRP Asphalts by AFM." *Petrolfeum Chemistry Division Preprints,* 48(1), 14-18.

[13] Pauli A. T., Grimes R.W., Beemer A., Miller J. J., Beiswenger J. D., and Branthaver J. F. (2009). "A Finite Element Based Chemo-Mechanical Model to Simulate Healing of Bitumen." *Proceeding of the International Workshop on Chemo-mechanics of Bituminous Materials*, Delft, Netherlands.

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

Work Done This Quarter

The draft final for report "M", which also includes findings from work elements F1d-6 and F2a was submitted in 508 format in the previous quarter. This quarter a document containing captions for figures to allow for interpretation by visually impaired was prepared and submitted.

In this quarter the ruggedness testing of the Linear Amplitude Sweep (LAS) test, as requested in the 21 month extension, continued. The research team attended the binder ETG and presented an update on the ruggedness testing and on the understanding of failure mechanism.

Significant Results

Ruggedness testing is performed to evaluate the sensitivity of results to various test parameters. The experimental factors considered in ruggedness testing of the LAS test are as follows:

- *A.* Test Temperature (T-0.1°C versus T+0.1°C)
- *B.* Sample Placement Method (Pellet from silicon mold versus pouring hot binder directly onto plate)
- *C.* Number of frequencies used in frequency sweep (8 versus 12)
- *D.* Range of frequencies used in frequency sweep (0.1 to 10 Hz versus 1 to 30 Hz)
- *E.* Strain during frequency sweep (0.05% versus 0.15%)
- *F.* Strain sequence during amplitude sweep (0.1%, 0.8%, 1.8%, 2.8%, 3.8%...29.8% versus 0.3%, 1.2%, 2.2%, 3.2%...30.2%)
- *G.* Number of loading cycles per strain step (80 versus 120)

Each factor will be considered at two levels (i.e., designated as +1 and -1). Assignment of levels is shown in table F2e.1. Four material types will be tested, two types of binders (unmodified, modified) at two aging levels (RTFO, PAV).

Table F2e.1. Level assignments.

Variable	-1	1
A	T-0.1°C	T+0.1°C
B	Pellet	Pouring
C	8	12
D	0.1 to 10 Hz	1 to 30 Hz
E	0.05%	0.15%
F	0.1%, 0.8%, 1.8%...	0.3%, 1.2%, 2.2%, …
G	80	120

Testing of the unmodified, PAV aged asphalt binder has been completed. Viscoelastic continuum damage analysis was conducted to determine the relationship between fatigue life and strain (i.e.,

$N_f = A\gamma^B$). Effects of factors on both *A* and *B* as response variables were evaluated. Results are presented in table F2e.2. Based on p-value results, sample placement method, frequency sweep strain, and strain sequence in amplitude sweep all have relatively significant effects on either or both the *A* and *B* parameters.

Table F2e.2. Ruggedness testing results.

	Determination Number									
Variable	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Pvalue - A**	**Pvalue -B**
Test Temperature (24.9 vs. 25.1)	-1	-1	-1	-1	1	1	1	1	0.489	0.889
Sample Placement (pellet vs. pouring)	-1	-1	1	1	-1	-1	1	1	0.028	0.001
No. of Frequencies in Frequency Sweep (8 vs. 12)	1	-1	1	-1	1	-1	1	-1	0.344	0.064
Range of Frequencies in Frequency Sweep (0.1 to 10 Hzvs. 1 to 30 Hz)	1	1	-1	-1	-1	-1	1	1	0.000	0.000
Frequency Sweep Strain (0.05% vs. 0.15%)	-1	1	-1	1	1	-1	1	-1	0.000	0.039
Strain Sequence (0.1%, 0.8%, 1.8%... Vs. 0.2%, 1.2%...)	1	-1	-1	1	1	-1	-1	1	0.000	0.156
No. of Loading Cycles in each Strain Step (80 vs. 120)	1	-1	-1	1	-1	1	1	-1	0.454	0.846

Work Planned Next Quarter

In the next quarter the team will focus on addressing all possible comments from reviewers, as well as implementing suggested revisions to the submitted report "M" Revise final report. As requested by the binder ETG, the ruggedness testing will be expanded to include two more DSRs at two other laboratories. Materials will be prepared and send to the volunteered labs.

CATEGORY F3: MODELING

Work Element F3a: Asphalt Microstructural Model

Work Done This Quarter

The overall research effort is approximated to be 75% complete. Efforts remaining entail incorporating results from molecular dynamics studies, property of interest including the complex modulus $|G^*|$ and phase angle δ as a function of frequency and temperature, into phase field simulations. Furthermore, coupling of phase field events are presently being incorporated into finite element simulations to show how phase separation properties of the binder influence mechanical properties of the binder in the mastic.

Subtask F3a-1. ab initio Theories, Molecular Mechanics/Dynamics and Density Functional Theory Simulations of Asphalt Molecular Structure Interactions (URI)

Work Done This Quarter

Work continued during the quarter on developing and implementing methods to extract important mechanical property information from molecular simulation results. The property of interest is the complex modulus |G*| and phase angle δ as a function of frequency and temperature, along with their equivalent representation as storage and loss moduli G', G". The basis for this calculation is the time correlation functions for the components of the instantaneous stress tensor, i.e. $\langle \sigma(0)\sigma(t) \rangle$. The equations that relate this correlation function to G* were provided in the December 2011 progress report.

An initial version of the code that implements an inverse Fourier transform for calculating $G'(\omega)$ and $G''(\omega)$ from the stress time correlation function was written during the quarter by the new PhD student on the project. Inverse transformation is required for this time-to-frequency conversion because of the mathematics of dynamic shear rheology for viscoelastic systems (Ferry 1980). Testing during the quarter was performed using molecular simulation results that were calculated in 2011 for the revised AAA-1 model asphalt system at 400, 443, and 533 K. Temperatures well above typical ambient conditions have been chosen because the faster relaxations at high temperatures enable convergence of the statistical mechanics calculations over the nanosecond time scales that can be reached in the simulation. The applicability of time-temperature superposition to the results will be checked during the next quarter.

Some additional progress was made on manuscripts that describe molecular dynamics simulations of a next-generation model asphalt that is representative of SHRP AAA-1.

Subtask F3a-2. Develop algorithms and methods for directly linking molecular simulation outputs and phase field inputs (URI, VT)

Work Done This Quarter

During the past quarter, a phase field approach for the residual thermal stress of asphalt binder based on a simplified asphalt chemistry model has been developed. The Marcusson model is employed to represent the asphalt compositions. This model simplifies the asphalt binder to two components, namely, resin and oil. The phase separation is modeled by the conserved Cahn-Hilliard dynamics, which is coupled with the thermal loading module in the commercial software COMSOL. At the current stage we only consider the one-way coupling, i.e., the phase separation effects on the thermal stress through the elastic modulus and the thermal expansion coefficient which are both phase dependent. In order to capture the deforming interface, a self-adaptive mesh is employed for the Finite Element calculations. The numerical results show that the phase separation has a significant effect on the residual thermal stress and results in a non-uniform stress distribution in the system. Besides, a large stress is observed near microstructure boundaries, which is in accordance with the previous results in literature.

Establishment of the coupled phase-field model:
The Marcusson model is used to identify the components of asphalt binder. In our calculation, it is simplified to two components: resin and oil. It is believed that the two components play the major role in the asphalt mechanical properties. An interpolation function is adopted to obtain elastic modulus at the interface:

$$C_{ijkl}(\phi) = C^0_{ijkl} + h(\phi)(C^1_{ijkl} - C^0_{ijkl}) \tag{F3a-2.1}$$

where $h(\phi) = -\frac{1}{4}\phi^3 + \frac{3}{4}\phi + \frac{1}{2}$ so as to satisfy $h(-1) = 0$, $h(1) = 1$, and $h'(-1) = h'(1) = 0$. Here the phase-field variable ϕ varies from 0 to 1 across the diffuse interface. For now, due to lack of data, we use equal thermal expansion coefficients in the two components.

Numerical simulation of thermal stress:
Using the method that we developed, we studied the residual thermal stress of asphalt binder under cooling. The major conclusions from the numerical simulations are as follows. Due to the phase separation, the elastic modulus is not uniform. As a result, the stress distribution becomes non-uniform. Especially, stresses in some regions even exhibit compressive instead of tensile stress. Large stress occurs at the interface between the resin phase and the oil phase. It appears and moves with the interface, which is shown in figure F3a-2.1. Due to the diffuse nature of the interface, the stress concentration factor is lower than that at a sharp interface. Shear stress is observed only on the interface. The oil phase, in which the elastic modulus is significantly lower than the other phase, has almost no stress.

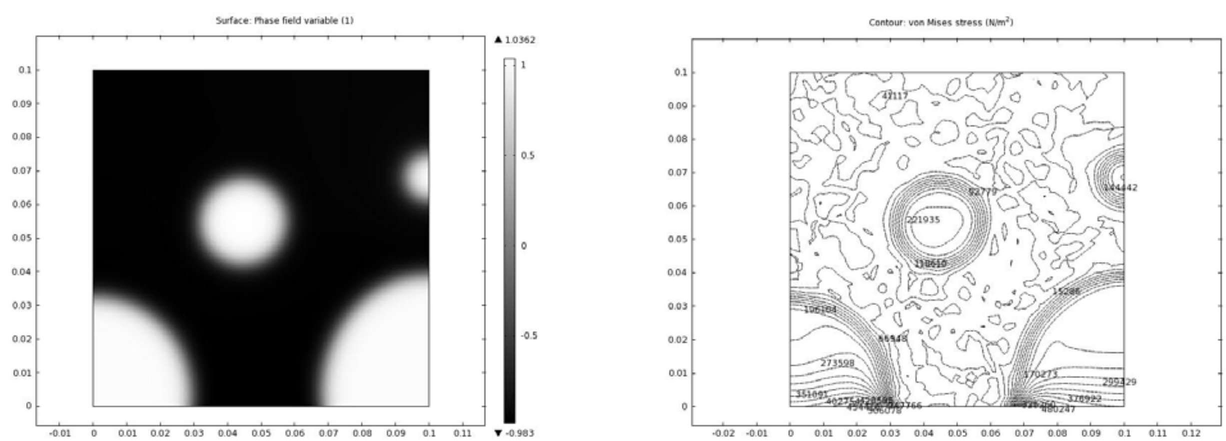


Figure F3a-2.1 (a) Phase separation at t=0.5s (b) von Mises stress distribution at t=0.5s

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

Molecular dynamics simulations were continued for new models of SHRP asphalts AAK-1 and AAM-1. The initial simulations are at a high-temperature (473 K) to enable fast relaxations.

Subtask F3a-4. Simulate changes in asphalt dynamics after inducing representations of chemical and/or physical changes to a model asphalt (URI)
Subtask F3a-5. Molecular mechanics simulations of asphalt-aggregate interfaces (VT)
Subtask F3a-6. Modeling of fatigue behavior at atomic scale (VT)
Subtask F3a-7. Modeling of moisture damage (VT)
Subtask F3a-8. ab initio Calculations of Asphalt Molecular Structures and Correlation to Experimental Physico-Chemical Properties of SHRP Asphalts (WRI-TUDelft)

Nothing to report.

Significant Problems, Issues and Potential Impact on Progress

The overall effort of this work element has remained slightly behind schedule given the change in personal originally proposed to conduct specific projects, specifically, NIST being a major contributor to the original work plan. Virginia Tech has assumed the technical research work plan originally proposed by NIST, and has done a very good job of catching up the overall efforts.

Work Planned Next Quarter

Subtask F3a-1

Testing will be completed for computer software that converts stress fluctuation data from molecular simulations into predictions of complex modulus. Results for different model asphalt systems will be compared with experimental data for SHRP and ARC asphalt binders.

Manuscripts that describe the equilibrium and dynamics properties for the AAA-1 system will be completed and prepared for publication. Molecular simulations will be continued to additional temperatures for the model AAK-1 and AAM-1 bitumen systems.

Data analysis and manuscripts will be completed on a spontaneous wax formation event in a molecular simulation. This work was delayed from the prior quarter in order to focus efforts on conducting and analyzing the AAA-1 molecular simulations.

Subtask F3a-2

Currently, we still do not have experimental data to verify our numerical results. Our next work is to carry out experiments on asphalt binder during a cooling process. Meanwhile, we will use the phase-field method to investigate crack propagation

Thermal stress:
Currently the numerical results show that there exists abnormal stress distribution along the interface. But the high stress concentration needs to be verified by experiments. Asphalt binders will first be heated and then quickly cooled. The corresponding thermal stress will be measured and compared with numerical simulations.

Cracking:
Different from phase separation, the crack propagation requires a non-conserved phase-field model, i.e., the Allen-Cahn model. The theoretical work on the phase-field modeling of cracks is already under way. Once the governing equations are determined, we will use COMSOL to simulate cracking under thermal stress and other types of external loading. The results will be compared with available experimental data

Awards

Michael L. Greenfield of URI received the 2011 Global Road Achievement Award in Research from the International Road Federation in honor of his earlier work simulating asphalt on the molecular level. His nomination was co-sponsored by the Rhode Island Department of Transportation and the URI Transportation Center. A video that describes this research for a general audience is available at http://www.youtube.com/watch?v=DtQyL2iz4t0

Presentations and Publications

A detailed description of the use of molecular simulations for describing model bitumen systems on the molecular level was presented by Prof Michael Greenfield at the spring 2012 American Chemical Society Meeting. This invited talk was part of the 9th International Symposium on Heavy Oil Upgrading, Production, and Characterization that was organized within the Petroleum Chemistry (PETR) division by Dr. John Schabron of WRI. The target audience was researchers on heavy oils who were potentially unaware of the detailed asphalt/bitumen research being conducted in the ARC.

Greenfield, M. L. 2011, Composition Models for Molecular Simulation of Asphalts (invited), American Chemical Society Spring Meeting, PETR 108, San Diego, CA, March 27, 2012.

Troy Pauli will present work entitles “Material Property Testing of Asphalt Binders Related to Thermal Cracking in a Comparative Site Pavement Performance Study” authored by A.T. Pauli, M.J. Farrar and P.M. Harnsberger, at the the 7th International RILEM Conference on Cracking in Pavements, 20-22 June 2012, Delft, The Netherlands. The work is in support of fatigue-healing related to wax composition in asphalts, subtask ***F3a-8***.

References

Ferry, J. D., 1980, *Viscoelastic Properties of Polymers, 3rd ed.*, New York: Wiley.

Work Element F3b: Micromechanics Model

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

Work Done This Quarter

In the last quarter, we have worked on the final report. A draft final report completed was submitted to the Texas A&M University for review.

Significant Problems, Issues and Potential Impact on Progress

None.

Work Planned Next Quarter

In the next quarter we will update the final report based on feedback/comments from the Texas A&M University.

Lattice Micromechanical Model (NCSU)

Work Done This Quarter

Lattice Micromechanical Model

The algorithm developed for virtually generating air voids in existing aggregate structures shows promise when applied to images captured from real specimens. Part of the effort in this quarter focused on improving the performance of this algorithm for virtually-generated microstructures, but it was not successful. Including realistic aggregate particle silhouettes instead of random octagons is one of the modifications that showed visual improvement in the aggregate structure, but it led to no improvement in the air void structure. Work is ongoing to improve the current algorithm in order to obtain realistic air void structures.

In parallel, significant effort was spent this quarter on verifying the lattice-based scale-up of the modulus using experimental data, as explained below.

The multiscale lattice framework is intended to bridge the gap between the component material properties and the mix performance. However, significant size discrepancies are evident within the aggregate particles, and thus, multiple scale-up steps are required. In this research, the range of aggregate particles is divided into three scales: mastic, FAM and mix. Therefore, the binder properties, along with aggregates smaller than the #200 sieve, are used in the lowest scale to simulate the behavior of the mastic, i.e. the complex modulus (E^*), which can be converted to the dynamic shear modulus (G^*).The resulting mastic G^* is then used to find the G^* associated with FAM and ultimately the mix G^*. Before using this multiscale framework on a routine basis, it is desirable to isolate the effect of each scale-up step and compare it with the real behavior of the material at the corresponding scale. To this end, the lattice simulation results for the S9.5B mix are compared with the G^* values measured by Underwood [1]. This comparison can be found in **Error! Reference source not found.**, which clearly indicates that lattice modeling under-predicts the modulus scale-up, which is most noticeable for the mastic to FAM step.

Continuum Damage to Fracture

Work Done This Quarter

From previous analyses, it was concluded that the drop of phase angle in middle-failure specimens was related to the large distortion in stress shapes due to fracture. It was also observed that the phase angle could usually drop to zero for middle failure. In this quarter, the drop of phase angle for end-failure specimens is investigated. For end-failure tests, the strain gauge measures the region outside of localization and fracture region. After fracture, the material outside localization region is experiencing relaxation in the control-crosshead tests. Since the on-specimen strain is diminishing, the material is actually coming back to the linear viscoelastic state. In this case, the time dependency (phase angle) is returning to the initial value, not zero (figure 3b-1.1). This is also confirmed by using the linear viscoelastic property and convolution integral to predict strain response given stress history. The conclusion is that, not surprisingly, linear viscoelasticity applies to the whole material for the entire history, except for the region where localization happens. With this confirmation, the focus has been shifted to analyze the localization region in an appropriate way to shed some light on phase angle drop. Since the constitutive behavior of the region away from localization is well known, the displacement associated with the localization region is calculated from the LVDT measurements of middle-failure specimens. This deformation can in turn be used develop appropriate models for the localization region – this is currently under investigation.

In parallel, the development of comprehensive failure criterion is being explored with the help of a larger database.

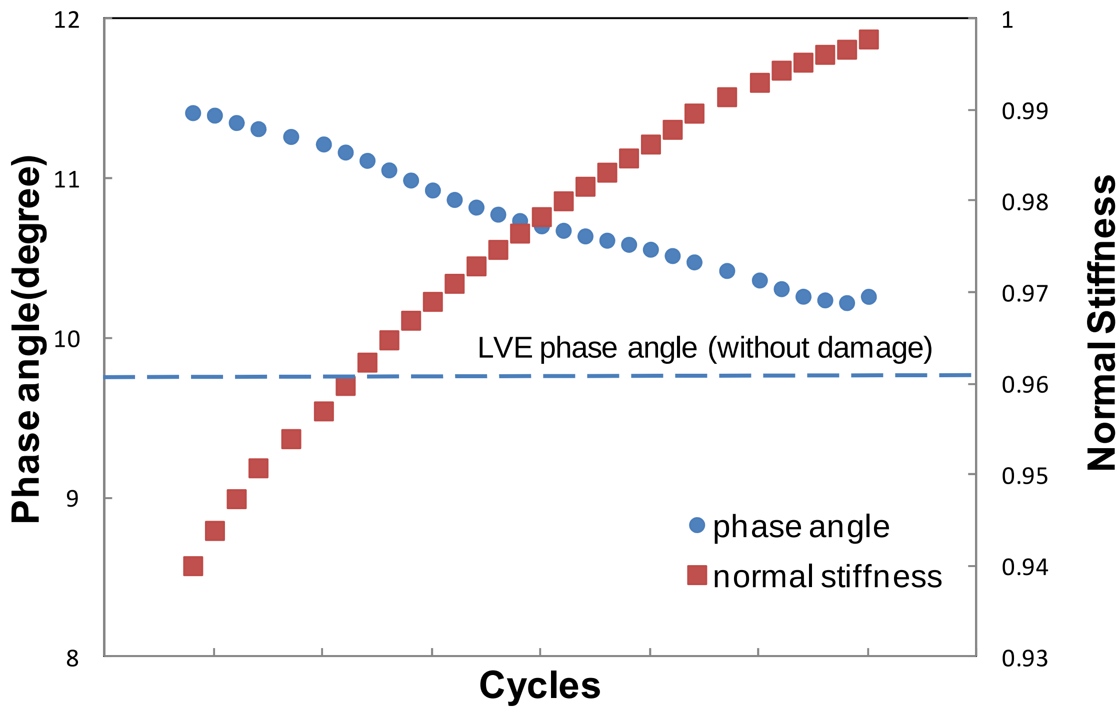


Figure F3b-1.1. Post-localization performance of end failure specimen.

Significant Results

Lattice Micromechanical Model

None

Continuum Damage to Fracture

None

Significant Problems, Issues and Potential Impact on Progress

None

Work Planned Next Quarter

Lattice Micromechanical Model

- Calibration of the air void fabrication algorithm on virtually generated microstructure.
- Evaluating the fatigue performance of the specimen with virtually fabricated air voids and comparing with experimental results.

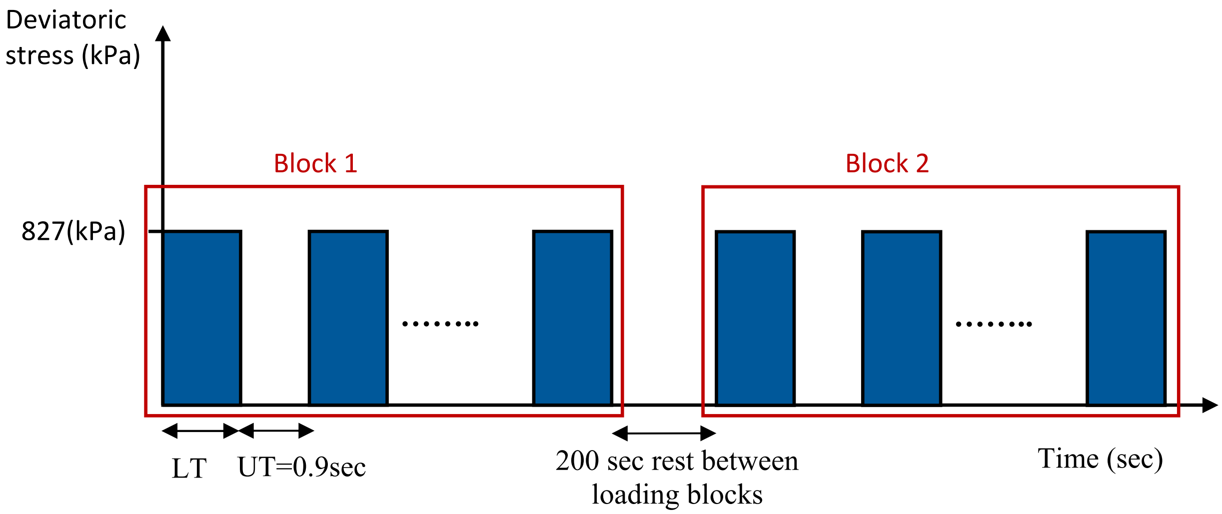
Continuum Damage to Fracture

- Further understand post-localization deformation
- Continue the exploration of fracture criterion of asphalt concrete

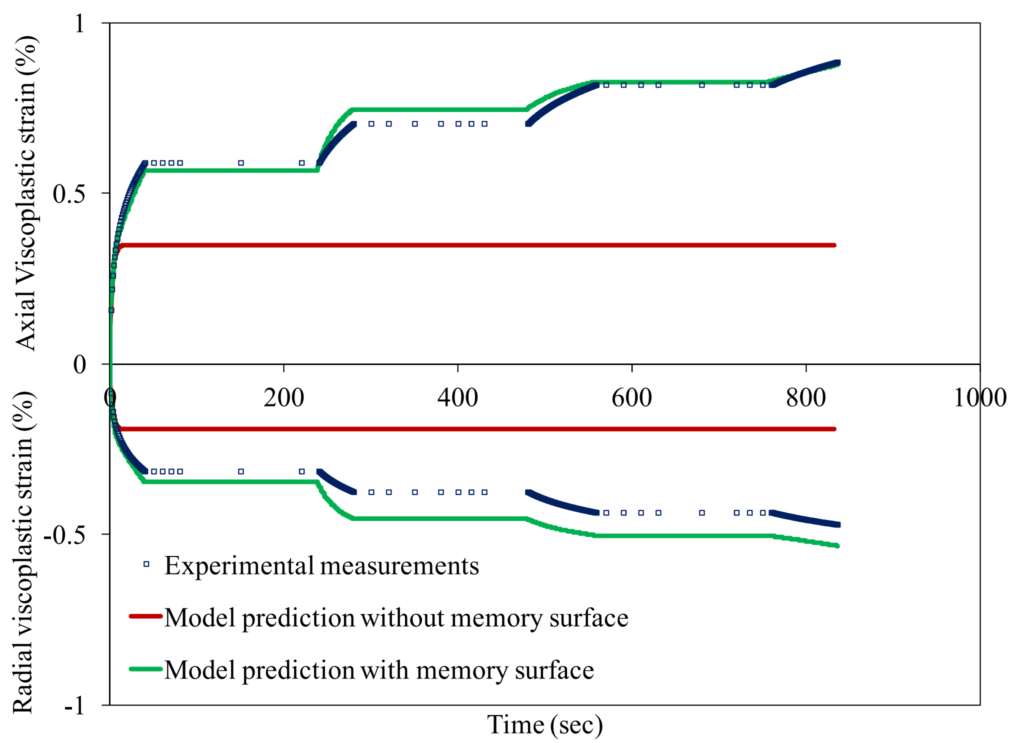
Work Element F3c: Development of Unified Continuum Model (TAMU)

Work Done This Quarter

See M4c for details on the progress in the development of the continuum-based moisture-induced damage mode. Also see F1d-8 on the development of the continuum-based micro-damage healing model. We have completed the calibration and validation of the nonlinear viscoelastic and viscoplastic constitutive models in PANDA using the ALF laboratory data based on compression and tension data under different temperatures. The emphasis is placed on development of a hardening-relaxation viscoplastic model that significantly enhances the prediction of rutting in asphalt pavements. The proposed hardening-relaxation viscoplastic model is validated against ALF experimental data in compression. It is shown that the model accurately captures the permanent deformation response of asphalt concrete during different loading conditions. This study has led to the development of a three-dimensional multi-axial thermo-viscoplastic hardening/hardening-relaxation model based on a new novel concept which is the "hardening-relaxation memory surface" (Darabi et al. 2012; Huang et al. 2011). Figure F3c.1 shows an example of the validation of the memory surface concept against the ALF repeated creep-recovery test in compression.



(a)



(b)

Figure F3c.1. (a) Schematic representation of the stress input for the constant loading time test (CLT); (b) Experimental measurements and model prediction with and without the hardening-relaxation memory surface for CLT at 55°C in compression when the loading time is 0.1 sec, Darabi et al. (2012).

Furthermore, we have analyzed the ALF experimental data in tension and validated the fatigue damage model against cyclic displacement controlled and cyclic stress controlled tests at different displacement/stress amplitudes.

Work has been continued on applying realistic loading conditions from single- and dual-tires such that normal and shear contact pressures are taken into consideration. This is crucial for the accurate prediction of rutting and fatigue damage in asphalt pavements. Dr. Imad Al-Qadi from University of Illinois-Urban is helping in this task through predicting the contact pressures from different types of tires at different temperatures. Those predictions will be used as inputs into the realistic rutting and fatigue damage simulations using PANDA. The most conventional wide-base tire (425/65R22.5) is adopted for the 3-D rutting simulations under single tire, and 11R22.5 sized tire is used for the simulation under dual tire. Finally, a parametric study is being conducted to see the effect of viscoplastic hardening/softening model on the rutting predictions under different tire loading conditions. Wheel realistic loading conditions due to normal and shear contact pressure are taken into consideration and their effect is investigated thoroughly.

Significant Results

We have developed a model to account for the viscoplastic hardening-relaxation behavior of asphalt mixtures under repeated loading. This model was proven to be essential for predicting accumulation of permanent deformation and rutting in asphalt pavements. Moreover, it is found that the longitudinal and transverse contact shear pressures are as important as the normal contact pressures and should be considered in the rutting and fatigue damage simulations.

Significant Problems, Issues and Potential Impact on Progress

None

Work Planned Next Quarter

We will work on the simulations of the structural response of the ALF pavements. In the next quarter, the focus will be in creating finite element-based structural models for pavements that can be used in conducting the rutting and fatigue damage simulations through using PANDA.

Cited References

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

Huang, C.W., Darabi, M.K., Masad, E.A., Abu Al-Rub, R.K., Little, D.N., "Development, Characterization and Validation of the Nonlinear Viscoelastic-Viscoplastic and Softening Model of Asphalt Mixtures," 2011 (In preparation).

Continuum-based Model for Aging

Work Done This Quarter

The data that has been obtained from the ARC testing using the dynamic modulus test at various aging times (0, 3, and 6 months) has been analyzed in order to calibrate the developed aging evolution law. This test has been done at five different temperatures varying from -10 to 54 ˚C and at different frequencies. Also, specimens were prepared to have 4, 7, and 10 percent air voids in order to investigate the effects of air voids on aged behavior of asphalt mixes. A systematic procedure has been developed using Excel spreadsheet in order to obtain the linear viscoelastic parameters including the time-temperature shift factor and Prony series coefficients.

In order to construct the master curves, the principal of time-temperature superposition was utilized at a specific aging time. The data at various temperatures were shifted with respect to frequency until the curves merge into single smooth function. In this procedure, a sigmoidal-type function was used and time-temperature shift factors were extracted for the whole data set. Linear viscoelastic parameters (Prony coefficients) were then obtained based on the master curves created and using the Excel spreadsheet in a systematic way.

Currently, the linear viscoelastic parameters are being used for obtaining the nonlinear viscoelastic parameters and for decoupling the recoverable strain from the total strain response in a repeated creep-recovery test with various loadings at a high temperature. Then, based on the irrecoverable strain response, viscoplastic material parameters will be identified.

Significant Results

There are no significant results for this quarter.

Significant Problems, Issues and Potential Impact on Progress

None

Work Planned Next Quarter

The aging model as part of PANDA will be validated against the available experimental data from the ARC testing. The data from North Carolina State University are not available yet. As soon the data are received, the calibration and validation of the PANDA's oxidative aging model will be accomplished.

TABLE OF DECISION POINTS AND DELIVERABLES FOR FATIGUE

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
F1a: Cohesive and Adhesive Properties (TAMU)	Draft Report	Draft Report on Cohesive and Adhesive Properties, 508 compliant	11/11	N/A	N/A
	Final Report		6/30/12		
F1b-1: Nonlinear viscoelastic response under cyclic loading (TAMU)	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	3/31/13	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	6/30/13	
F1b-2: Viscoelastic properties under monotonic loading (TAMU)	Draft Report	Documentation of PANDA Models and Validation Including the Method for Analysis of Viscoelastic Properties	11/11	12/31/12	N/A
	Final Report (M5, M4c, F1b-1, F1c, F1d-8, F3c, and V3c)		3/12	3/31/13	N/A
F1c: Aging (Unified Continuum Model for Aging) (TAMU)	Draft Report	Draft Report on the aging modeling	03/12	12/31/12	N/A
	Final Report (M5, M4c, F1b-1, F1c, F1d-8, F3c, and V3c)		3/31/12	3/31/13	Validation of the aging model based on the ARC testing.
F1c-2. Experimental Design (TAMU)	Report	Experimental Design Report	1/09	Complete	N/A

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 (TAMU)	Models and Algorithm	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	06/30/11	3/31/13	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		
F1d-6: Evaluate relationship between healing and endurance limit of asphalt binders (UWM)	Draft Report	Report summarizing major findings for evaluation of healing of binders by means of cyclic testing with rest periods	12/11	Complete	First draft submitted to FHWA for review. (report “M”)
	Final Report	Final report in 508 format on healing characterization of binders and its relation to fatigue performance	1/12	6/12	Draft report “M” has been submitted in 508 format with all accompanying files. Final report is pending FHWA peer review feedback.
F1d-8: Coordinate Form of Healing Parameter with Micromechanics and Continuum Damage Models (TAMU)	Draft Report (M5, M4c, F1b-1, F1c, F1d-8, F3c, and V3c)	Draft Report on the self-healing modeling	12/11	12/31/12	Validation based on ARC testing.
	Final Report (M5, M4c, F1b-1, F1c, F1d-8, F3c, and V3c)	Report on the self-healing modeling	3/12	3/31/13	Validation based on ARC testing.

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
F2a-5: Analyze data and propose mechanisms (UWM)	Draft Report	Report summarizing major findings for the effect of modification on asphalt binder performance at high and intermediate temperatures.	10/11	Complete	Draft report "M") has been submitted in 508 format with all accompanying files. Final report is pending FHWA peer review feedback.
	Final Report	Report in 508 format summarizing major findings for the effect of modification on asphalt binder performance at high and intermediate temperatures	1/12	6/12	
F2d: Structural Characterization of Micromechanical Properties in Bitumen using Atomic Force Microscopy (TAMU)	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	Complete	The test protocol was successfully used to measure the micro rheology of aged and unaged asphalt binders. The findings and method are current being reviewed as a journal article.
	Evaluation of Impact of Aging and Moisture Conditioning	Complete	12/15/10	Complete	N/A
	Final Research Report		2/28/12	N/A	N/A
F2e-2: Selection of Testing Protocols (UWM)	Draft Report	Report on the development and implementation of the Binder Yield Energy (BYET) test and the Linear Amplitude Sweep Test (LAS)	4/09	Complete	First draft submitted to FHWA for review. (report "M")
	Final Report		7/09		
	Draft Report		4/10		
	Final Report		7/10		
F2e-4: Verification of Surrogate Fatigue Test (UWM)	Draft Report	Correspond to reports in F2e-2	10/10	Complete	
	Final Report		1/11		

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
F2e-6: Recommendations for Use in Unified Fatigue Damage Model (UWM)	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	11/11	10/11	Draft report "M") has been submitted in 508 format with all accompanying files. Final report is pending FHWA peer review feedback.
	Final Report	Final report in 508 format on the development and implementation of the Linear Amplitude Sweep (LAS) Test. It includes the latest AASHTO standard.	1/12	6/12	
F3b-1: Micromechanics Model Development (Fatigue) (UNL)	Models and Algorithm	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. Multiscale modeling of asphaltic mixtures and pavements: modeling methodology, constitutive theory, and parametric analyses of the model.	3/31/11	Complete	Model to be included in final report.
	Draft report		06/30/11	12/31/11	This subtask needs more time for model validation and the final report.
	Final report		12/31/11	8/14/12	
F3c: Development of Unified Continuum Model (TAMU)	PANDA Workshop	Workshop on PANDA Models and Validation Results	8/11	4/13	Waiting for complete validation of PANDA models.
	Draft Report	Documentation of PANDA Models and Validation	11/11	12/31/12	
	Final Report		3/12	3/31/13	
	UMAT Material	PANDA Implemented in Abaqus	3/12	3/31/13	
	PANDA standalone finite element software	Standalone two-dimensional and three-dimensional finite element software for PANDA	3/31/12	3/31/13	Creating the user friendly interface for PANDA

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													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**		P	P	P(2)		P(2)				P(2)		JP	
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				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													
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								**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	P(2)	P(4)		P(2),JP	
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		**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																	
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)

Work Done This Quarter

Three technical presentations were made at the Transportation Research Board (TRB) 91st Annual Meeting in January 2012, which were entitled “Selective Absorption of Asphalt Binder by Limestone Aggregates in Asphalt Mixtures,” “Dissipated and Recoverable Energy in Asphalt Mixtures Under Repeated Direct Tensile Loading,” and “Evaluation of Stiffness Gradient Transition of Field-Aged Asphalt Layers Using Direct Tension Test.”

Two technical papers were accepted for publication in the ASCE Journal of Materials in Civil Engineering, including “Characterization of Asphalt Mixtures Using Controlled-Strain Repeated Direct Tension Test” and “Complex Stiffness Gradient Estimation of Field-Aged Asphalt Concrete Layers Using the Direct Tension Test.” Another technical paper, entitled “Modeling Fatigue Crack Growth in Asphalt Mixtures Using Pseudo Strain Energy Balance,” was submitted for publication to the ASCE Journal of Materials in Civil Engineering.

In this quarter, additional laboratory experiments were performed on full mixtures, fine mixtures and field cores from asphalt pavements to evaluate their fatigue and healing properties.

1. **Laboratory Tests on Full Mixtures Using Material Testing System (MTS)**

In the previous quarters, an energy-based mechanistic approach has been developed to characterize the fatigue damage and healing of asphalt mixtures, which is distinct from common empirical or phenomenological methods. This mechanistic approach uses fundamental engineering material properties of asphalt mixtures that are measured from simple mechanical tests, and it models the crack growth and the healing process based on their causal relationships. Because of the mechanistic nature of this approach, it is believed that the approach can be applied to various types of asphalt mixtures and other materials. Demonstration of the applicability and rationality of this novel mechanistic approach was initiated this quarter. This approach has been employed to evaluate the fatigue resistance and healing ability of twenty different types of asphalt mixtures, which are detailed as follows.

Materials

The asphalt mixtures tested are laboratory-mixed-laboratory-compacted (LMLC) hot asphalt mixtures. There are four types of asphalt binders: the binder AAD and binder AAM from the Strategic Highway Research Program (SHRP) Materials Reference Library (MRL) (Jones 1993); the binder designated “NuStar” that is supplied by the NuStar Energy, Paulsboro, New Jersey; and the binder designated “Valero” that is supplied by the Valero Refining, Benicia, California. There are two types of aggregates: Texas limestone as mentioned in the previous sections and

Hanson limestone from New Braunfels, Texas. There are two levels of air void content: 4% and 7%., and three different laboratory aging periods: 0, 3, and 6 months. Combination of all these variables yields twenty types of asphalt mixtures, as shown in table E1a.1. In the first column of table E1a.1, for example, “M1” is one type of asphalt mixture using AAD and Texas limestone with 4% air voids and is aged for zero months. The mixture design, process of fabrication of cylindrical specimens, test machine, and the test set up are the same as those in the previous quarterly reports, which will not be repeated here.

Table E1a.1. Material information of tested asphalt mixtures.

Type of Asphalt Mixture	Design Variables			
	Asphalt Binder	Aggregate	Air Void Content	Aging Period
M1	AAD	Texas limestone	4%	0
M2				6
M3			7%	0
M4				6
M5	AAM		4%	0
M6				6
M7			7%	0
M8				6
M9	NuStar	Hanson limestone	4%	0
M10				3
M11				6
M12			7%	0
M13				3
M14				6
M15	Valero		4%	0
M16				3
M17				6
M18			7%	0
M19				3
M20				6

Experiments
The twenty different types of asphalt mixtures are subjected to a series of laboratory tests in order to characterize the fatigue and healing properties. The controlled-strain repeated direct tension (RDT) test performed by the Material Testing System (MTS) is used to obtain the fatigue properties and the creep and step-loading recovery (CSR) test is used to obtain the healing properties, as shown in table E1a.2. Detailed test configuration, test procedure, measured properties, and analysis method have already been presented in the previous quarterly reports. The test results are given in the following to verify the findings that were presented in the previous reports, and, additionally, to evaluate the change of the fatigue resistance and healing by changing the design variable of asphalt mixtures.

Table E1a.2. Testing procedure of laboratory experiments.

	Testing Procedure	Temperature	Asphalt Mixtures
Fatigue cracking	1. X-ray CT Test 2. Nondestructive controlled-strain RDT test 3. Destructive controlled-strain RDT test	20°C	M1, M2, M3, M4, M5, M6, M7, M8, M9, M10, M11, M12, M13, M14, M15, M16, M17, M18, M19, M20
Healing	1. Normal creep recovery test 2. Nondestructive CSR test at loading level 1 3. Nondestructive CSR test at loading level 2 4. Nondestructive CSR test at loading level 3 5. Destructive CSR test	20°C	M1, M2, M3, M4, M5, M6, M7, M8
	1. Normal creep recovery test 2. Nondestructive CSR test 3. Destructive CSR test	10°C	M9, M10, M11, M12, M13, M14, M15, M16, M17, M18, M19, M20
		20°C	

Variation of Material Properties in Controlled-Strain RDT Test

The first finding obtained from the controlled-strain RDT test is that the stress is always composed of a tensile stress portion and a compressive stress portion when the strain is controlled as a standard haversine shape. It is found that the tensile material properties which are measured in the tensile stress portion are different from the quasi-compressive material properties that are measured in the compressive stress portion in each loading cycle of the RDT test. This difference is due to the crack opening (crack growth) and crack closure (healing) in this loading cycle. Both of the material properties do not change in the nondestructive RDT tests, but change in the destructive RDT tests. These findings are verified for all asphalt mixtures, regardless of the type of asphalt binder, aggregate, air void content, and the aging period. As an example, the tensile and quasi-compressive complex moduli of the AAD mixtures are given in figures E1a.1 to E1a.4. In the legend of all the figures, the number “4%” or “7%” represents the air void content; the number “0”, “3”, or “6” represents the aging period. For example, “4%, 3” indicates that the air void content is 4% and the specimen is aged for 3 months.

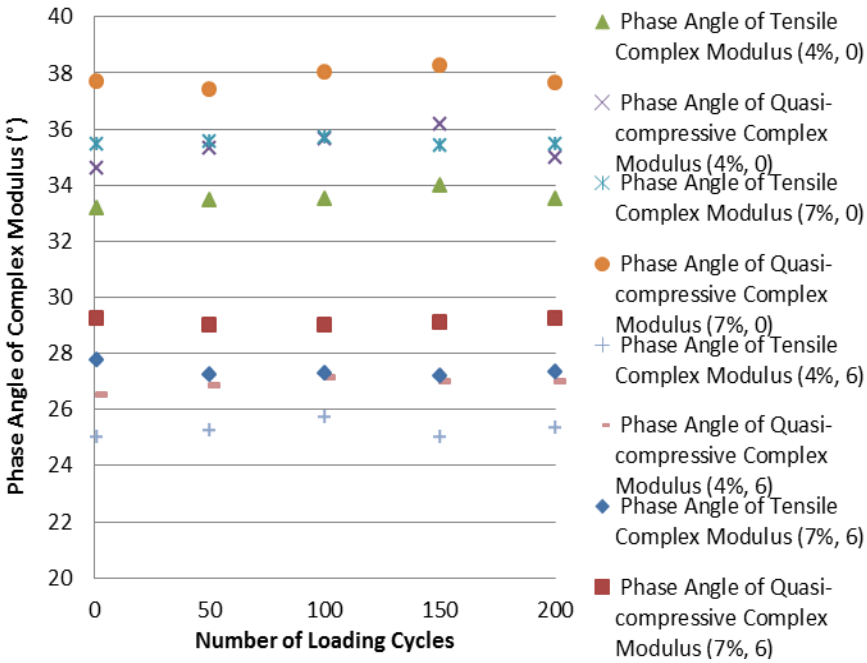


Figure E1a.1. Phase angle of complex modulus in nondestructive RDT test.

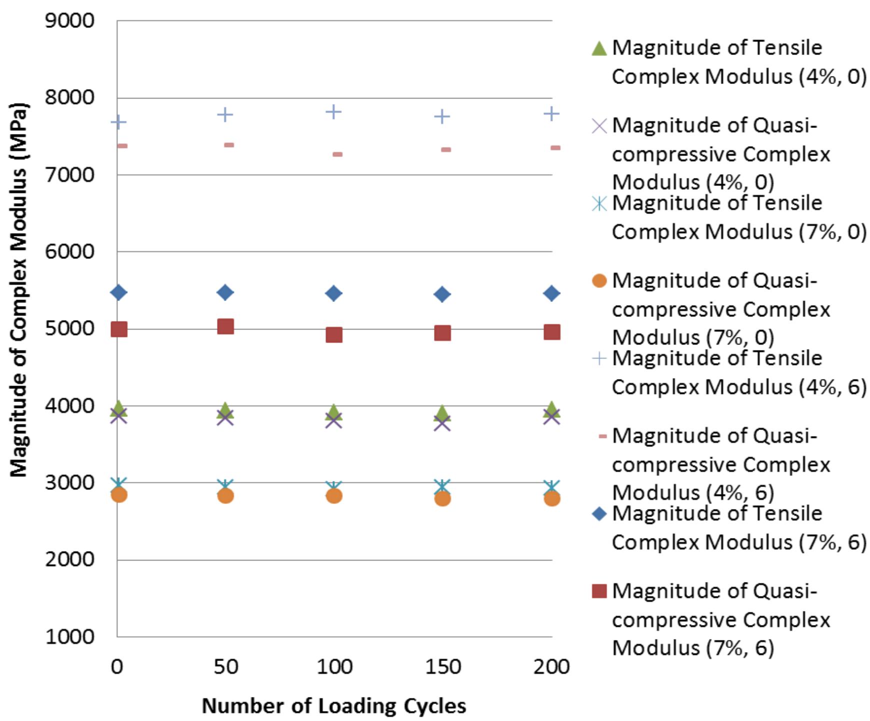


Figure E1a.2. Magnitude of complex modulus in nondestructive RDT test.

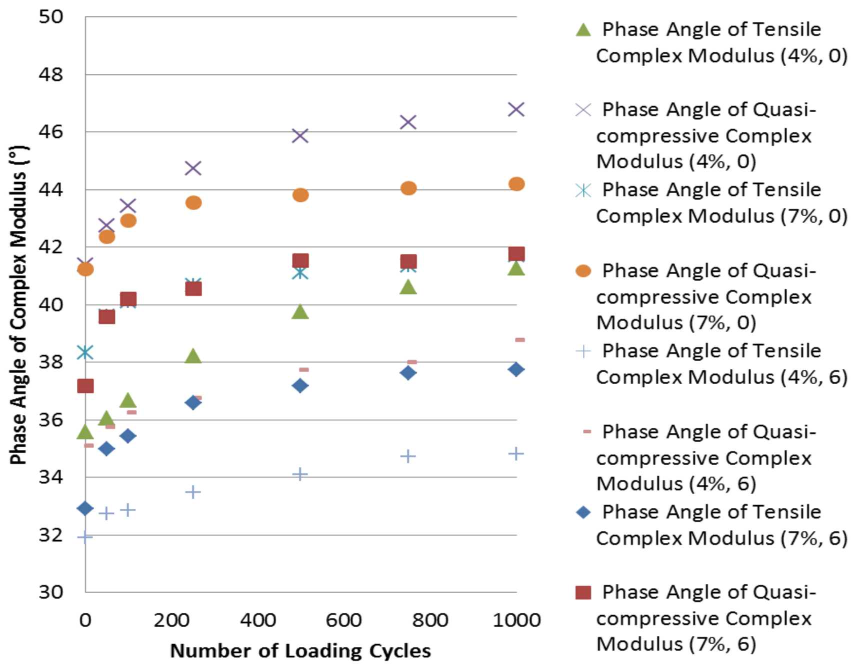


Figure E1a.3. Phase angle of complex modulus in destructive RDT test.

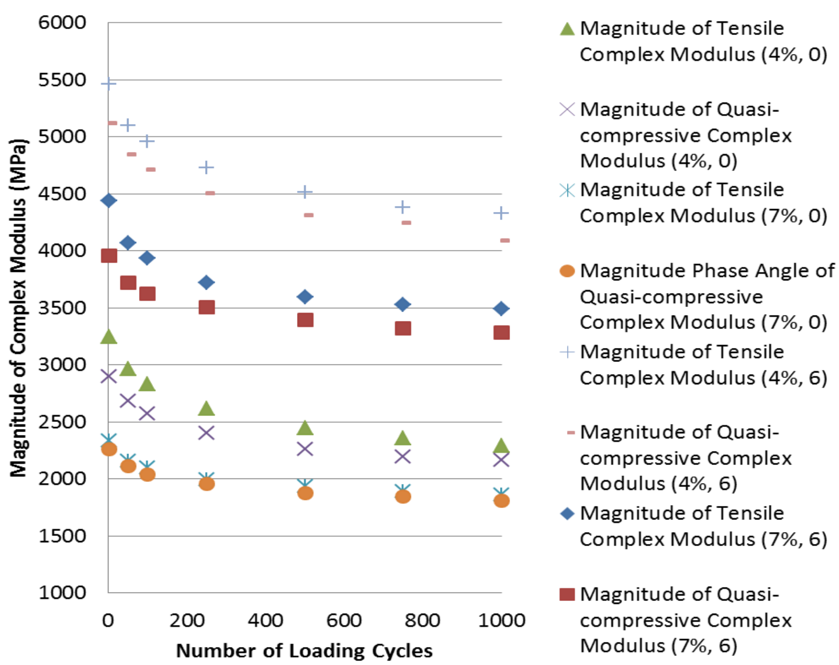


Figure E1a.4. Magnitude of complex modulus in destructive RDT test.

Average Air Void Size and Number of Air Voids

Another important contribution which is by applying the energy-based mechanistic approach to the test data of the controlled-strain RDT tests is the ability to more accurately determine the average air void size and number of air voids. The average air void size and number of air voids calculated using the energy-based mechanistic approach are compared to those measured by the X-ray Computed Tomography (X-ray CT) system. The calculated average air void size is smaller than that measured by the X-ray CT since the measurement with the X-ray CT is restricted by its own limitations, such as the image resolution and the threshold gray-scale intensity. This fact is also found for all the twenty types of asphalt mixtures. Comparison of the calculated and measured values is presented in figures E1a.5 and E1a.6.

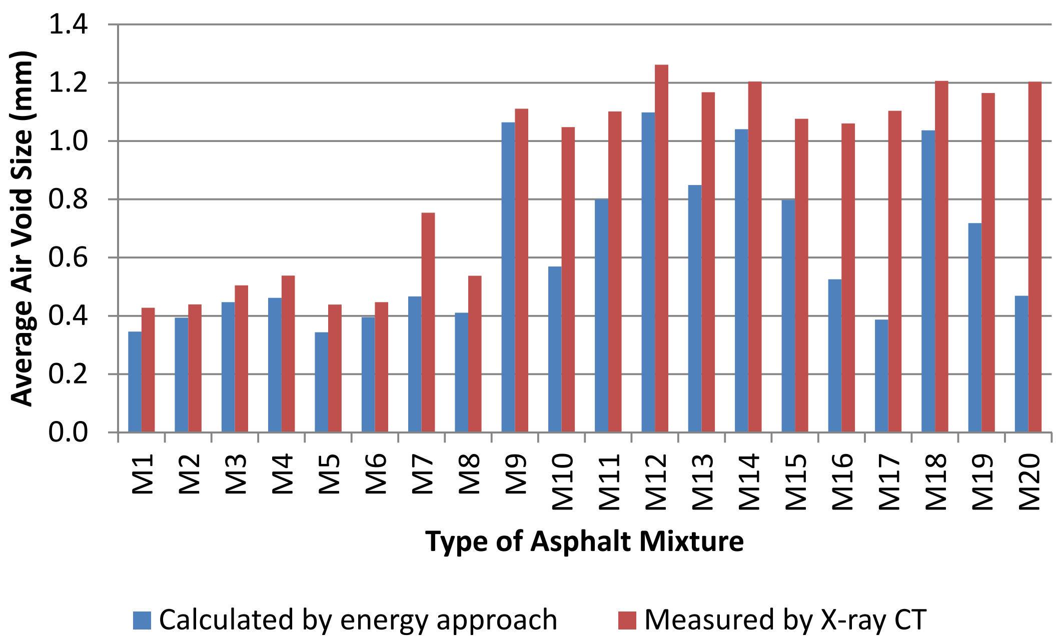


Figure E1a.5. Calculated and measured average air void size.

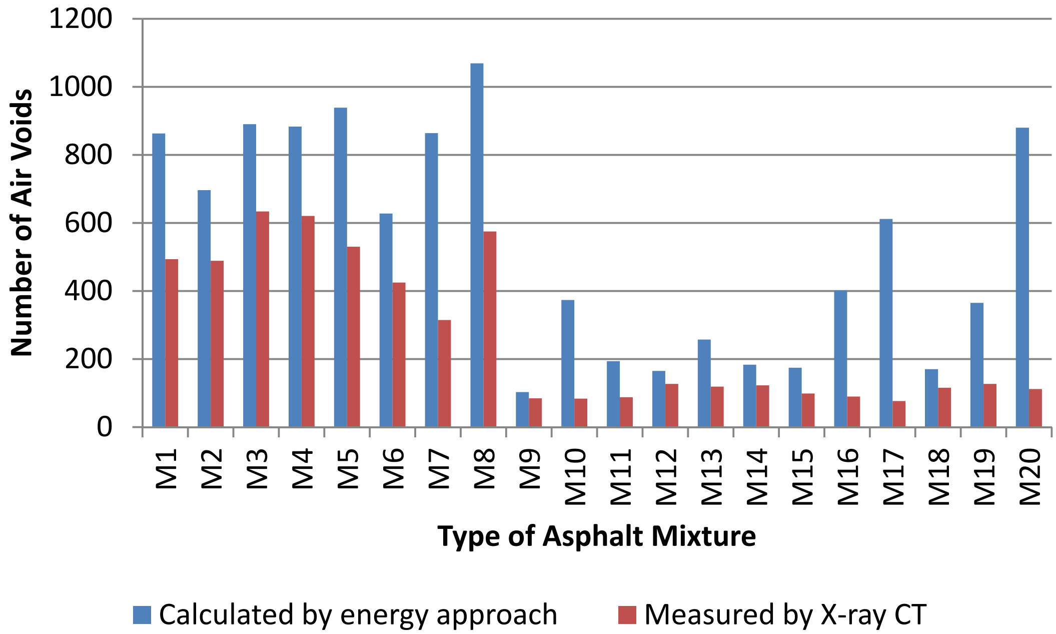


Figure E1a.6. Calculated and measured number of air voids.

2. Laboratory Test on Fine Asphalt Mixtures

The water vapor diffusion model developed in the last quarter clearly illustrates that the water vapor accumulates in the pavement at a rapid rate and it reaches a nearly saturated vapor pressure within a period of 6 months. Moreover, wetting processes in the pavement layer brought by the subsurface water vapor diffusion process occurs continuously. Therefore, it is concluded that the presence of water due to vapor diffusion in the asphalt surface layer is one of the major water movement mechanisms in a pavement and it greatly accelerates the deterioration of the asphalt mixture. Moreover, water vapor diffusion can be significantly accelerated if the wind blows across the pavement and removes the vapor from the pavement surface and thus results in the asphalt layer reaching water vapor saturation at a faster rate.

Fatigue cracking is a major form of distress in asphalt pavement and the key material property that affects fatigue cracking is the bond energy between asphalt binder and aggregates. In general, because the affinity of the aggregates for water is far greater than it is for the asphalt binder, regardless of whether the water is in the form of liquid or gas, the presence of moisture tends to strip the asphalt binder from the aggregate surface, which significantly accelerates the fatigue cracking in pavement. As presented in the previous quarterly report, the vapor pressure building in the FAM specimens after being conditioned in the vacuum desiccator for six months significantly accelerates the fatigue crack growth rate of the asphalt mixture material. The initial variation of air voids which existed among the specimens may still affect the crack growth rate after 6 months of moisture conditioning, but the presence of moisture plays the essential role in speeding up the fatigue crack growth in FAM.

In this quarter, the fundamental fracture properties for the AAM and AAD specimens were evaluated using the principal of strain energy equivalence. In fracture mechanics, the widely used model for fatigue cracking is the power-law of Paris' Law, which relates the crack growth per loading cycle to the J integral by two coefficients A and n and can be expressed as follows:

$$\frac{dc}{dN} = AJ^{n} \tag{E1a.1}$$

where dc/dN is the crack growth per cycle; A and n are regression coefficients determined from experiments; and J integral can be formulated as follows:

$$J_R = \frac{\partial W_{R1}}{\partial(crack\ surface\ area)} = \frac{\frac{\partial W_{R1}}{\partial N}}{\frac{\partial(crack\ surface\ area)}{\partial N}} \tag{E1a.2}$$

where W_{R1} is the pseudo-strain energy dissipated to induce cracks in asphalt mixture. However, the Paris' Law in fracture mechanics was developed to make a quantitative prediction of the remaining life of a crack of a specific size, and it is not intended to model a cluster of cracks such as what is happening in asphalt material during cyclic loading. In order to apply Paris Law to multiple cracks, it is modified to model the damage density of an asphalt mixture, which can be treated as a single parameter. The equation E1a.1 was reformulated as follows:

$$\frac{d\phi}{dN} = A^{'}J^{n^{'}} \tag{E1a.3}$$

where $d\phi/dN$ is the damage density growth per cycle.

The plot of W_{R1} versus N is fitted with a linear function as:

$$W_{R1} = c + dN \tag{E1a.4}$$

where W_{R1} is the strain energy dissipated for fatigue cracking; c is the intercept; and d is the slope. Substituting equation E1a.2 and E1a.4 into E1a.3, and integration of both sides of the equation to the number of N loading cycles, gives:

$$\phi = \phi_0 + A^{\frac{1}{n+1}} \left(\frac{1}{2A_F} \right)^{\frac{n}{n+1}} \left(cd \right)^{\frac{n}{n+1}} \frac{n+1}{dn+1} N^{\frac{dn+1}{n+1}} \tag{E1a.5}$$

Then the measured damage density is fitted as follows:

$$\phi = \phi_0 + aN^{b} \tag{E1a.6}$$

where *a* and *b* are the fitting parameters. Comparing equations E1a.5 to E1a.6, the coefficients $A^{'}$ and $n^{'}$ from modified Paris' law can be derived from the damage density as loading cycles proceed.

$$n^{'} = \frac{1-b}{b-d} \tag{E1a.7}$$

$$A^{'} = \frac{a*(dn+1)^{(n+1)}*(2A_f)^n}{cd^n*(n+1)^{n+1}} \tag{E1a.8}$$

All of the calculated $A^{'}$ and $n^{'}$ values are summarized in table E1a.3, as the conditioning relative humidity increases to 100%, the fracture parameter $n^{'}$ tends to increase for both AAM and AAD specimens, which indicates that the moisture vapor pressure in the specimens significantly increases the fatigue potential of asphalt mix material. The modified Paris' Law parameter $A^{'}$ tends to decrease as the relative humidity condition increases. However, it is believed that this decrease is not adequate to offset the increase of $n^{'}$. Therefore, it is concluded that the moisture presence in the asphalt due to vapor diffusion does increase the rate of fatigue cracking of an asphalt mix significantly.

Table E1a.3. Summary of the fracture parameters for AAM and AAD.

Aggregate	Binder Type	Specimens ID	Air Void (%)	Conditioning RH (%)	Fracture Parameters	
					A'	n'
Limestone	AAM	18	2.23	0	1.84E-16	3.09
		13	1.82	100	1.11E-21	4.32
	AAD	2	3.62	0	8.63E-22	4.65
		1	3.64	100	3.01E-27	5.44

3. Laboratory Testing and Modeling of Field Cores from Asphalt Pavements

In the previous quarterly report, the analytical procedure to find the actual crack growth, healing and fracture properties of the asphalt mixes were successfully verified using laboratory compacted specimens in the Overlay Tester (OT) test. In this quarter, a more comprehensive Finite Element (FE) model was developed to be used for both laboratory compacted and field aged asphalt mixtures. The stiffness gradient for the field specimens was calculated using the monotonically loaded nondestructive direct tension test and the analytical method that was presented in earlier quarterly reports in the ARC project. The FE model uses the moduli in different depths as an input and produces the strain profiles above the crack for the different crack lengths.

The specimen in the FE model was divided into several sublayers, and different material properties are assigned to these sublayers. Furthermore a UMAT subroutine program in the FE program ABAQUS was developed to be used for very thin specimens for more accurate stiffness gradient inputs. This program can be used for both plane stress and plane strain conditions. The

UMAT can determine the stiffness gradient mathematical function as an input and produce the strain profiles above the crack for various crack lengths. This model also can be used to evaluate the effect of the aging phenomenon on different fracture and healing properties of asphalt mixtures in the OT test. The advantage of this model is that it can use the measured continuous function of the stiffness gradient as an input. The accuracy of the computations of the crack growth can be increased by simply using a finer mesh. The strain profile above the crack tip for different crack lengths in a field aged specimen from a 9 year old pavement section in Arizona is shown in figure E1a.7.

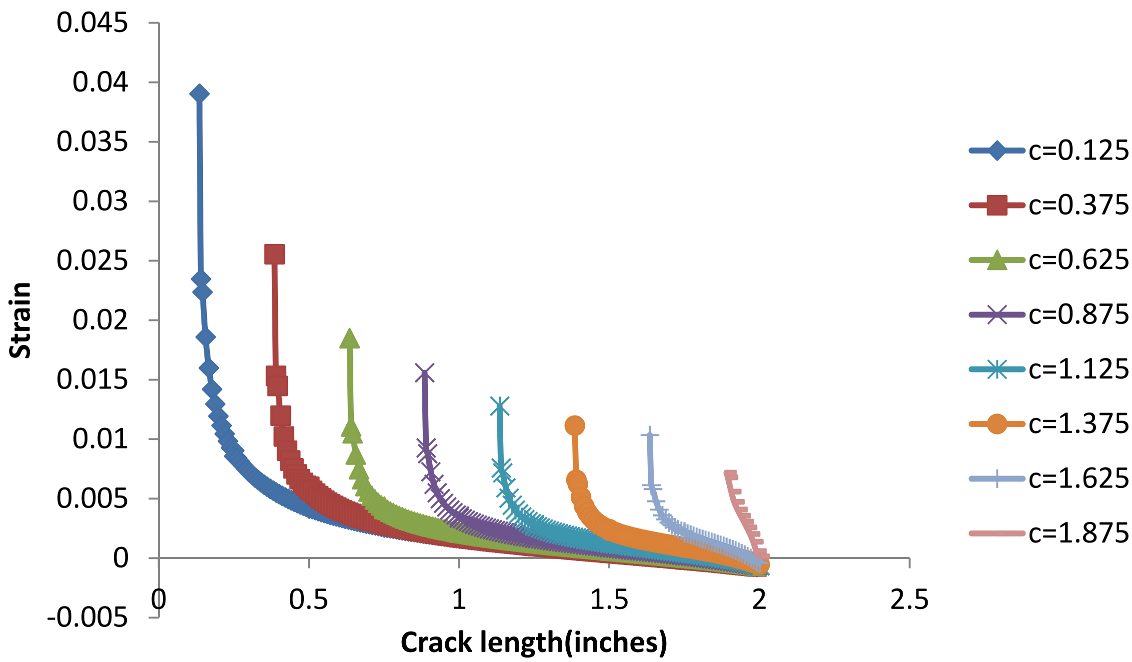


Figure E1a.7. Strain profiles above the tip of crack in a field aged specimen.

Figure E1a.7 shows that the top half inch in a 2 inch thick OT sample is under compression. As the crack enters the compressive zone, the crack speed reduces and this explains the variability of the previously used methods of using the OT test such as counting the number of load cycles to the failure. However, the compressive zone does not affect the accuracy of the developed FE method. The fracture mechanics based method which is developed in this research is able to calculate the number of load cycles for the crack growth to any specific depth in general cases including different sample sizes and mixture properties.

The OT test method for laboratory compacted specimens has been modified to be used for the aged specimens. The aged field specimens are very brittle; therefore the machine displacement has been reduced from 0.025 inches to 0.0125 inches to provide a large enough number of load cycles for the analysis. The trial tests on dummy field specimens showed that the crack grows to the top of the specimen after a few cycles using the 0.025 inch displacement. The number of loading cycles to reach a crack length of 1-inch also increased to 200 from the previous value of

150 cycles for lab specimens. Other modifications were applied to the FE model and analysis method in order to account for field samples different geometry and material properties such as thickness, length of specimen and the modulus gradient.

The test protocol provided for field aged samples includes two major mechanical tests. First the specimens are tested using the Viscoelastic Characterization (VEC) method in order to find the dynamic modulus gradient at three different temperatures; subsequently the VEC output is used as the input to calculate the crack growth, fracture and healing properties of the surrogate field specimen using the OT test. Eight field cores from Arizona were tested and analyzed using the VEC method at three different temperatures. Figure E1a.8 shows the stiffness gradient for the specimen AZ1-2A top lift at three different temperatures. Table E1a.4 shows the results of VEC tests on the 9 year old aged cores from Arizona at three different temperatures. The high values of *n* indicate that the stiffness changes significantly near the surface. As expected, the mean value of *n* in the samples from the top lift is less than those of the bottom lift. This shows that there are larger stiffness changes in the top lifts. The behavior of the highly aged specimens is more elastic which is verified by the small imaginary part in the results of the moduli calculations.

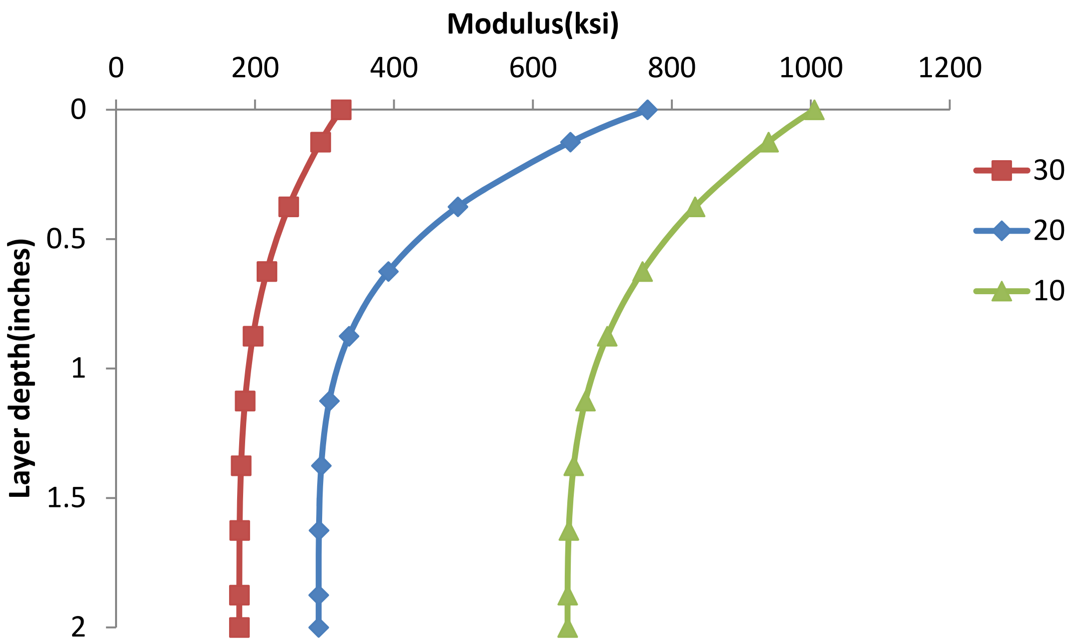


Figure E1a.8. Stiffness gradient for specimen AZ1-2A top lift in three different temperatures.

Table E1a.4. The stiffness gradient analysis for the AZ field cores.

Sample ID	Coring Location	Testing Frequency (Hz)	Test Temperature	n	n Phase Angle	k	k Phase Angle	Surface Modulus(Psi)	Surface Modulus phase angle	Bottom Modulus(Psi)	Bottom Modulus phase angle
AZ1-1A	TOP LIFT	20.00	20.00	**4.57**	-61.19	**1.37**	-6.71	**672474.85**	0.01	**491080.00**	0.01
AZ1-2A	TOP LIFT	20.00	20.00	**4.14**	-57.73	**2.62**	-46.70	**764968.56**	0.00	**291470.00**	0.00
AZ1-3A	TOP LIFT	20.00	20.00	**4.57**	-74.14	**2.97**	-51.28	**1138691.26**	0.00	**382940.00**	0.00
AZ1-4A	TOP LIFT	20.00	20.00	**4.29**	-56.79	**2.86**	-44.58	**807179.23**	0.00	**281850.00**	0.00
AZ1-1A	BOTTOM LIFT	20.00	20.00	**1.71**	-68.70	**3.52**	-73.32	**653838.16**	0.00	**185850.00**	0.00
AZ1-2A	BOTTOM LIFT	20.00	20.00	**3.69**	56.46	**1.45**	17.19	**461261.38**	0.01	**317020.00**	0.01
AZ1-3A	BOTTOM LIFT	20.00	20.00	**4.95**	83.51	**1.67**	-22.57	**739204.93**	0.00	**443250.00**	0.00
AZ1-4A	BOTTOM LIFT	20.00	20.00	**3.46**	-61.73	**1.91**	-58.73	**1122075.74**	0.00	**588370.00**	0.00
AZ1-1A	TOP LIFT	20.00	10.00	**4.90**	64.48	**1.42**	-1.61	**975926.97**	0.00	**687000.00**	0.00
AZ1-2A	TOP LIFT	20.00	10.00	**3.18**	-69.99	**1.55**	-70.74	**1005062.82**	0.00	**649890.00**	0.00
AZ1-3A	TOP LIFT	20.00	10.00	**4.39**	-68.93	**3.24**	-55.18	**1902152.10**	0.00	**587070.00**	0.00
AZ1-4A	TOP LIFT	20.00	10.00	**3.62**	-69.96	**1.99**	-66.27	**1246933.86**	0.00	**627210.00**	0.00
AZ1-1A	BOTTOM LIFT	20.00	10.00	**3.51**	-73.63	**1.82**	-71.76	**1029010.34**	0.00	**564930.00**	0.00
AZ1-2A	BOTTOM LIFT	20.00	10.00	**4.11**	-48.95	**2.91**	-40.82	**1660501.85**	0.00	**571230.00**	0.00
AZ1-3A	BOTTOM LIFT	20.00	10.00	**2.31**	-3.98	**1.42**	-6.87	**704992.87**	0.00	**496400.00**	0.00
AZ1-4A	BOTTOM LIFT	20.00	10.00	**5.19**	68.53	**1.36**	-4.21	**1395308.69**	0.00	**1023200.00**	0.00
AZ1-1A	TOP LIFT	20.00	30.00	**0.00**	0.00	**0.00**	0.00	0.00	0.00	0.00	0.00
AZ1-2A	TOP LIFT	20.00	30.00	**3.49**	-65.42	**1.83**	-61.19	**323792.35**	0.01	**177320.01**	**0.01**
AZ1-3A	TOP LIFT	20.00	30.00	**5.06**	66.83	**1.45**	-1.97	**432284.28**	0.01	**297950.01**	**0.01**
AZ1-4A	TOP LIFT	20.00	30.00	**4.13**	-57.77	**2.62**	-47.17	**456032.38**	0.01	**174180.00**	**0.01**
AZ1-1A	BOTTOM LIFT	20.00	30.00	**3.36**	-77.29	**1.56**	-77.39	**297136.15**	0.01	**190770.00**	**0.01**
AZ1-2A	BOTTOM LIFT	20.00	30.00	**3.24**	-62.80	**1.42**	-57.09	**278361.62**	0.01	**196390.01**	**0.01**
AZ1-3A	BOTTOM LIFT	20.00	30.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	**0.00**
AZ1-4A	BOTTOM LIFT	20.00	30.00	**4.07**	-56.74	**2.60**	-46.87	**453509.95**	0.01	**174190.00**	**0.01**

Significant Results

Extensive testing sequences are designed to evaluate the applicability and rationality of the proposed testing protocols and the energy-based mechanistic approach. It is intended to provide measurable engineering material properties, both undamaged and damaged, for various loading and environmental conditions, protocols for measuring them efficiently and accurately, and analytical methods for deriving engineering properties from the test data and predicting the development of damage and healing in asphalt mixtures.

The current test and analysis results successfully confirm two of the findings which were presented in the previous quarterly reports for twenty different types of asphalt mixtures. The first one is that the material property variation, i.e. difference between the tensile and quasi-compressive properties, always exists in a loading cycle of both the nondestructive and destructive controlled-strain RDT tests. The second one is that applying the energy-based mechanistic approach on the test data of the controlled-strain RDT test can produce more accurate average air void size and number of air voids more efficiently than the X-ray CT system. In addition, the energy-based mechanistic approach has extended the ability to model the crack growth in every loading cycle of the RDT test, which is impossible to be obtained by the X-ray CT system because of the large amount of healing that occurs during the scan by the X-ray CT system.

This energy-based mechanistic approach is also applied to fine asphalt mixtures that are conditioned at different levels of relative humidity. The fracture properties are calculated in terms of Paris' Law coefficients A and n. When the relative humidity increases from 0% to 100%, the coefficient A decreases but n increases.

Laboratory testing and FE modeling are performed on field cores taken from asphalt pavements to determine their stiffness gradient and fracture properties in terms of Paris' Law coefficients A and n.

Significant Problems, Issues and Potential Impact on Progress

The data analysis on the controlled-strain RDT test and the CSR test involves complex calculations and analysis techniques. Even though all the algorithms have been embedded in the Excel template and all the calculation are automatic, an extensive testing plan still requires a large amount of time to reduce and analyze the data. The analysis work that has not been finished in this quarter will be continued in the next quarter.

The lab is going through a renovation and the DMA machine only became available in March. The machine time of the Overlay Tester is also limited.

Work Planned Next Quarter

The test results presented in this report are only a small part of the final analysis results. The data analysis on all the tests in Table E1a.2 continues in the next quarter in order to provide comprehensive information in terms of the ability to predict fatigue and healing in asphalt mixtures using the energy-based mechanistic approach. Expected results include: 1) comparison of fatigue resistance of twenty types of asphalt mixtures; 2) the characteristics of the recovery modulus; 3) the healing ability of twenty types of asphalt mixtures; 4) relating the healing rates to fundamental material properties, etc.

Laboratory tests on fine asphalt mixtures will be continued on both unaged and unaged specimens made Nustar PG67-22 binder and samples made with the Valero PG64-16 binder.

The field cores have been tested using the OT test with replicate samples. The fracture and healing properties will be calculated after resolving the minor issues in the field specimens' OT analysis method.

References

Jones, D. R., 1993, "SHRP Materials Reference Library: Asphalt Cements: A Concise Data Compilation." *Strategic Highway Research Program Rep. No.SHRP-A-645*, National Research Council, Washington, D.C.

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

Subtask E1b-1: Rutting of Asphalt Binders

Work Done This Quarter

This quarter the team focused on determination of critical binder stress levels that contribute to asphalt pavement rutting. This was done through microstructure characterization of asphalt mixtures using 2D imaging by means of the recently developed iPas^2 software imported into the ABAQUS finite element software package. High resolution images of asphalt mixtures obtained using a flatbed scanner were converted to binary images using digital imaging processing techniques. Finite Element Method used at multiple scales to determine the range in stresses in binder domains in typical mixtures. A memorandum to summarize the results and express concerns regarding the current TP70 procedure was drafted and will be submitted to the ETG next quarter.

Significant Results

As the imaging techniques and filters cannot accurately capture aggregate particles smaller than 1.18 mm, a "mortar scale" model was used for the aggregates between 1.18 mm and 0.075 mm (#200 sieve). A program was written using MATLAB to randomly generate the mortar aggregates according to the inputted gradation. The matrix in the mortar phase consists of mineral filler and binder, which was modeled as the "mastic scale". The filler distribution was generated using the aforementioned MATLAB code, using filler gradations measured using Laser Diffraction. Experimentally derived visco-elastic binder properties were inputted into the mastic scale model, completing the multi-scale model representation of the asphalt mixture, as shown in figure E1b-1.1.

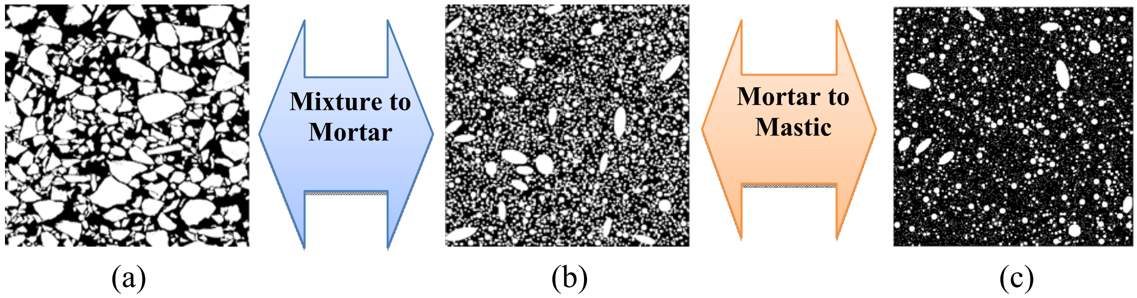
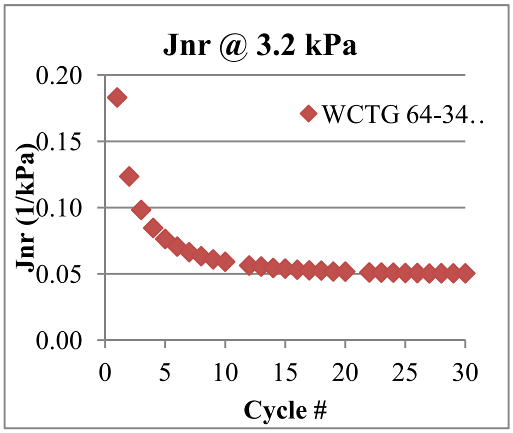


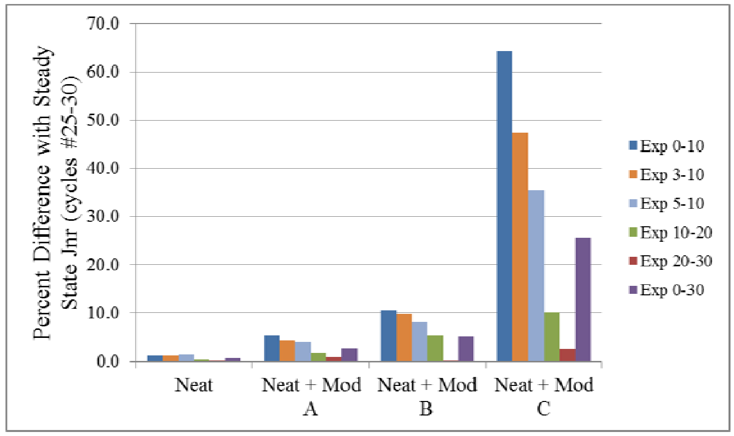
Figure E1b-1.1. Image. Multi-scale analysis scheme: (a) iPas2 processed binary image for mixture scale, (b) artificially produced mortar scale, (c) artificially produced mastic scale.

The model was subjected to load representing 18 kips truck axle loading and the stress distribution in the binder phase was derived through a step by step multi-scale modeling process. Study of the principal stresses of the binder phase showed that for an 18 kip load applied assuming a simple 150 mm diameter circular load application area, the average binder phase stress is between 20 and 30 kPa for the two extreme aggregate connectivity conditions considered. These values are an order of magnitude more than the highest stress level, 3.2 kPa, used in the current MSCR test procedure. These results are from a couple of extreme aggregate structure cases, thus further aggregate structures, volume fractions and binder properties must be considered to finalize analysis of representative critical binder stress for rutting performance.

Another aspect of the work this quarter was dedicated to explore the effect of number of cycles and steady state on binder rutting resistance. As discussed in previous quarterly reports, a topic of concern when analyzing MSCR results, especially for highly stiff binders or those with considerable delayed elastic response is the unstable or non-steady state of J_{nr} values calculated from the first cycles of each stress level. The average J_{nr} of different selections of cycles was compared to the steady state response achieved in cycles 25 to 30 for a number of binders with a range of modification types, tested to 30 cycles 70°C (figure E1b-1.2). It is seen that for some binder systems the non-steady state behavior from cycle to cycle can considerably affect the results. Overall testing to 30 cycles and averaging cycles 20 to 30 seems to yield the best results for binders exhibiting significant non-steady state behavior.



(a)



(b)

Figure E1b-1.2. Graphs. (a) Non-steady behavior of Jnr in fist 10 cycles of MSCR loading. (b) Analysis of J_{nr} variability in different cycles. Steady state J_{nr} is calculated by averaging cycles #25 to 30.

Work Planned Next Quarter

Moving forward, further gradations and binder properties as well as more realistic tire-pavement contact areas will be considered in the multi-scale modeling to further investigate the representative stress levels in the binder phase of a mixture for possible use in the MSCR test procedure.

Furthermore in the next quarter the team will begin collaboration with the Asphalt Institute with the purpose of determination and finalization of the optimum MSCR test procedure to achieve repeatable and representative results. This collaboration will bring together UWM's ideas, resources and data from the E1b-1 subtask, FEM experience and the WCTG round-robin database with the data, resources and experience that AI has had with the MSCR test. The result of this collaboration will be in the form of revised AASHTO MP-19 and AASHTO TP-70 specifications.

Subtask E1b-2: Feasibility of Determining Rheological and Fracture Properties of Asphalt Binders and Mastics using Simple Indentation Tests

Work Done This Quarter

The research team worked on analyzing in more details the mastic indentation results reported in previous quarter. This task is expected to help with quantifying the effects of fillers on important rutting performance and provide a complimentary measure to the dust to binder (D/B) ratio used in mixture design. If effort is successful, a simple index value measured in a HMA facility can be implemented to qualify the interaction between filler and binder.

Two different fillers (i.e., Andesite-AN1 and Limestone-LH1) at three concentrations (i.e., 10, 30, and 40%) were tested at room temperature. As it can be seen in figure E1b-2.1, the indentation test can capture the stiffening/reinforcement effect of the mineral filler at different concentrations. Collaboration between the research team at UW-Madison and the asphalt group at the Universidad Técnica Federico Santa María in Chile continued this quarter with focus on the development of closed-form equations for the correction factors needed to address size effects in the indentation test.

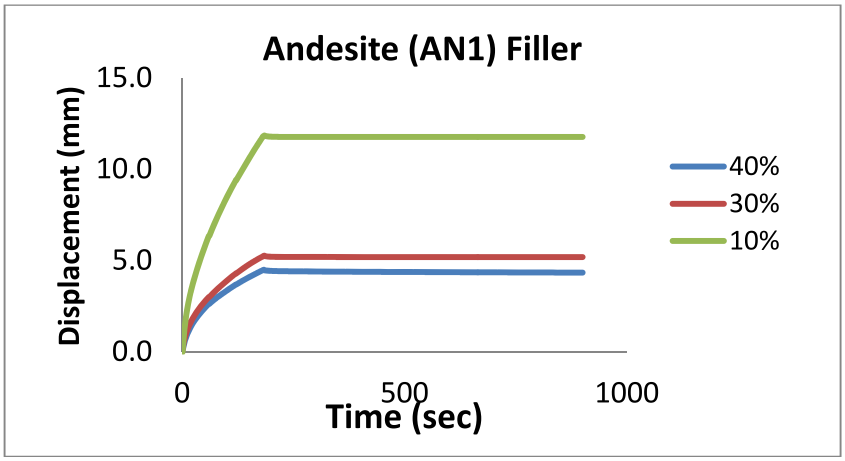


Figure E1b-2.1. Graph. Indentation testing of Andesite mastics.

<u>Significant Results</u>

Figure E1b-2.2 is an example of data collected that indicate the indentation test has the potential to identify the reinforcement effect of different mineral fillers on asphalt binders. The base binder used in the preparation of the mastics was the same (Flint Hills PG 58-22). Note that the Rigden Voids (RV), measured in a previous study by UW-Madison team, are significantly different: Andesite (43%) and Limestone (33%). As it can be seen, at a concentration of 10%, the linear visco-elastic response measured in the indentation test is very similar for the mastic tested. However, when volume fraction increases, significant differences between these two mastics are observed. These results indicate that at low concentration the filler-binder interactions are not filler dependent. However, when concentration increases the interaction effect becomes an important part of the mastic mechanical response.

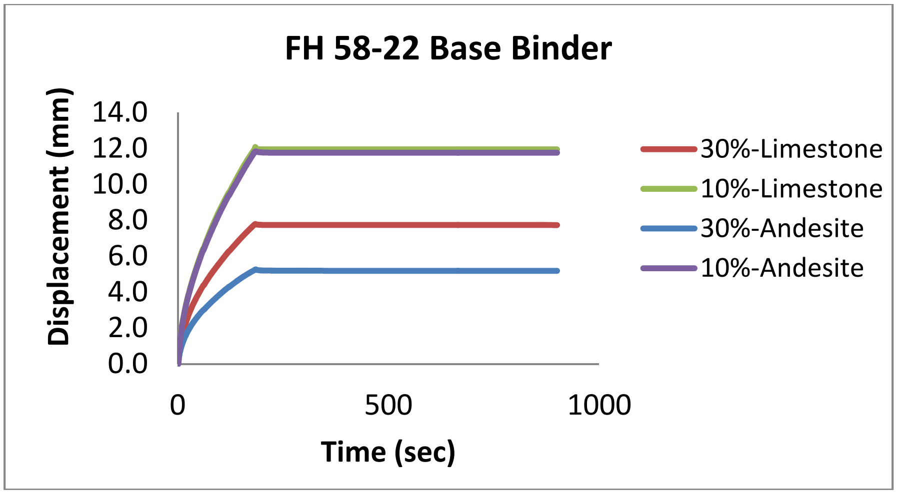


Figure E1b-2.2. Graph. Comparison of indentation testing of two mastics prepared with same base binder.

Work Planned Next Quarter

Work next quarter will focus on changing the current water bath system for controlling the temperature to a more flexible setup. Also, the closed-form solutions for size correction developed at Universidad Técnica Federico Santa María-Chile will be implemented in the analysis spreadsheet of the indentation test.

Work Element E1c: Warm and Cold Mixes

Subtask E1c-1: Warm Mixes (UWM)

Work Done This Quarter

The research team continued pursuit of the optimum compaction temperature concept through investigation of the effect of compaction temperature on the mixture volumetrics and workability. Literature review and analysis of previously collected data found that a temperature range exists at which the mix is able to achieve optimum density (Bennert et al. 2010). The temperature range is dependent on WMA additive type, concentration and binder grade. The research team presented initial findings on this subject in a poster session at the 2012 TRB meeting (Teymour et al. 2012). In parallel, asphalt binder viscosity and lubricity testing was conducted in an effort to define the role of asphalt binder as a lubricant during compaction and the contribution of changing binder properties to the trends observed in mixture data. The Stribeck relationship was applied to asphalt lubricity test data, results found that the test fixture was unable to define the transition of the binder from mixed to boundary lubrication. The test procedure is currently under review to modify the test apparatus to allow for measurement of the entire Stribeck curve. A commercial tribology fixture was also obtained to verify the trends observed in the laboratory fixture developed in-house

Work continued in investigation of the impacts of WMA additives and lower production temperatures on intermediate and low temperature asphalt binder and mixture properties. Binder performance properties evaluated included the G*sinδ parameter at intermediate temperatures and low temperature creep properties. Results found the presence of WMA additives resulted in significantly less age hardening during PAV aging, demonstrated by reductions in the G*sinδ parameter and S(60). A corresponding increase in the m-value was also realized. BBR parameters were estimated using well known interconversion methods to convert shear to flexural properties. Work continues to assess the impacts of these findings on binder performance grading.

The low temperature performance of mixtures was investigated through the glass transition (Tg) test. The experiment focused on the effects of reduced compaction temperature on thermo-volumetric properties of the mix, comparing results for samples compacted at 145°C and 115°C. In addition to measuring the Tg of the mixtures, digital imaging analysis methods using the iPas2 software were used to allow for consideration of changes in aggregate structure due to use of lower compaction temperatures in analysis of the data.

The research team has been unable to obtain WMA field projects with WisDOT, however efforts for coordination continue. UNR continues to test the materials collected on PTH14 in Manitoba. In addition UW and UNR provided input to proposed new WMA LTTP sections, a representative of the research team is meeting with Ohio DOT in early April.

Chapters 1-4 of the draft final report were completed. These chapters cover the problem statement/introduction, literature review, experimental design, and results/analysis. The report will be focused on evaluating the impacts of WMA additives on binder workability and the effects of WMA additives and reduced temperatures on performance. The report is currently under internal review.

Significant Results

Examples of results collected for variation of air voids with temperature using the gyratory compactor are presented in figure E1c-1.1. These results verify the optimum compaction temperature concept for a single binder type compacted at four temperatures, confirming that an increase in air voids is observed at both high and low compaction temperatures. It is expected that the WMA additives can change the optimum range significantly depending on type of additive and concentration. It should be mentioned that this trend has been confirmed using data from previous published studies conducted at Texas Transportation Institute and Rutgers University.

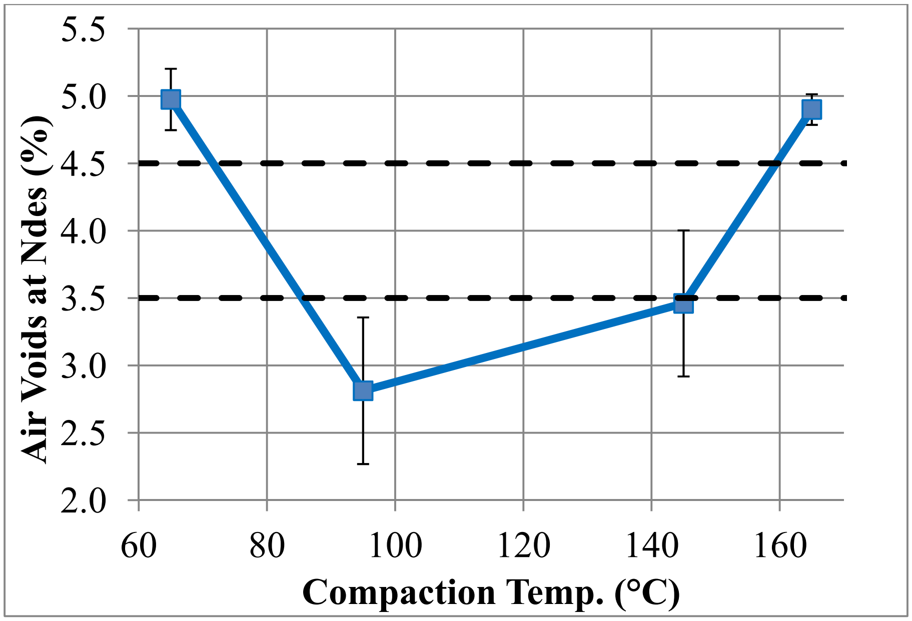


Figure E1c-1.1. Effect of compaction temperature on mixture volumetrics.

To study effects of reduced gaining temperature on low temperature performance, preliminary results for mixture glass transition (Tg) were collected. The results indicate that reduced compaction temperatures resulted in lower values of the liquid phase CTE, α_l. Values of α_g remained relatively constant in all cases. Digital imaging using the iPas-2 software, found that compaction temperature influenced aggregate structure as demonstrated by a change in the ISI. Furthermore, a strong correlation between ISI and CTE was observed, indicating that a change in aggregate structure contributes to changes observed in the CTE of mixes.

Significant Problems, Issues and Potential Impact on Progress

Submittal of the draft final report was delayed due to new information discovered regarding the lubricity results and the optimum compaction temperatures. The report is currently under internal review and revisions.

Work Planned Next Quarter

Development of Mixing and Compaction Guidelines for WMA

The research team will continue to investigate the optimum compaction temperature concept and how it applies to recommendation of production temperatures. Lubricity and viscosity data collected will be compared to mixture workability results to validate the use of coefficient of friction as a measure of binder workability and to define the contribution of asphalt binder workability to mixture densification. To better define mixing temperatures, development of a new aggregate coating procedure based on absorption will continue.

Impacts of WMA Additives and Reduced Production Temperatures on Mixture Performance

Efforts will continue to further evaluate the effect of reduced aging temperatures and aging time on the performance of mixtures. Candidate test methods selected include the flow number (FN) test and Thermal Strained Restrained Specimen Test (TSRST) and glass transition test (Tg) to investigate high and low temperature performance properties. A final testing plan will be developed in consultation with University of Nevada Reno to finalize the suite of performance tests selected and determine how best to incorporate ARC Core Materials. Image analysis will continue to quantify the impacts of reduced compaction temperatures on aggregate structure and its relationship to performance.

References

Bennert, T., G. Reinke, W. Mogawer, and K. Mooney, 2010, Assessment of Workability/Compactability of Warm Mix Asphalt. The Transportation Board of the National Academies, Washington, D.C.

Teymour, P., L. Tashman, and H. U. Bahia, 2012, Critical Considerations in Mixture Design of Warm Mix Asphalts Washington D.C. Transportation Research Board of the National Academies. Annual Meeting of the Transportation Research Board.

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

Work Done This Quarter

The research team focused on the investigation of factors influencing the coating process of aggregates by emulsions. The mixing process and imaging software analysis developed and calibrated in the previous quarter's work were applied to the testing matrix outlined in table E1c-2.1. After the image analysis process, a statistical analysis of the 3^3factorial-design experiment (with factors of gradation, residual AC, and aggregate moisture content) was performed. The matrix was analyzed for both the non-agitated mixtures as well as the 24-hour agitated mixtures (the samples used in the non-agitated study we left 24-hours and remixed for 2.5 minutes and analyzed). Note that three replicates of each mixture were scanned.

Table E1c-2.1. Factors and levels for coating study.

Factor	Level	Specification
Aggregate Types	1	Limestone/Natural Sand Blend
Aggregate Gradation	3	Base, Fine, Coarse
Emulsion Type	1	Anionic 'E-150'
Residual Asphalt Content	3	3.5%, 4.5%, 5.5%
Aggregate Moisture Content	3	SSD, SSD - 2% , SSD + 2%
Mixing Time	1	2.5 mins
Mixing Method	2	Non-Agitated, Agitated

Significant Results

Table E1c-2.2 shows the ANOVA statistical analysis results for the non-agitated mixtures. Table E1c-2.3 shows the ANOVA statistical analysis results for the agitated mixtures. Table E1c-2.4 shows the statistical analysis for the coated mixtures considering agitation as a factor.

From the statistical analysis results it is possible to conclude that absorption is an important factor. When the aggregates have no porosity (e.g. natural sand aggregate) there will be less coating, while with aggregates having higher porosities (e.g. limestone coarse aggregates) the asphalt absorption increases, thus the coating process is increased.

The presence of moisture in the pores of aggregates had only a minor effect on the asphalt-aggregate coating process. This result can be explained by the fact that when the coating material (emulsion) is an oil base material and water is used to wet the aggregate surface, the incompatibility of oil and water will decrease the coating-absorption process (Chapman & Anderson, 1972).

Table E1c-2.2. Analysis of coating effects on non-agitated mixtures.

Effects	**F**	**P**	**Effect on Coating**
Gradation	73.5	4.04E-14	Coarse > Base > Fine
Moisture	40	2.88E-10	SSD-2% > SSD > SSD+2%
AC%	101.3	<2.2E-16	5.5% > 4.5% > 3.5%
Gradation-Moisture	4.6	0.004	Lower Moisture, More Coarse to increase coating
Gradation-AC%	6.2	0.0005	Higher AC, More Coarse to increase coating
Moisture-AC%	0.43	0.732	NOT SIGNIFICANT
Gradation-Moisture-AC%	0.95	0.445	NOT SIGNIFICANT

Table E1c-2.3. Analysis of coating effects on agitated mixtures.

Effects	**F**	**P**	**Effect on Coating**
Gradation	219.5	<2.2E-16	Coarse > Base > Fine
Moisture	1.5	0.232	NOT SIGNIFICANT
AC%	339.0	<2.2E-16	5.5% > 4.5% > 3.5%
Gradation-Moisture	5.53	0.0009	Lower Moisture, More Coarse to increase coating
Gradation-AC%	18.0	3.298E-09	Higher AC, More Coarse to increase coating
Moisture-AC%	8.43	2.815E-05	NOT SIGNIFICANT
Gradation-Moisture-AC%	4.38	0.0005	NO EXPLANATION

Table E1c-2.4. Analysis of coating effects on coated mixtures including agitation as a factor.

Effects	F	P	Effect on Coating
Gradation	285.75	<2.2E-16	Coarse > Base > Fine
Moisture	5.17	0.007	SSD-2% > SSD > SSD+2%
Agitation	221.67	<2.2E-16	Agitation > Non-Agitation
AC%	442.49	<2.2E-16	5.5% > 4.5% > 3.5%
Gradation: Moisture	6.79	8.029E-05	Lower Moisture, More Coarse to increase coating
Gradation: Agitation	12.57	1.535E-05	Coarse, Agitated to increase coating
Moisture: Agitation	1.74	0.182	NOT SIGNIFICANT
Gradation: AC%	22.34	7.781E-13	Higher AC, Coarse to increase coating
Moisture: AC%	10.21	7.283E-07	Increasing AC shows more sensitivity to moisture
Agitation: AC%	8.10	0.0006	Agitated, High AC to increase coating

After including the agitation process as a factor on the statistical analysis, the moisture content showed lower significance (as compared to the other main effects) on the asphalt-aggregate coating process. Therefore, the results indicate that aggregate gradation and the asphalt content are the most significant factors to consider during the coating process of CMA.

A more rigorous analysis is underway that includes the replicates as a factor and will examine the adjusted coefficient of determination (R^2_{Adj}) of each factor as a way to better explain the role that controlled factors play in achieving aggregate coating. A high coefficient of determination for the overall model indicates that the majority of the coating results can be explained by the factors studied.

Significant Problems, Issues and Potential Impact on Progress

The scanning process for mixtures with higher percentage of moisture content needs to be refined in order to be more practical.

Work Planned Next Quarter

The research team will work on finalizing the testing matrix for asphalt-aggregate coating evaluation. Different aggregates with different levels of absorption will be analyzed with different asphalt binder emulsion.

References

Chapman, B. N., and J. C. Anderson, 1972, “Science and Technology of Surface Coating.” *The Basic Principles of Electrostatic Coating*, Academic Press Inc., London, pp. 28-42.

CATEGORY E2: DESIGN GUIDANCE

Work element E2a: Comparison of Modification Techniques (UWM)

Work Done This Quarter

In the past quarter to a framework for binder modification selection tool was developed to take into account energy and cost on a performance basis. The intended audience for this tool is both the owners and the contractors of asphalt pavements. This tool will be the basis for the modification selection guideline, which is one of the main deliverables of this work element.

Significant Results

The tool under development uses an MS Excel™ platform, and includes 4 different stages. In the first stage, the required project specific information and ultimately comparing different possible alternatives. This approach is intended to be as simple as possible to appeal to wider range of potential users. The required input data are reduced to the essential information needed, and default values are provided for all categories. In addition to the project condition, design assumptions and reliability information, users can input climatic information containing average temperature values and standard deviations. Such information is available from weather stations across the United States through "LTPPBind" online application. Expected project life time traffic volume and expected project speed are commonly calculated for all highway projects and thus are available for any given project. Fuel cost values are known to fluctuate significantly, thus the user is highly encouraged to input values depending on pricing at project construction time. Storage time of binders after modification is added depends on the logistics of the operation, and should be known by the project manager. On the other hand, default software fuel consumption rates for both heating and maintaining constant temperatures based on average typical values are provided. Project specific values for these parameters may not be known, thus default values will most likely be used in this category.

The second stage of the spreadsheet requires the input of the PG results for the available unmodified base binder. Based on the selected level of reliability, the climatic temperature conditions and the life cycle traffic volume, the spreadsheet will calculate the required performance grade limits to meet project conditions. By comparing these values to the base binder inputted PG data the spreadsheet will then define the required level of HT PG and LT PG improvement needed through the use of modification. The same procedure is carried out for PG plus tests such as the LAS and MSCR results of the base binder, in comparison with project traffic level and climatic condition LAS and MSCR minimum needs

In the third stage (figure E2a.1) the user is provided with a table of available modification types from which the user can combine percentage dosage of different modification types to achieve three hybrid alternatives to be used in the comparative analysis. For each modification type, default values are provided by the spreadsheet for the calculation of change in unit cost, performance indices such as HT PG and LT PG, and energy indices such as change in required construction and storage temperature. Optional sections are also available with default values of change in LAS and MSCR test parameters with type and dosage. The default values were defined based on a large pool of samples tested and evaluated throughout the E2a subtask as well as some data from F2a and V3a (WCTG) subtasks. The user may add their own choice of modification in the available slots in the table, provided they have the relevant pricing, performance, and energy related supporting data.

				Unit Price		High Temperature PG		Low Temperature PG		Mixing Temp (MT)		Storage Temp (ST)	
Modification Type	Alt 1 (%et.)	Alt 2 (%wt.)	Alt 3 (%wt.)	Input $/%/m^3	Default $/%/m^3	Input %/HT°C	Default %/HT°C	Input %/LT°C	Default %/LT°C	Input ΔMT/%	Default ΔMT/%	Input ΔST/%	Default ΔST/%
Polymer A	3.5	0	0		20		1.5		-0.3		2		4
Polymer A (Cross-Linked)	0	0	0		22		2		-0.3		3		6
Polymer B	0	3	0		25		1.5		-0.4		1		2
Acid A	0	1	1.5		15		3		-0.2		0		1
Acid B	1.5	0	2		22		1.5		-0.5		3		6
WMA A	0	0	0		5		0.2		0.5		3		6
WMA B	0	0	0		5		-0.5		-1.5		-3		-6

Figure E2a.1. Image. Modification alternative selection and performance input level of spreadsheet (displayed values are fictitious).

In the final stage the spreadsheet uses the inputted and default values to calculated performance gains at both low and high temperatures (LT PG and HT PG) and PG Plus tests such as LAS and MSCR for each alternative and compares with the calculated grade improvement requirements. Dosages of the modifiers may be adjusted until meeting the requirements. The change in production and storage temperature for the combined effects of the modifiers in each alternative are also calculated and converted to added or saved liters of fuel. These values are calculated through the usage of the inputted (or default) magnitudes of fuel consumption to heat or maintain temperature for unit volume of binder (1 m^3). Ultimately these values are converted to monetary values per unit volume of modified binder, based on the unit pricings of the modifiers and the fuel consumption rates and used as the basis of comparison between different alternatives. It must be noted that this program by default uses average experimental values collected in this study, considering the combined effects of modifier combinations to be linearly additive. The results can only be used as an initial basis of modifier combination selection and approximate added costs or savings. The calculated performance values are not to be used in the place of experimental data for design purposes. Where possible, the user is encouraged to input project specific data in place of default values for most accurate results.

<u>Work Planned Next Quarter</u>

Work next quarter will continue to populate the spreadsheet with performance gain per modifier percentage data and further refine framework of analysis. Focus will be on derivation of accurate and reliable default energy consumption rates for heating and storage. Efforts will also continue for the preparation of the draft final report.

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

Work Done This Quarter

The research team refined the binder blending test procedure to address issues of sample geometry distortion in the DSR. Custom molds were constructed to make samples with uniform thickness. The primary research effort this quarter was to isolate the effect of conditioning temperature using the modified testing procedure. Fresh binder and artificial RAP binder mastic samples are placed on each other in the custom DSR molds. Samples were conditioned at two different temperatures with the same time intervals. To inspect the effect of binder aging during the conditioning, the fresh asphalt binder is conditioned at the same temperatures and time intervals.

The paper entitled: “Recommendations for the Characterization of RAP Aggregate Properties Using Traditional Testing and Mixture Volumetrics” was presented at the 2012 Association of Asphalt Paving Technologists (AAPT) meeting in Austin, TX.

Significant Results

Natural sand retained on the 0.075 µm sieve (#200) is used to create the mastic samples. Neat asphalt binder with PG grade of 58-28 and artificial RAP (two-PAV cycle) of the same source were mixed with the fine aggregate holding the binder content constant at 30% by weight. One wafer of Fresh mastic and another one of artificial RAP mastic are placed on top of one another together and placed in the oven (figure E2b.1). Two conditioning temperatures of 120 and 140 C were chosen to observe the effect of conditioning temperature on the blending rate between the mastic samples. Sampling time intervals were selected as 5, 30, 60, 120 and 140 min. After conditioning, molds are allowed to cool down. Samples were demolded and tested in the DSR after various conditioning times. The G* as the indication of mixing developed between two material is measured. The same procedure was conducted for just fresh mastic samples to determine the effect of aging during the conditioning.

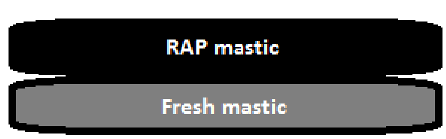


Figure E2b.1. Schematic of used samples before conditioning.

Results for conditioning temperatures of 120 and 140 C are displayed in figure E2b.2. Results are plotted on a log G* - time scale as is typical for blending charts. The slope of the fresh mastic lines is an indicator of binder aging, and it is seen that the samples conditioned at 140 C demonstrated more aging than samples conditioned at 120 C, as expected. The slope of the RAP Mastic/Fresh Mastic lines indicates that blending does occur after accounting for binder aging as the slopes are significantly higher than the Fresh Mastic slope alone for each respective temperature. Results also show that the higher temperature facilitated faster and more complete blending through diffusion as compared to the lower conditioning temperature. It should be noted that the RAP Mastic alone had a shear modulus of 105,000 MPa, while the Fresh Mastic had a value of approximately 15,000 MPa. Based on these values a complete blending of the RAP Mastic and Fresh Mastic (if no aging is assumed) would result in a complex modulus in the range of 60,000 MPa (the average of the RAP Mastic and Fresh Mastic at zero conditioning time. Note that the samples conditioned at 140 C approached this 60,000 MPa value given sufficient time.

It appears that this method has merits in evaluating the relative blending that can occur between two binder samples as a function of time and temperature. Researchers are validating these results with finite element models and physical blending charts of the two binders.

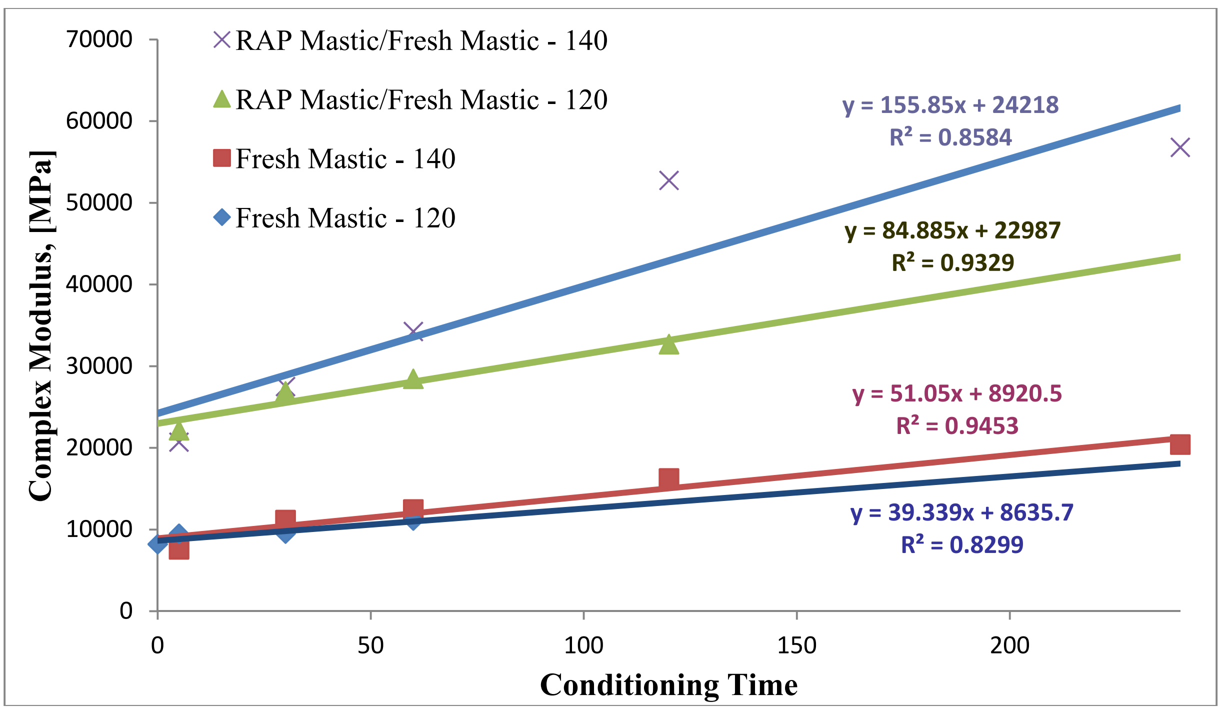


Figure E2b.2. Effect of time and temperature on blending of fresh and RAP mastic. Testing was conducted at 64°C.

Significant Problems, Issues and Potential Impact on Progress

None

Work Planned Next Quarter

For the next quarter the following work is under development:

- To derive a relationship between blending time and temperature, a simple blending chart is developed for the asphalt binder source. Physically blended samples are tested in DSR and the logarithmic scale of G* is plotted versus the content of artificial RAP asphalt binder. The plot shows a linear relationship for the material.
- Two binder sources are planned to be investigated with the developed procedure to verify possible influence of compatibility.
- The conditioning temperature effect will be further studied by adding more temperature intervals.

Subtask E2b-2: Compatibility of RAP and Virgin Binders

Work Done this Quarter

There was little activity this quarter because of staff resignations.

Significant Results

None.

Significant Problems, Issues and Potential Impact on Progress

Some delay in schedule has been caused by staff change.

Work Planned Next Quarter

In the next quarter, preparation and testing of the laboratory RAP blended samples should commence.

Work element E2c: Critically Designed HMA Mixtures (UNR)

Work Done This Quarter

Addresses the review comments and submitted a revised copy of the report: “Repeated Load Permanent Deformation Triaxial Testing Conditions of Asphalt Mixtures”. Work continued to evaluate the applicability of the recommended deviator and confining stresses for the flow number test. As part of the FHWA FN task group, nine mixtures were evaluated for permanent deformation behavior. In order to validate the proposed approach, two additional rut susceptible mixtures from WesTrack project were included in the work plan. (i.e. NV55-6422 and NV19-6422). Table E2c.1 summarizes the general project information provided for all selected mixtures. A presentation was given at the FHWA Mixture and Construction ETG that was held in Baton Rouge, Louisiana. Furthermore a summary of the test results was submitted to the ETG.

Table E2c.1. List of evaluated mixtures in this study.

Design Traffic Level, MESAL	State	Asphalt Binder Grade	Mixture ID
3	Wisconsin	PG58-28	WI-5828
	North Carolina	PG64-22	NC-6422
	Texas	PG70-22	TX-7022
10	Wisconsin	PG64-28	WI-6428
	Indiana	PG64-22	IN-6422
30	Alabama	PG67-22	AL-6722
	Florida	PG67-22	FL-6722
	California	PG70-10	CA-7010
	New Jersey	PG76-22	NJ-7622
0.58[1]	Nevada, WesTrack, Cell 55	PG64-22	NV55-6422
4.8[1]	Nevada, WesTrack, Cell 19	PG64-22	NV19-6422

[1] Applied MESALs

Significant Results

Table E2c.2 summarizes the flow number test results for the evaluated mixtures along with the testing conditions for braking and non-braking conditions.

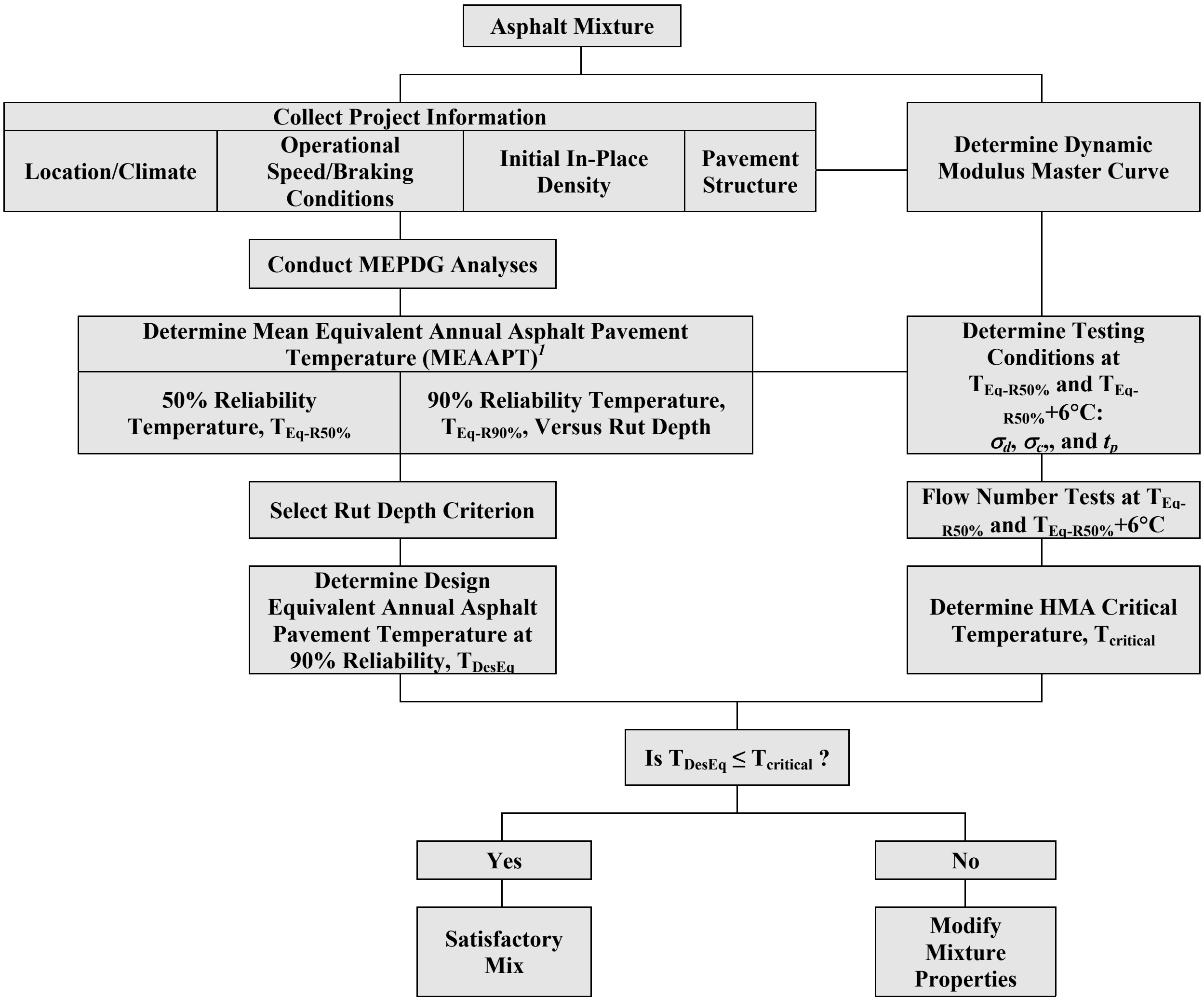
Table E2c.2. Testing conditions and flow number test results.

Mixture ID	Test Spec. Mean Air Voids (%)	Braking	Test Temp. (°C)	Traffic Speed (mph)	HMA Layer Thick. (in.)	Deviator Stress (psi)	Confining Stress (psi)	Pulse Duration (sec)	Mean Flow Number[2]
WI-5828	7.05	No	29.8	45	4.0	79[1]	44[1]	0.03[1]	No Flow[3]
	7.14		35.8			78[1]	43[1]	0.03[1]	1,995
	4.27	No	33.0	45	4.0	78[1]	50[1]	0.03[1]	No Flow[3]
	4.16		39.0			77[1]	44[1]	0.03[1]	3,295
NC-6422	7.25	No	34.1	40	6.0	78	47	0.03	No Flow[3]
	7.33		40.1			77	42	0.03	7,195[2]
TX-7022	7.38	No	36.2	60	6.0	79	44	0.02	No Flow[3]
	7.07		42.2			76	48	0.02	3,545
WI-6428	7.31	No	26.3	55	7.0	82	45	0.02	No Flow[3]
	7.24		32.3			80	41	0.02	6,595
	4.09	No	32.3	55	7.0	74	42	0.02	No Flow[3]
	4.21		38.3			75	36	0.02	5,995
IN-6422	7.37	No	35.2	70	6.0	78	51	0.02	No Flow[2]
	7.28		41.2			78	44	0.02	2,895
AL-6722	7.10	No	29.3	45	9.1	73	44	0.03	No Flow[3]
	7.35		35.3			73	39	0.03	3,345
FL-6722	6.95	No	41.6	75	6.0	75	63	0.02	No Flow[3]
	6.88		47.6			75	55	0.02	7,445
	7.25	Yes	36.0	10	6.0	111	50	0.16	No Flow[3]
	7.13		42.0			112	44	0.16	1,295
CA-7010	6.87	No	47.2	65	9.6	60	52	0.02	No Flow[3]
	7.01		53.2			60	50	0.02	1,645
NJ-7622	7.14	No	50.2	65	6.0	76	41	0.02	No Flow[3]
	7.25		56.7			77	36	0.02	6,145
	7.18	Yes	42.0	10	6.0	112	45	0.16	No Flow[3]
	7.36		48.0			112	40	0.16	4,995
NV55-6422	4.15	No	40.0	40	6.0	77	42	0.03	No Flow[3]
	4.07		45.0			77	39	0.03	5,345
NV19-6422	7.97	No	35.0	40	6.0	76	59	0.03	No Flow[3]
	8.15		40.0			76	53	0.03	3,845

[1] Testing conditions were determined for 6 in. asphalt layer; [2] Determined using the Francken model;
[3] No Flow after 20,000 load cycles

As part of the study a proposed procedure for determining rutting potential of HMA mixtures have been developed. Figure E2c.1 shows the preliminary overall flow chart for the proposed procedure.

Rutting potential was determined for each mixture under each project condition and environmental characteristics. Figure E2c.2 shows the rutting potential of the evaluated mixtures.



Note: [1] Modified NCHRP 09-30A Procedure

Figure E2c.1. Preliminary flow chart for the proposed procedure.

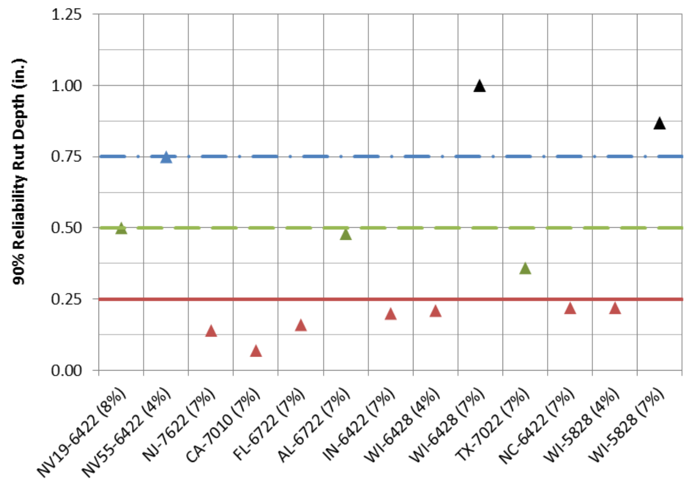


Figure E2c.2. Rutting potential of evaluated mixtures.

A series of 2D-Imaging analyses have been conducted for all mixtures. Figure E2c.3 illustrates the relationship between the number of aggregate contact points and the HMA critical temperatures. A good relationship between the aggregate interlock and the HMA critical temperature can be observed.

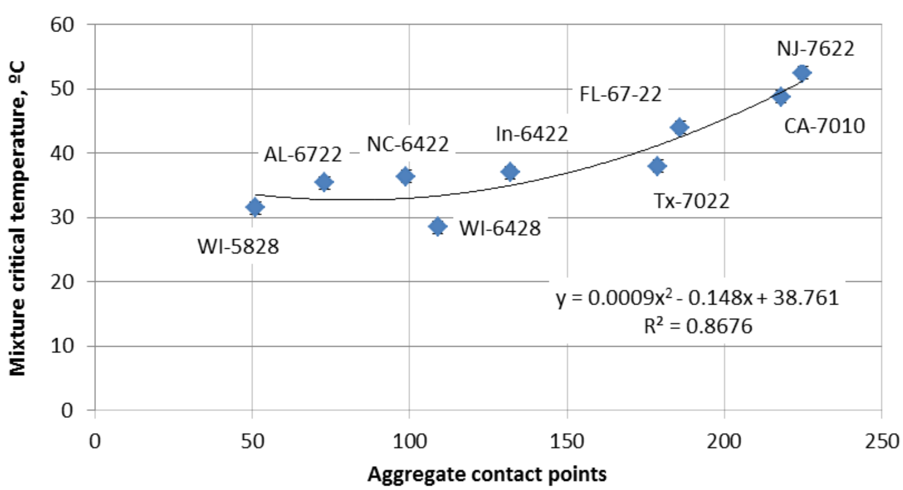


Figure E2c.3. Aggregate contact points versus mixture critical temperature.

Significant Problems, Issues and Potential Impact on Progress

The large number of mixtures and testing conditions delayed the progress of this effort. The research team will work on summarizing all the test results and findings by end of next quarter.

Work Planned for Next Quarter

Summarize the findings in a report and recommend a standard practice for the flow number procedure.

Work element E2d: Thermal Cracking Resistant Mixes for Intermountain States (UNR & UWM)

Work Done This Quarter

This work element is a joint project between University of Nevada Reno and University of Wisconsin–Madison. As of this quarter, all of the E*-compression testing, extraction and recovery testing, and the Carbonyl Area (CA) measurements have been completed for the mixture evaluation task. Nearly 80% of the mixture evaluation testing has been completed. Progress continues on the low shear viscosity (LSV) and binder master curve measurements, with nearly 85% of that testing having been completed from this subtask. Further refinement of the Thermal Stressed Restrained Specimen Test (TSRST) testing procedure is mostly finalized. Validation of the final test protocol is underway.

Further efforts have continued on the field validation sites for the developing thermal cracking modeling efforts. Two locations in Nevada and four more from Minnesota are included are undergoing the necessary aging in the kinetics ovens. Although each location is at different stages or testing the kinetics portion of the field validation efforts are roughly 60% complete.

Very near the end of this quarter the second DSR has been installed and is undergoing production testing on both the mixture and binder hardening susceptibility testing.

Effort of this quarterly also focused on a practical approach to estimate the Prony's series coefficient of the generalized Maxwell model for the relaxation modulus determined from the TSRST test measurements. Representing relaxation modulus by means of Prony's series has several advantages. One of the main advantages is that it facilitates the numerical computation of the Boltzmann constitutive equation.

The UW research team focused on further developing the Finite Element (FE) model for glass transition of asphalt mixtures. This model can be used to understand how the glass transition and coefficients of thermal expansion/contraction (CTE) of the asphalt mastic and the aggregate structure relates to the mixture glass transition behavior. The simulations were used to assess the effect of volumetric fraction and aggregate structure properties of the mix (e.g., aggregate to aggregate contact length and number of contact zones) on the glass transition of the mixture.

The simple model discussed in the previous quarterly report highlighted how the internal aggregate structure can be an important factor in the determination of the thermo-volumetric properties of the mixture. In this quarter, the research team used the number of aggregate to aggregate contact zones, and the overall length of the aggregate to aggregate contact zone to study the effect of microstructure on the thermo-volumetric properties of asphalt mixtures. These internal structure parameters are calculated using the iPas[2], which is a 2-D image analysis software for asphalt mixtures. Analysis showed that aggregate connectivity has a clear effect on the coefficients of thermal expansion/contraction (CTE) of the mixtures.

Significant Results

The expected final TSRST test protocol is expected to have been developed. Following the short validation testing experiment, the established procedure is expected to be set.

The generalized Maxwell model was used to obtain the relaxation modulus from the dynamic modulus data. An Excel worksheet and a Matlab code were developed to obtain the optimum Prony's series fit and interconverting viscoelastic properties. Effort is undergoing to find a relationship between the chemical and mechanical properties of asphalt mixtures as a function of aging. Figure E2d.1 shows, for illustration, the discrete distribution of the E_i Prony's series coefficients versus the relaxation time (ρ_i Prony's coefficients) for an asphalt mixture subjected to 0, 3, 6, and 9 month of oven aging at 60°C. The presented behavior will be evaluated for all other mixtures.

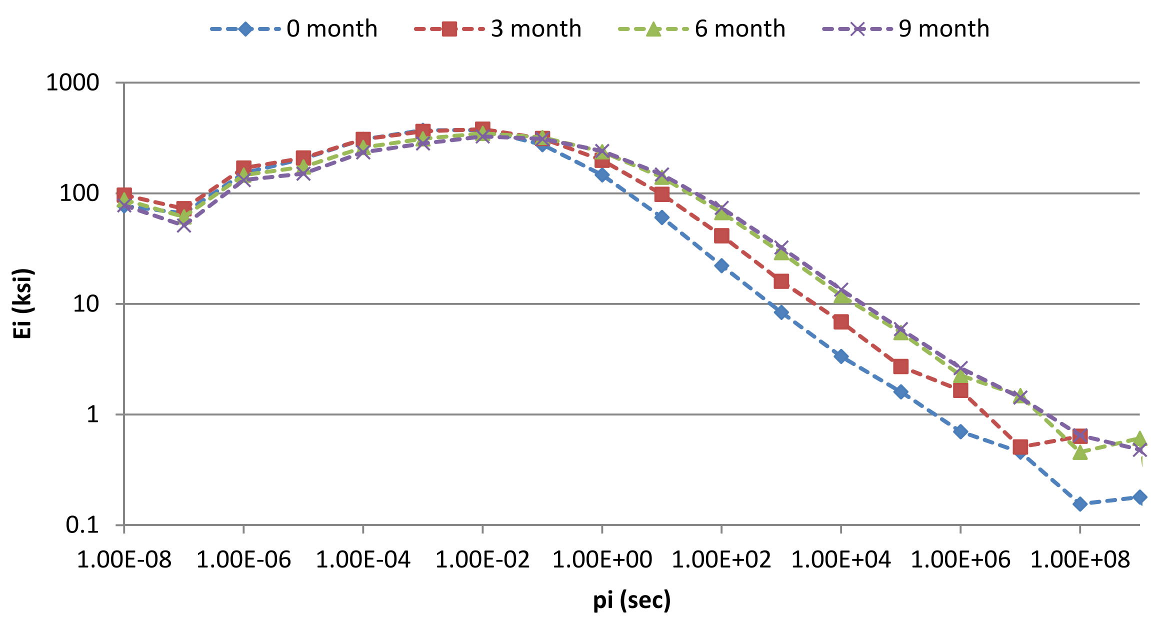


Figure E2d.1. Ei (relaxation strength) distribution of the generalized Maxwell model for asphalt mixture at different level of aging

Different mixtures with different aggregate structures and over a range of gradations covering most of the allowable range of gradations for a 12.5 mm nominal maximum aggregate size (NMAS) were used for simulations. Mastic properties were calculated based on dilatometric tests run on the binders. Figure E2d.2 shows the binary images obtained from iPas[2] for two of the analyzed mixtures having the highest and lowest number of aggregate contact zones, (i.e., connectivity).

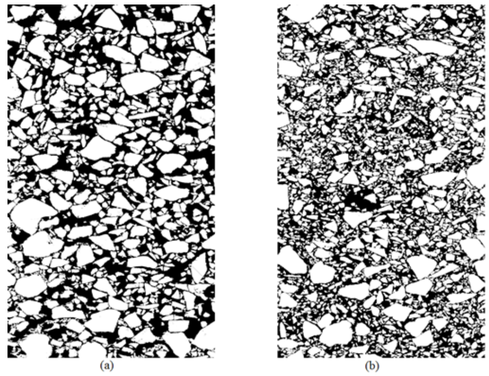


Figure E2d.2. Image. Binary representation of asphalt mixtures (a) lowest number of contact zones (b) highest number of contact zones.

Using the CTE and modulus of mastics as input, and knowing the volume fraction for the mastic and aggregate phases for each mixture, an FE model using ABAQUS software was used to estimate the thermal strain and to calculate the CTE for each mixture as temperature decreased.

Based on the number of aggregate to aggregate contact zones, it was observed that increasing the number of contact zones generally will cause a reduction in the calculated thermal contraction coefficient (CTE), determined using the model. Figure E2d.3 shows the relation between contact points/zones and CTE below and above glass transition temperature (T_g) for one mastic and different aggregate structures. In this figure, α_l and α_g are shown versus the number of contact zones for five different mixtures considered. It is observed that there is a good correlation between the number of contact zones and α_l, and a fair correlation with α_g.

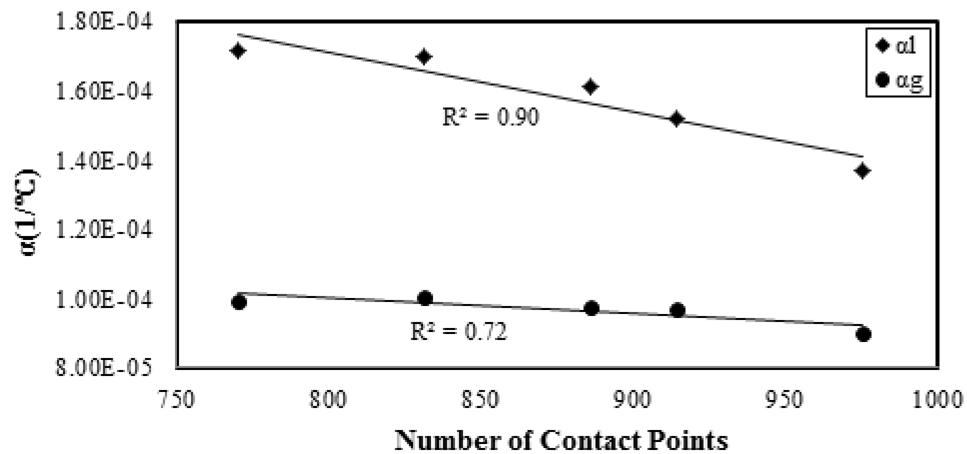


Figure E2d.3. Graph. CTE vs. number of contact zones/points for mixtures with same mastic but different aggregate structures.

Based on the simulations performed, it was observed that a decrease in the number of aggregate contact zones (points), which may implies a less effective aggregate skeleton structure, and an increase in the modulus of the mastic phase will result in an overall increase in the level of contribution of the mastic phase to the total thermal contraction coefficient of the composite mixture.

Significant Problems, Issues and Potential Impact on Progress

Progress on the E*-tension testing has been delayed due to further evaluation of the current testing system. Pending further evaluation, the testing will either continue or may potentially be dropped from the evaluation.

Work Planned Next Quarter

The binder kinetics testing will continue for the field validation efforts. With the additional DSR installed the low shear viscosity and binder master curves are to be completed for the laboratory phase during this quarter. Testing on the TSRST samples are also expected to get underway as the exact testing conditions are validated. Efforts will continue to perform the necessary measures for the selected field validation sections.

The UW research team will continue investigating the relationship between the thermo-volumetric properties of the mixture and relevant properties of its constituents (i.e., mastic and aggregate) to better understand the process of thermal contraction. Collaboration will continue with UNR on developing and implementing a user-friendly software for estimation of thermal cracking based on the findings of this work element. The research team has also made considerable progress in writing the first draft of the E2d final report. These efforts will continue in the next quarter.

Work element E2e: Design Guidance for Fatigue and Rut Resistance Mixtures (AAT)

Work Done This Quarter

Hirsch Model Refinements

Laboratory work continued this quarter on the experiments to refine the Hirsch model. Three experiments were planned to improve the Hirsch model: (1) curing time experiment, (2) limiting modulus experiment, (3) stress dependency experiment. Each of these experiments addresses a specific aspect of the Hirsch model and dynamic modulus testing. The curing time experiment addresses whether specimen aging significantly affects measured dynamic modulus values. The limiting modulus experiment address whether the limiting maximum modulus in an HMA mixture is significantly affected by the modulus of the aggregate used in the mixture. Finally, the stress dependency experiment address the effect of stress level on the limiting minimum modulus of HMA.

Data collection for the limiting modulus and stress dependency experiment was completed this quarter. Data have been collected on eight different mixtures. All data except the 90 day tests on two of the eight mixtures has been completed for the curing time experiment.

Data on refinement of the Hirsch model was also analyzed during the past quarter. Specifically, the relationship between aggregate specific gravity and the "aggregate modulus term" in the Hirsch model was analyzed (limiting modulus experiment). This aggregate modulus term is currently a constant value of 4,200,000 lb/in^2. The results were good, with an R^2 value of 46 % between the aggregate modulus term and aggregate bulk specific gravity. Incorporation of this information into the Hirsch model should improve the accuracy of the model. Further analysis will be possible as other data on the Hirsch model experiments become available.

A preliminary analysis of data from the curing time experiment was also done, calculating average modulus values at different ages, temperatures and frequencies, for of four of the eight mixes. It appears that curing time does affect the modulus of HMA mixes, but in a highly variable way. For some mixes, the modulus at 90 days is about 20 percent higher than that at 3 days. For other mixes, however, the modulus appears to be essentially unchanged by curing time. It is likely that such age-hardening is a significant source of error in modulus measurements for hot mix asphalt.

Resistivity Model Refinements

The objective of this work is to refine the rutting model developed in NCHRP Projects 9-25 and 9-31 to better address modified binders by using data from the multiple stress creep recovery tests to characterize the binders. A final experimental design for the resistivity model refinements was developed based on the aggregates selected for the Hirsch model refinement. It included ten binders with high temperature grade ranging from PG 58 to PG 82 and eight different aggregates. Five of the binders are polymer modified, two are PPA modified, and three are neat. Eighteen mixtures will be tested. A total of 34 binder/mixture/temperature combinations will be used in the testing.

Flow number and associated binder testing for the complete resistivity model experiment was completed this quarter. The data have been assembled for subsequent analysis.

Fatigue Model Refinements

As discussed last quarter, the research team decided to pursue the continuum damage fatigue testing using AAT's general purpose servo-hydraulic load frame after Interlaken's software engineer left for another job opportunity. NCHRP's Interlaken Asphalt Mixture Performance Tester does not provide the capability for the user defined programming needed to conduct the geometric stress progression and rest period testing planned for this experiment.

Programming of AAT's general purpose load frame was completed this quarter and several trial tests were conducted using a soft mixture with PG 58-28 binder and a stiff mixture with polymer modified PG 76-22 binder to determine temperatures, stress levels, and loading cycles that produce localization in all tests. An important component of the continuum damage analysis of pavements is the damage tolerance, which is the damage ratio where localization (cracking) occurs. Therefore, it is important to carry all of the geometric stress progression tests to failure.

A paper was presented at the Annual Meeting of the Association of Asphalt Paving Technologists, entitled "Modeling of Fatigue Damage Functions for Hot Mix Asphalt and Application to Surface Cracking." This paper will be published in the AAPT Journal next year. It discussed further refinements in the reduced cycles approach to continuum damage theory (CDT), and its use in predicting surface cracking observed in the ALF I and ALF II fatigue experiments conducted at the Turner-Fairbank Highway Research Center of the FHWA.

One of the most useful features of the reduced cycles approach to damage analysis is that the fatigue damage curves for a wide range of mixtures can be predicted with good accuracy using only the modulus and related data. However, one potential problem in this approach has been explaining two apparent anomalies in the approach:

(1) According to CDT, the value of alpha should be the inverse of the m value. For asphalt concrete, you would then expect alpha to have a value of approximately 90 divided by the phase angle. However, in the reduced cycles analysis, it appears that alpha can be considered to be a constant, with a value typically ranging from about 2 to 3 depending on the mix.

(2) If the value of alpha is constant, then CDT suggests that all damage curves should collapse to a single function. However, using the reduced cycles approach, even though alpha appears constant or nearly constant, the damage curves do not collapse to a single function.

After much effort during the past quarter, these anomalies can now be explained. CDT was developed to explain how damage accumulates in viscoelastic materials such as asphalt cement binder. Asphalt concrete is actually a composite, which is composed of about 85 % aggregate, 10 % asphalt binder and 5 % air by volume. In other words, the vast majority of volume in asphalt concrete is made of aggregate, a linear elastic material with a modulus 1 to 3 orders of magnitude greater than that of asphalt binder. This means that the strains in the asphalt binder will be much greater than those measured in the bulk concrete. Furthermore, the relationship between the bulk mix strain and the binder strain will not be constant, but will vary with temperature and loading rate.

An approximate analysis was made in which CDT was applied only to the asphalt binder of the asphalt concrete, estimating the strains in the binder by application of the Hirsch model. Then, the Hirsch model was again used with the damaged binder modulus to estimate the damaged mix modulus. This approach was applied to all 9-25/31 mixes and worked very well. When applied to the binder alone, the anomalies discussed above completely disappear—the value of alpha was found to be 90 divided by the phase angle. Furthermore, it was found that the location parameter for the damage curves was a function only of alpha and the glassy modulus of the binder—in other words, for a single value of alpha, the binder damage curves would in fact collapse to a single function. The binder CDT approach was applied to the large experiment, although in this case the binder properties had to be estimated by matching the mix modulus values as predicted using the Hirsch model. The resulting predicted damage curves matched the observed curves well, and exhibited the same puzzling lack of collapse. It can be concluded that the observed anomalies in the reduced cycles approach are in fact the result of applying CDT to the bulk mix, rather than to the asphalt binder alone.

It should be pointed out that although theoretically incorrect, application of CDT to the bulk mix is in fact very useful, as stated above, it has been used to generate a very useful model for predicting damage curves for hot mix asphalt mixes. Furthermore, it appears that application of CDT to the binder alone, although a useful theoretical exercise, involves many simplifications and assumptions, and for that reason the results do not appear suitable for developing predictive models. For this reason, efforts will continue to focus on CDT applications to asphalt concrete, but with a better understanding of why the CDT damage curves behave in a somewhat unusual way.

One further development in CDT analysis that has grown out of these efforts is that it appears that the assumed mathematical relationship used to model the mixture damage curves exhibits some lack of fit, and an improved function (the hyperbolic function tanh) has been found. Use of this function should allow significant improvement in the predictive model and in the testing protocol being developed for uniaxial fatigue testing.

Work Planned Next Quarter

The remaining tests for the Hirsch model curing time experiment will be completed next quarter. Analysis of the Hirsch model experiments and resistivity model experiments will also be completed. It is anticipated that most of the testing for the continuum damage experiment will also be completed. Data from all of the experiments will be uploaded to the ARC database.

Significant Problems, Issues and Potential Impact on Progress

The continuum damage fatigue testing remains behind schedule. The test protocol has been nearly finalized and the technicians at AAT are now proficient at conducting the tests. Upon finalization of the test protocol data collection for the fatigue experiment will be completed.

TABLE OF DECISION POINTS AND DELIVERABLES FOR ENGINEERED MATERIALS

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
E1a- Model and Algorithm for Modeling Cracking Damage in Asphalt Mixtures (TAMU)	Model and Algorithm	The model and algorithm for testing and analysis of damaged asphalt mixtures in tension	9/1/11	12/12	Late arrival of aggregates for fabrication specimens.
E1a – Characterize Fatigue Properties and Model Fatigue Crack Growth in Asphalt Mixtures (TAMU)	Draft Report	Report on developing an energy-based mechanistic approach to characterize fatigue properties of different types of asphalt mixtures, and model crack growth using evolution of damage density and fracture coefficients from the damage density.	12/ 12		New
E1a – Modeling Healing in Asphalt Mixtures (TAMU)	Model and Algorithm	The model and algorithm for testing and analysis of damaged asphalt mixtures to obtain recovery and healing properties using their true driving forces.	3/13		New
E1a – Characterize Recovery Properties and Model Healing of Asphalt Mixtures	Draft Report	Report on developing an energy-based mechanistic approach to characterize recovery properties using the internal stress, and model healing of asphalt mixtures using its true driving forces.	3/13		New
E1a- Continuum Damage Permanent Deformation Analysis for Asphalt Mixtures (TAMU)	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	8/31/12	Late arrival of aggregates
E1a- Develop a RDT DMA Testing Protocol (TAMU)	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	Complete	Presented as Technology Development #14
E1a- Standardize Testing Procedure for Specifications (TAMU)	AASHTO Specification	Develop a Standard Specification to use as a comparative test to evaluate fracture properties, healing and moisture damage of FAM	4/30/11	Submitted	Expanded scope

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
E1a- Develop a New DMA Testing Protocol for Compression (TAMU)	AASHTO Specification	Develop a Standardized testing method to use as a comparative test to evaluate compressive properties of FAM	9/15/11	3/15/12	More time need due to the machine data acquisition deficiency (machine built-in LVDT cannot meet needed strain precision) will fabricate special grip to incorporate the external magnetic sensor
E1b1-5: Standard Testing Procedure and Recommendation for Specifications (UWM)	Draft Report	Report on final conclusions and proposed procedures and specifications	7/11	12/12	Deadline for report “O” moved forward to accommodate FHWA request to stagger delivery dates.
	Final Report		1/12	8/13	
E1b-2i. Literature review (UWM)	Draft Report	Review of previous work on indentation and closed formed solution to the indentation problem.	7/09	12/12	Deadline for report “O” moved forward to accommodate FHWA request to stagger delivery dates.
E1b-2iii. Preliminary testing and correlation of results (UWM)	Draft Report	The use of indentation test for characterization of asphalt binders.	1/10	8/13	
E1b-2iv. Feasibility of using indentation tests for fracture and rheological properties (UWM)	Draft Report	Report on Finite element simulations of the indentation test and correlations with DSR results.	1/11	12/12	
	Final Report		4/11	8/13	
E1c-1ii. Effects of Warm Mix Additives on Mixture Workability and Stability (UWM)	Draft Report	Report of reviewed relevant literature and studies (to be combined with final report)	10/08	Complete	Additional work planned in the project extension. (Integrated with report “P”)
	Final Report		1/09		
	Draft Report	Impacts of WMA Additives on Asphalt Binder Performance and Mixture Workability	4/11	3/13	
	Final Report		1/12	10/13	
E1c-1v. Field Evaluation of Mix Design Procedures and Performance Recommendations (UWM)	Draft Report	Report on WMA Field Evaluation of Mix Design Procedures and Performance	10/11	3/13	
	Final Report		1/12	10/13	

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
E1c-2: Improvement of Emulsions' Characterization and Mixture Design for Cold Bitumen Applications (UWM)	Practice	Mix design method for cold-in-place recycling (CIR) that is consistent with the Superpave technology and that can be used to define the optimum combination of moisture content and emulsion content.	12/11	3/13	Additional work planned in project extension. (Integrated with report "Q")
	Practice	Mix design method for cold mix asphalt (CMA) that is consistent with the Superpave technology and that can be used to define the optimum combination of moisture content and emulsion content.	03/12	10/13	
E1c-2i: Review of Literature and Standards (UWM)	Draft Report	Review of Literature and Standards that will be combined with the final draft reports (to be combined with E1c-2vii and E1c-2ix final reports)	7/08	Complete	Additional work planned in project extension. (Integrated with report "Q")
	Final Report		10/08		
	Draft Report		4/09		
	Draft Report		7/09		
	Draft Report		1/10		
E1c-2iii: Identify Tests and Develop Experimental Plan (UWM)	Draft Report	Reports outlining the required tests and experimental plan for the study (to be combined with E1c-2vii and E1c-2ix final reports)	4/09	Complete	
	Draft Report		10/09		
E1c-2v. Conduct Testing Plan (UWM)	Draft Report	Report on the results and analysis of tests run in accordance to test plan (to be combined with E1c-2vii and E1c-2ix final reports)	10/09	Complete	
E1c-2vii. Validate Guidelines (UWM)	Draft Report	Draft report of the performance and Rheological and Bond Properties of Emulsions (to be combined with E1c-2vii final report)	7/09	9/13	Deadline for report "Q" moved backward to accommodate FHWA request to stagger delivery dates.
	Final Report	Final report of the performance and Rheological and Bond Properties of Emulsions	4/11	6/14	
E1c-2ix. Develop CMA Performance Guidelines (UWM)	Draft Report	Draft and final report of the performance guidelines of Cold Mix asphalt pavements	10/11	9/13	
	Final Report		1/12	6/14	

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
E2a-4: Write asphalt modification guideline/report on modifier impact over binder properties (UWM)	Draft Report	Report summarizing effect of modification on low, intermediate, and high temperature performance of asphalt binders. It includes guidelines for modification and cost index for different modification types	10/11	9/13	Deadline for report "N" moved to stagger delivery dates and allow for increased work load of project extension on extenders and solubility.
	Final Report	Report in 508 format that addresses comments/concerns from Draft Report	1/12	6/14	
E2b-1: Develop a System to Evaluate the Properties of RAP Materials (UNR with UWM input)	Draft Report	Report on Test Method to Quantify the Effect of RAP and RAS on Blended Binder Properties without Binder Extraction (To be combined with E2b1-b draft and final reports) (UWM input)	4/09	6/30/2013	Additional work planned in the project extension. (All reports integrated into report "G")
	Final Report		4/09	12/31/2013	
	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	6/30/2013	
E2b-1.b: Develop a System to Evaluate the Properties of the RAP Binder (UWM)	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	6/30/2013	Additional work planned in project extension. (All reports integrated into report "G")
	Final Report		1/12	12/30/2013	
E2b-3: Develop a Mix Design Procedure (UNR)	Draft report	Report summarizing the laboratory mixing experiment.	02/12	6/30/2013	Additional work planned in project extension. (All reports integrated into report "G")
	Final report		08/12	12/31/2013	
E2b-4: Impact of RAP Materials on Performance of Mixtures And E2b-5: Field Trials (UNR)	Draft report	Report summarizing the laboratory and field performance of field mixtures.	02/12	6/30/2013	
	Final report		08/12	12/31/2013	
E2c-2: Conduct Mixtures Evaluations (UNR)	Draft report	Approach to identify critical conditions of HMA mixtures	09/11	Complete	N/A
	Final report		03/12	N/A	N/A

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
E2c-3: Develop a Simple Test (UNR)	Draft report	Report summarizing the evaluation of mixtures from the Flow Number Task Force group.	11/11	04/12	Preliminary Draft submitted to FHWA ETG
	Final report		05/12	N/A	N/A
E2c-4: Develop Standard Test Procedure (UNR)	Practice	Recommended practice to identify the critical condition of an HMA mix at the mix design stage to avoid accelerated rutting failures of HMA pavements.	12/11	10/12	The large number of mixtures and testing conditions delayed the progress of this effort.
E2c-5: Evaluate the Impact of Mix Characteristics (UNR)	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		08/12	N/A	N/A
E2d-2: Identify the Causes of the Thermal Cracking (UNR)	Draft report	Report summarizes the testing and findings for materials from LTPP sections.	12/11	4/30/2013	Additional work planned in the project extension. (All reports integrated into report "I")
	Final report		06/12	10/31/2013	
E2d-3: Identify an Evaluation and Testing System (UNR with UWM input)	Draft report	Low Temperature Cracking Characterization of Asphalt Binders by Means of the Single-Edge Notch Bending (SENB) Test (UWM input)	04/11	4/30/2013	Additional work planned in the project extension. (All reports integrated into report "I")
	Final report		10/11	10/31/2013	
E2d-4: Modeling and validation of the Developed System (UNR with UWM input)	Draft report	Thermal cracking characterization of mixtures by means of the unified Tg-TSRST device. (UWM input)	10/11	4/30/2013	
	Final report		04/12	10/31/2013	
	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	4/30/2013	
E2d-5: Develop a Standard (UNR with UWM input)	Draft standard	Draft standards for the use of the SENB, binder Tg and the ATCA device (Mixture Tg). (UWM input)	10/11	4/30/2013	Additional work planned in the project extension. (All reports integrated into report "I")
E2d-5: Develop a Standard (UNR with UWM input)	Final standard		01/12	10/31/2013	

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
E2d-5: Develop a Standard (UNR with UWM input)	Draft standard	Draft standard for the use of the TSRST with cylindrical specimens compacted using the SGC.	03/11	4/30/2013	Delayed due to issues with specimens breaking at the edge. Working on refining sample preparation. Added the capability of measuring the strain change during testing. (Report "I")
	Final standard		01/12	10/31/2013	
E2e: Improved Models	Models	Improved composition to engineering property models. • Hirsch Model for dynamic modulus • Resistivity Model for rutting resistance • Continuum Damage Fatigue Model • Permeability	1/1/2012	6/30/12	Testing delays
E2e: New Model	Model	Damage tolerance as a function of mix fracture properties	12/31/2012	N/A	New work
E2e: Report documenting Work Element E2e	Draft Report	Draft Report for Design Guidance for Fatigue and Rut Resistance Mixtures	1/1/2012	12/31/2012	Dates corrected. Testing delays and addition of damage tolerance as a function of mix fracture properties.
	Final Report		3/31/2012	6/30/2013	

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									D,JP				
E1a-2: Analytical Micromechanical Models of Modified Mastic Systems									D				
E1a-3: Analytical Models of Mechanical Properties of Asphalt Mixtures			P(2)			P(2)			D,JP		P(2)	JP	
E1a-4: Analytical Model of Asphalt Mixture Response and Damage						P(2)			D		P	JP	
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			JP										
E1b1-5: Standard Testing Procedure and Recommendation for Specifications	P			D		JP							
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										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													
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			
E1c-1iii. Mixture Performance Testing													
E1c-1iv. Develop Revised Mix Design Procedures													
E1c-1v. Field Evaluation of Mix Design Procedures and Performance Recommendations										D			
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					JP								
E1c-2-vi. Develop Performance Selection Guidelines					JP							F	
E1c-2-vii. Validate Performance Guidelines													
E1c-2-viii. Develop CMA Mix Design Guidelines												P	
E1c-2ix. Develop CMA Performance Guidelines												P	

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			D, JP		
E1a-2: Analytical Micromechanical Models of Modified Mastic Systems				P, JP	JP	P	P			P		P			D		
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	JP(2)	P(2)	D, JP	P(2), JP	
E1a-4: Analytical Model of Asphalt Mixture Response and Damage				P, JP	JP	P	P					P		P(2)	D	P, JP	
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			
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				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																	
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				WRI
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	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	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-2iii: 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		JP			
E1c-2vi. Develop Performance Selection Guidelines										JP		P		JP		F	
E1c-2vii. Validate Guidelines						D2											
E1c-2viii. Develop CMA Mix Design Procedure																P	
E1c-2ix. Develop CMA Performance Guidelines																P	

Deliverable codes
D: Draft Report
F: Final Report
M&A: Model and algorithm
SW: Software
JP: Journal paper
P: Presentation
DP: Decision Point

Deliverable Description
Report delivered to FHWA for 3 week review period.
Final report delivered in compliance with FHWA publication standards
Mathematical model and sample code
Executable software, code and user manual
Paper submitted to conference or journal
Presentation for symposium, conference or other
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)

Work Done This Quarter

The final draft was submitted in 508 formatting this quarter. A document containing captions for figures to allow for interpretation by visually impaired was prepared and submitted to FHWA.

Significant Problems, Issues and Potential Impact on Progress

None.

Work Planned Next Quarter

Revise final report (if necessary).

Cited References

None

Papers Submitted

None

CATEGORY VP3: MODELING

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

Work Done This Quarter

The activities on many fronts continued during this quarter on our work on 3D-Move Analysis software. They are: (1) Integration of Principal Stress and Strain Evaluations in the Results of Response Window; (2) Continued development of the Pavement Performance Module (PPM); and (3) Development of User Guide. Brief descriptions on selected significant components are presented below. These activities will be integrated into 3D-Move version 2.0 software, which has been under further internal evaluation for bugs and errors.

Thus far attention relative to pavement response has been directed to all components of stresses and strains. Time histories of these components under Dynamic Response option are already available. These response values are what required in PPM evaluations in both NCHRP 1-37A and VESYS models. However, many current users have requested that they would like to also see Principal Stresses and Strains. This option has been integrated into the main Output window as shown in figure VP3a.1. This enables the users to view and plot as necessary these response histories.

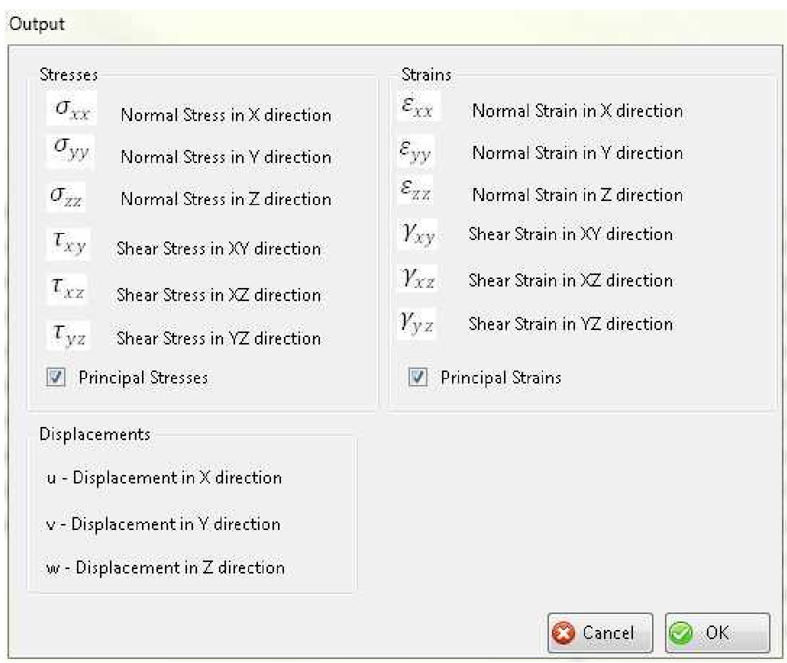


Figure VP3a.1. Incorporation of principal stress and strain time history option in output window.

As we have noted in the past, the work on Pavement Performance Model (PPM) continued to present many unexpected problems. Many of such issues can be directly traced to the difference in US vs. SI units as many of the Pavement Performance Models are unit sensitive. In addition, some performance models require certain specific inputs that are unique to those models and they have to be evaluated to use such models. It should be noted that the PPM work is based mainly on NCHRP 1-37A (MEPDG) and VESYS models. NCHRP 1-37A performance model comprises of six failure modes: AC Top down cracking, AC Bottom up cracking, AC rutting, Base rutting, Subbase rutting and Subgrade rutting, whereas VESYS performance model contains the following four failure modes: Fatigue cracking, Layer rutting, System rutting, and Roughness.

We have included many additional windows to clearly report the PPM model and the corresponding performance equations used in the performance calculations. For example, such details in the case of NCHRP 1-37A model for AC Top Down Cracking and Subgrade Rutting are shown in figures VP3a.2a and VP3a.2b. These equations require many input parameters and some of those inputs are material properties that have been previously defined. In such cases, the window will populate those pre-defined values and the user is to only provide the other addition inputs. The critical response parameter, for example the Tensile Strain at the Bottom of the AC Layer will be directly come from the completed 3D-Move run.

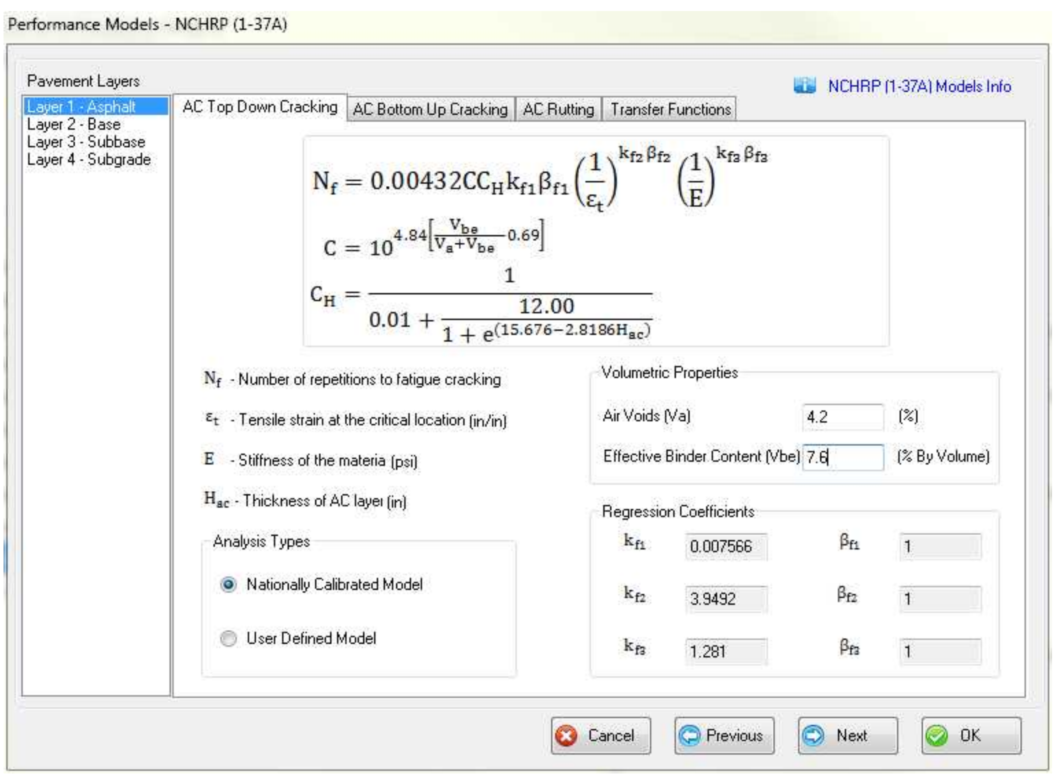


Figure VP3a.2a. NCHRP 1-37A performance model for AC top down cracking.

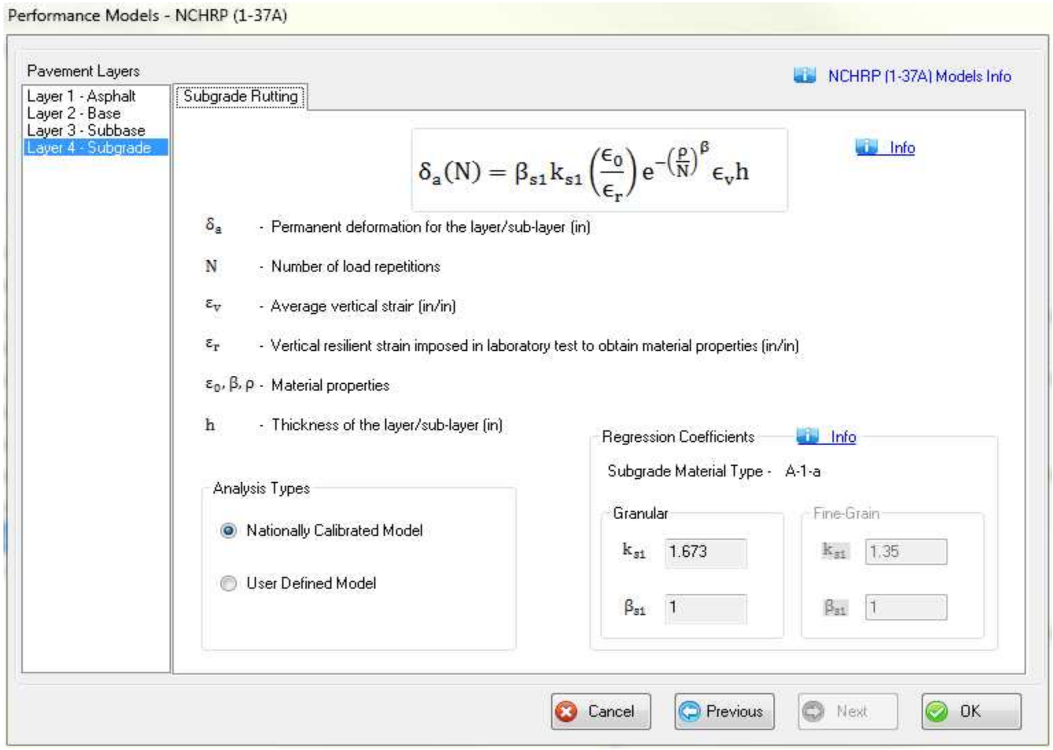
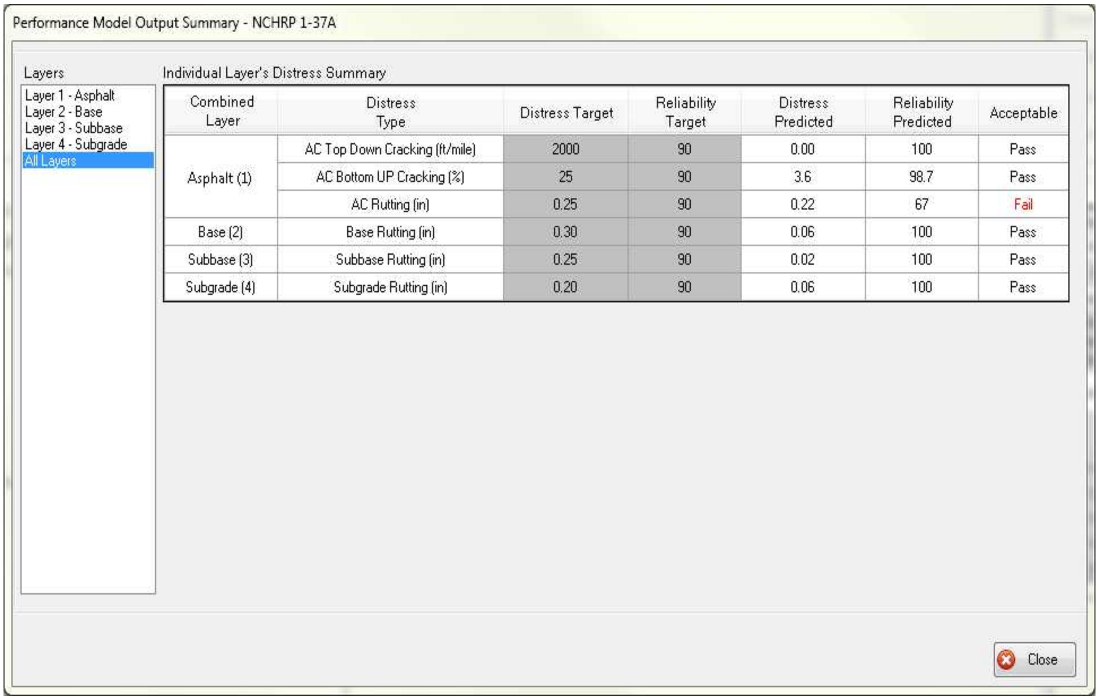


Figure VP3a.2b. NCHRP 1-37A performance model for subgrade rutting.

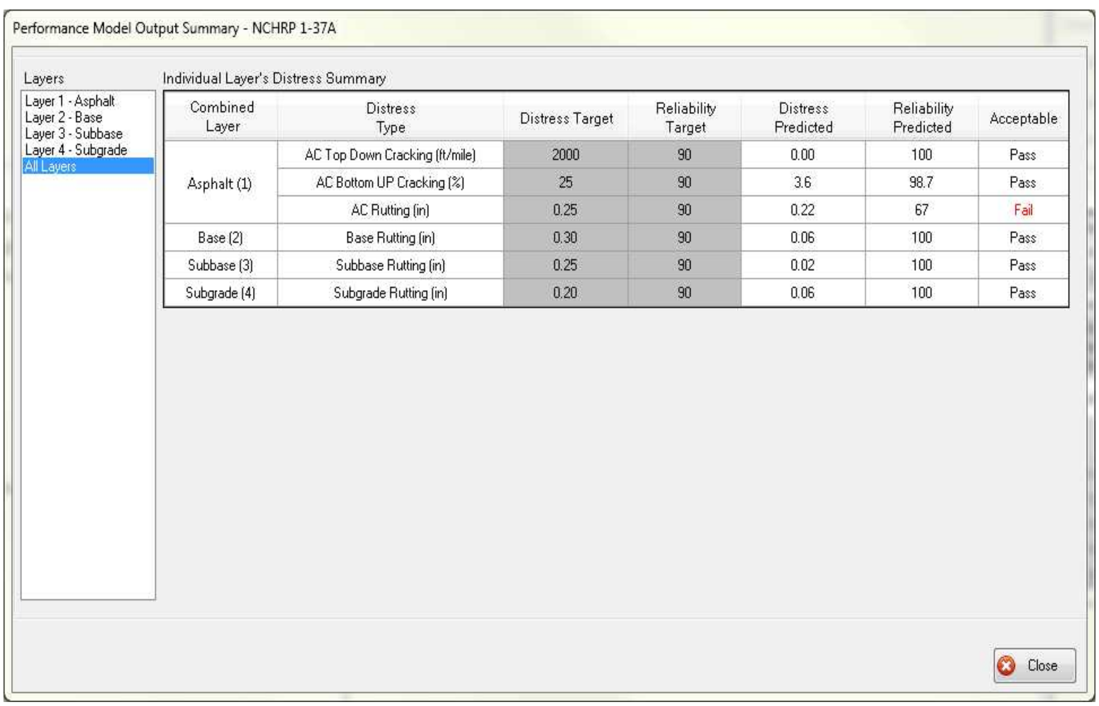
In addition, to test for any discrepancies or bugs relative to unit sensitivities (US and SI) associated with the use of the PPM, many cases of typical pavement structures and material properties were input by selecting both US and SI units. The performance results given by the 3D-Move Analysis software were compared to ascertain that the results are insensitive to selection of the unit system. Figures VP3a.3a and VP3a.3b show the performance comparison and it is seen that the results are identical.

This quarter was also was spent on assisting users with issues ranging from usage questions, concepts clarifications, and bugs. The 3D-Move Analysis software developing team worked on fixing the reported bugs.



Combined Layer	Distress Type	Distress Target	Reliability Target	Distress Predicted	Reliability Predicted	Acceptable
Asphalt (1)	AC Top Down Cracking (ft/mile)	2000	90	0.00	100	Pass
	AC Bottom UP Cracking (%)	25	90	3.6	98.7	Pass
	AC Rutting (in)	0.25	90	0.22	67	Fail
Base (2)	Base Rutting (in)	0.30	90	0.06	100	Pass
Subbase (3)	Subbase Rutting (in)	0.25	90	0.02	100	Pass
Subgrade (4)	Subgrade Rutting (in)	0.20	90	0.06	100	Pass

Figure VP3a.3a. NCHRP 1-37A performance model results with US units.



Combined Layer	Distress Type	Distress Target	Reliability Target	Distress Predicted	Reliability Predicted	Acceptable
Asphalt (1)	AC Top Down Cracking (ft/mile)	2000	90	0.00	100	Pass
	AC Bottom UP Cracking (%)	25	90	3.6	98.7	Pass
	AC Rutting (in)	0.25	90	0.22	67	Fail
Base (2)	Base Rutting (in)	0.30	90	0.06	100	Pass
Subbase (3)	Subbase Rutting (in)	0.25	90	0.02	100	Pass
Subgrade (4)	Subgrade Rutting (in)	0.20	90	0.06	100	Pass

Figure VP3a.3b. NCHRP 1-37A performance model results with SI units.

Significant Results

After considerable effort, many thorny issues with the integration of PPMs with both US and SI unit systems have been resolved. Now the Output window includes options for viewing and plotting histories of both Principal Stresses and Strains.

The new version of 3D-Move (version 2) has been further alpha-tested and the beta-testing is continuing. It is anticipated that this version will be released in the upcoming quarter.

Significant Problems, Issues and Potential Impact on Progress

The release of version 2.0 of the software was delayed because of extensive verification of the Pavement Performance Module (PPM).

The 3D-Move Analysis verification plan was postponed until the release of the version 2.0 of the software that will have the various new features and address the various bugs.

Work Planned Next Quarter

Continue working on the 3D-Move model to make it a versatile menu-driven software. Complete the beta-testing of version 2.0 of the software. Continue to solve any issues and bugs that users may encounter. Continue to maintain the 3D-Move Forum.

TABLE OF DECISION POINTS AND DELIVERABLES FOR VEHICLE-PAVEMENT INTERACTION

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for Changes in Delivery Date
VP2a-4: Run parametric studies on tire-pavement noise and skid response (UWM)	Draft Report	Draft report on proposed design guideline for noise reduction, durability, safety and costs	1/10	12/11	Draft report "R" has been prepared in 508 format and submitted to FHWA with accompanying documents.
VP2a-7: Proposed optimal guideline for design to include noise reduction, durability, safety and costs (UWM)	Final Report	Final report on proposed design guideline for noise reduction, durability, safety and costs	1/12	9/12	
VP3a-4: Overall Model (UNR)	Software	Release of version 2.0 of the 3D-Move pavement response model	06/11	06/12	Extensive verification of the Pavement Performance Module (PPM) delayed the release of version 2.0 of the software.
	Draft report	Summarizing *3D-Move Analysis* software	12/11	06/12	The release of version 2.0 delayed this effort.
	Final report		06/12	N/A	N/A
	Software	Release of final version of the 3D-Move pavement response model	03/12	N/A	N/A

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				
(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		
(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
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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)

Work Done This Quarter

No WMA monitoring was planned for this quarter.

Significant Results

None.

Significant Problems, Issues and Potential Impact on Progress

None.

Work Planned Next Quarter

No WMA monitoring is planned for the next quarter.

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

Work Done This Quarter

No site monitoring activity was planned for this quarter. A list of seven possible new performance sites of interest to the ARC was prepared for the LTPP regional support contractors and sent. The list is for the LTPP contractors to present to the states where older LTPP sections are planned for rehabilitation or reconstruction. This is intended to help the ARC to take advantage of the wealth of data already collected at these sites by finding new experiments for continuing the LTPP sections.

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

Significant Results

None.

Significant Problems, Issues and Potential Impact on Progress

None.

Work Planned Next Quarter

It is planned to monitor the Kansas site in the next quarter.

CATEGORY V2: ACCELERATED PAVEMENT TESTING

Work element V2a: Accelerated Pavement Testing including Scale Model Load Simulation on Small Test Track

Work Done This Quarter

No activity this quarter. This work element was included in order to accommodate any accelerated testing that may occur during the project.

Significant Results

None.

Significant Problems, Issues and Potential Impact on Progress

None.

Work Planned Next Quarter

No accelerated (field) testing is planned.

Work element V2b: Construction of Validation Sections at the Pecos Research & Testing Center

This work element is included to indicate that this may be a possibility for accelerated pavement testing for ARC research because it is a facility in the TAMU system.

CATEGORY V3: R&D VALIDATION

Work element V3a: Continual Assessment of Specifications (UWM)

Work Done This Quarter

Research efforts focused on continuing asphalt binder testing as part of the Western Cooperative Test Group (WCTG) round-robin study. Researchers conducted performance-grade (PG) and performance-grade-plus (PG+) tests to continue investigation of method efficacy and repeatability. Binder testing also served as a check to ensure that laboratory test machines remain properly calibrated for all other work elements.

Also in this quarter, the research team arranged for a meeting with RMAUPG and WCTG leaders to discuss the mixture testing and field performance database. Research personnel attended the annual WCTG/RMAUPG annual meeting in Nevada to present summary of data collected to date and solidify continued participation in this binder testing program.

In preparation for the final reports, data and results collected for this element has been (and will continue to be) integrated into the final reports of other work elements (E1b-1 and E2d), as indicated in the 21 month extension work plan. Therefore, there will be no final report for this specific work element.

Significant Results

Results from WCTG binder testing will be added to the database of binders used for establishing limits (Jnr , %R, and number of cycles per stress level) for the MSCR test. The research team believes the binders included in the WCTG/RMAUPG database show merit in helping to better establish testing limits as they represent a broader range on modified and region-specific binders. These potential changes will be recommended to be included in the AASHTO TP-70 and MP-19 standards. As an example, figure V3a.1 shows the change in Jnr as a function of loading cycles. As shown in the plot, the Jnr value continues to change significantly after more than 10 cycles. It is therefore clear that taking the average of the first 10 cycles could be very misleading. Such information can be used to improve quality and repeatability of Jnr data collected.

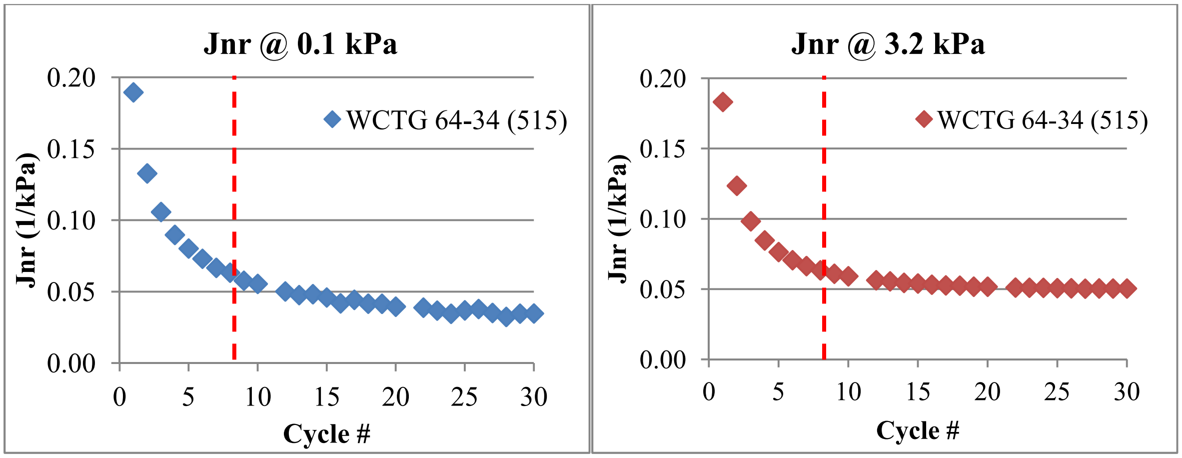

Figure V3a.1. Thirty cycles MSCR test results for binder with high delayed elasticity. Jnr does not reach steady state in first 10 cycles.

Problems and Implications for Work

Mixture testing remains on hold while mechanical testing equipment is repaired. It is expected that this equipment will be online within the next quarter. Binder testing equipment has been recently calibrated as well.

Work Planned Next Quarter

Work in the next quarter will focus on the following tasks:

- Participating in WCTG binder testing.
- Transitioning data collection and analysis templates to WCTG leadership.
- Fixing mixture testing equipment and continuing related 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 (Start Year 1, Year 2, and Year 3)

Subtask V3b-2: Additional Testing (Start Year 2, Year 3, and Year 4)

Work Done This Quarter

None

Significant Results

None

Significant Problems, Issues and Potential Impact on Progress

Only two agencies have committed to the construction of MEPDG sites: the Washoe RTC in northern Nevada in 2008, The South Dakota DOT in 2009/2010. The researchers are facing significant hesitation from the DOTs to use the MEPDG to design and construct HMA pavements. The level of this work element has been reduced.

Work Planned Next Quarter

None

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

Work Done This Quarter

In this quarter the research team contacted MnROAD engineers to use Minnesota Test Track for validation of ARC products. The research team discussed and selected potential validation sections with MnROAD managers from the mainline (figure V3b-3.1) and the low volume close-loop (figure V3b-3.2). Asphalt binders and mixtures from selected cells in MnROAD Phase I and Phase II (current) are available for validation of promising ARC products.

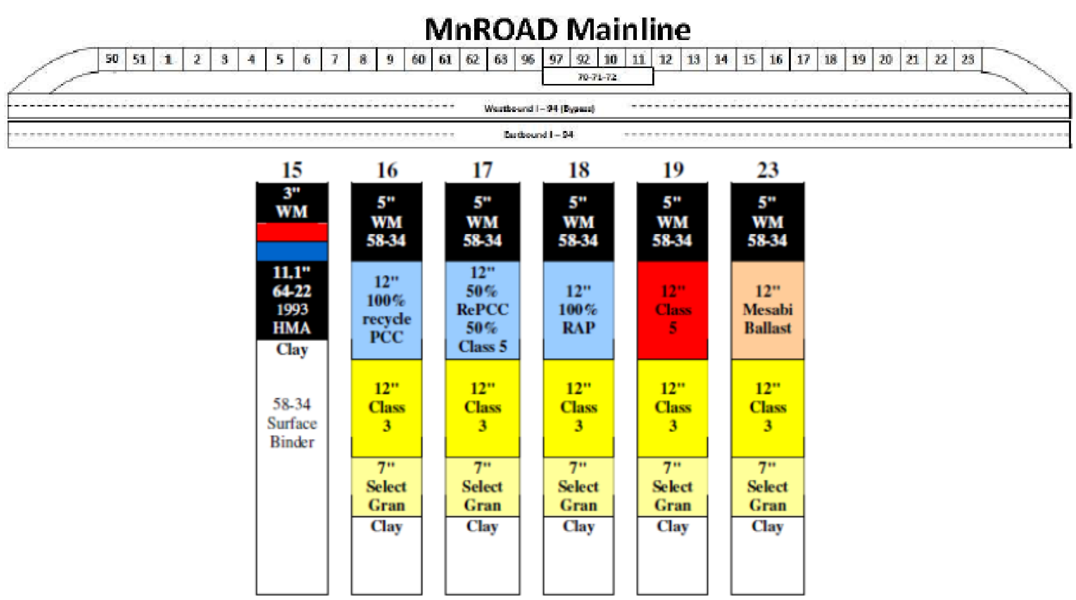

Figure V3b-3.1. Schematic. MnROAD Mainline cells selected for validation of ARC products (from http://www.dot.state.mn.us/mnroad/).

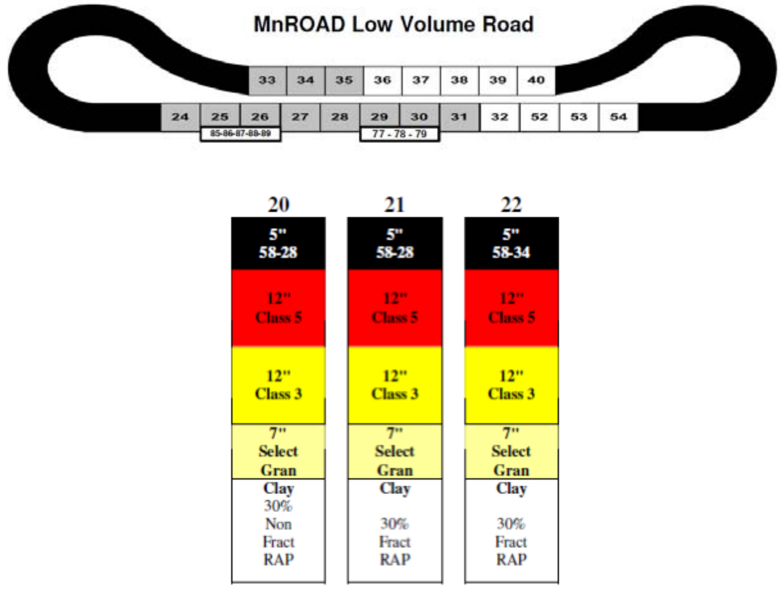

Figure V3b-3.2. Schematic. MnROAD Low Volume cells selected for validation of ARC products (from http://www.dot.state.mn.us/mnroad/).

Significant Results

MnROAD is located near Albertville, Minnesota, and consists of two road segments located next to Interstate I-94: (a) 3.5-mile mainline (ML) interstate roadway carrying regular traffic and (b) 2.5- mile closed- loop, low- volume road (LVR) carrying controlled traffic (i.e., 5-axle tractor-semi-trailer). MnROAD cells have a wide variety of sensors that measure variables such as temperature, moisture, strain, deflection, and frost depth, among others. The following sections have been identified as potential cells for validation of products in different areas:

- Low temperature cracking: Cells 20, 21, and 22 and shoulders constructed with shingles in Cells 13-15. For validation of SENB and Tg measurements.
- Fatigue cracking: Cells 27 and 28. For validation of LAS, BYET, and Healing test under development.
- Rutting: Cells 24 and 31. For validation of MSCR and indentation test.
- WMA: Cells 15, 16, 17, 18, 19, and 23. For validation of reduced temperature effects and aggregate structure (iPas2) results.

Work Planned Next Quarter

In the next quarter the research team will focus on collecting materials from MnROAD and developing a validation testing matrix for ARC products identified in work plan for 21-month extension. The team will also work on collecting valuable performance data available in MnROAD database.

Based on the work plan for the 21-month extension, validation efforts will not be reported independently in a single report as originally planned. The validation work for each ARC product will be reported in their respective final report.

Work Element V3c: Validation of PANDA (TAMU)

Work Done this Quarter

Please refer to the details presented in work elements M4c, F1d-8, and F3c. These work elements outline what has already been accomplished in validating the constitutive models that are implemented in PANDA as well as the validation work that will be carried out in the coming quarter.

In this quarter, emphasis has been placed on the development of a systematic procedure for identification of the model parameters. Systematic procedures for calibration of the nonlinear viscoelastic, viscoplastic, hardening-relaxation viscoplastic, and viscodamage models are developed. Specifically, the hardening-relaxation model is validated thoroughly against the ALF experimental data in compression. Moreover, the ALF database in tension is used to validate the viscodamage and micro-damage evolution functions. The significance of micro-damage healing during the cyclic displacement controlled test is presented. It is shown that the viscodamage and micro-damage healing models implemented in PANDA predict the fatigue damage of asphalt concrete reasonably.

Also, we have continued to carry out the ARC testing plan in compression. The dynamic modulus tests as well as the repeated creep-recovery test at various stress levels, conducted as part of the ARC testing plan, have already been used for calibrating the viscoelastic and viscoplastic models, respectively. The aging data based on the dynamic modulus test are available and currently used for calibration and validation of the oxidation aging model. The list of planned tests has been presented in the 6th year work plan. Dr. Richard Kim from North Carolina State University has finished the un-aged and un-moisture-conditioned tension testing for one mixture. Those data will be used in calibrating and validating the PANDA viscodamage evolution law.

Significant Results

See the significant results sections in work elements M4c, F1d-8, and F3c.

Significant Problems, Issues and Potential Impact on Progress

See the significant results sections in work elements M4c, F1d-8, and F3c.

Work Planned Next Quarter

Focus will be placed on validation of PANDA using the ARC testing plan. The compression testing is currently conducted at Texas A&M University whereas the tensile testing is conducted at North Carolina State University (NCSU). See the previous quarterly report for the list of planed tensile and compressive tests that will be conducted (tables V3c.3-8).

PANDA Software

Work Done This Quarter

In this quarter, all the implemented elements in PANDA (see figure V3c.1) have been verified for accuracy and robustness in conducting the simulations. Considerable effort has been focused on improving the computational efficiency of the finite element code through implementing numerical algorithms that accelerate convergence. Furthermore, all potential solution bugs have been resolved. Moreover, work has been started on transferring the developed constitutive models that have been developed as part of the UMAT subroutine in Abaqus to the standalone PANDA finite element software. All the constitutive models (linear-nonlinear viscoelasticity, viscoplasticity, viscodamage, moisture damage, healing, and aging models) have been transferred to PANDA. Therefore, at this stage of development, we have a working PANDA that can be used to simulate various types of problems; plane stress, plane strain, axisymmetric, and three-dimensional problems with various levels of accuracy and computational time. The two-dimensional elements (i.e. the plane stress, plane strain, and axisymmetric) can be used to simulate two-dimensional pavement sections or various laboratory testing setups (e.g. dynamic modulus test, creep-recovery test, uniaxial tension/compression tests, cyclic stress/strain controlled tests, etc). On the other hand, the three-dimensional elements can be used to conduct more realistic pavement performance simulations.

Currently, the steps in running PANDA are:

1. Create an input file:
PANDA works by reading and responding to a set of commands (called KEYWORDS) in an input file. The keywords contain the information to define the mesh, the properties of material, the boundary conditions, and to control output from the program.

2. Run PANDA program:
By double click on the execution file of PANDA.exe, the user will be asked to enter the name of the input file.

3. Post-processing:
There is one way for now to look at the results of a PANDA simulation. The results are printed to a file, which one can look at with a text editor. The output is not shown here since it is very large. But, the results include the stresses and strains at each integration point and the reactions and displacements at each node.

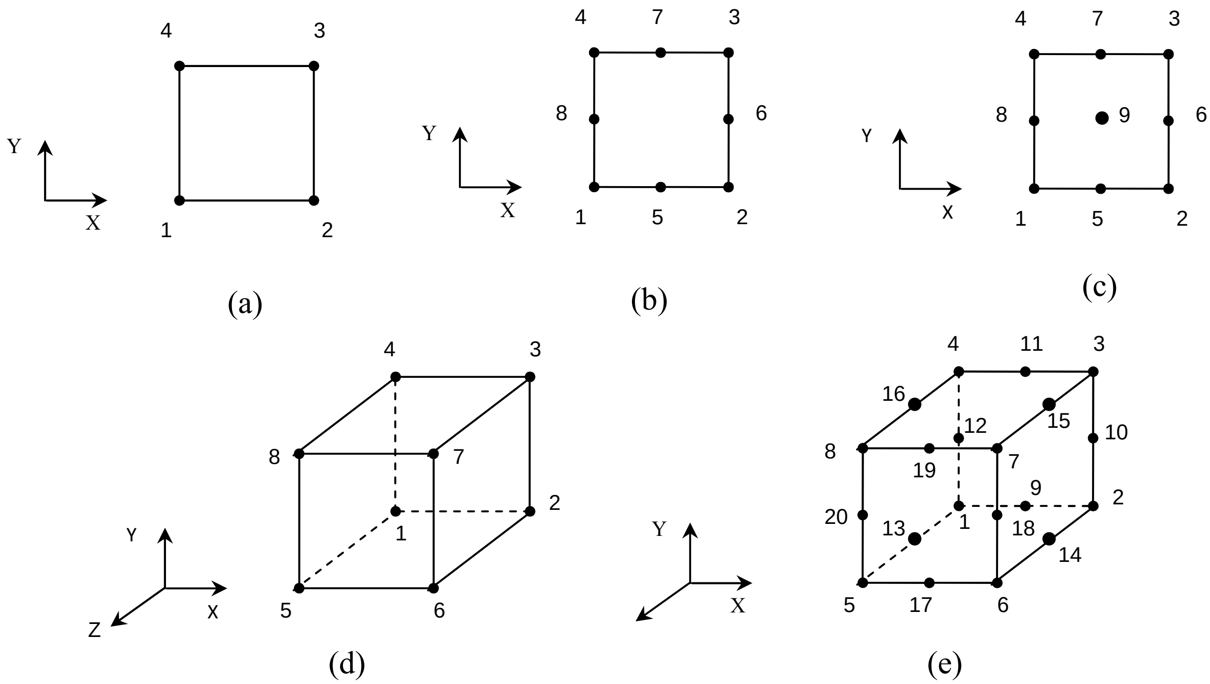

Figure V3c.1. The implemented 2D and 3D finite elements: (a) 2D four-node finite element, (b) 2D eight-node finite element, (c) 2D nine-node finite element, (d) 3D eight-node brick finite element, and (e) 3D twenty-node brick finite element.

<u>Significant Results</u>

None

<u>Significant Problems, Issues and Potential Impact on Progress</u>

None

<u>Work Planned Next Quarter</u>

In next quarter, the results from PANDA and UMAT-Abaqus will be compared to make sure that the transfer of the PANDA constructive models from PANDA-UMAT has been done correctly. Moreover, work is in progress of writing the installation and user manual of PANDA. Work is in progress in writing two chapters; the first on “Using PANDA” and the second on “Keywords” for writing the input file for PANDA. Work will be started in creating the user-friendly interface of PANDA.

Work Element V3d: Engineered Properties Testing Plan (TAMU)

Work Done this Quarter

The work completed this quarter relates to work described in Work Elements F2c and E1a.

Work Planned Next Quarter

Please refer to Work Elements F2c and E1a.

TABLE OF DECISION POINTS AND DELIVERABLES FOR VALIDATION

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
V3a-1: Evaluation of the PG-Plus practices and the motivations for selecting the “plus” tests. (UWM)	Draft Report	Detailed analysis of PG and PG+ tests	10/08	N/A	Additional work planned in project extension. V3a and V3b will not have independent reports. Results will be included as chapters in reports G, I, L, M, O, P and Q.
	Final Report	Report on 508 format on benefits of PG+ and new ARC tests in comparison to PG tests. Repeatability of PG+ and newly developed ARC procedures	12/08	N/A	
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 (UWM)	Draft Report	Refer to Draft Report for V3a-1	4/09	N/A	
V3a-4: Development of specification criteria for new tests based on field evaluation of construction and performance (UWM)	Draft Report	Refer to Draft Report for V3a-1	7/09	N/A	Refer to Draft Report for V3a-1
V3a-5: Interviews and surveys for soliciting feedback on binder tests and specifications (UWM)	Draft Report	Report summarizing collaboration between Western Cooperative Test Group (WCTG), the Rocky Mountain Asphalt User-Produce Group (RMAUPG) and UW-Madison	12/11	N/A	Refer to Draft Report for V3a-1
	Final Report	Report in 508 format on Development and maintenance of database for evaluation of PG, PG+, and new ARC tests.	1/12	N/A	

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for changes in delivery date
V3b-3: Select LTPP Sites to Validate New Binder Testing Procedures (UWM)	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.	12/11	N/A	Additional work planned in project extension. V3a and V3b will not have independent reports. Results will be included as chapters in reports G, I, L, M, O, P and Q.
	Final Report	Final report in 508 format on validation/verification of fatigue, thermal cracking, and moisture damage procedures using LTPP binders.	1/12	N/A	
V3c: Validation of PANDA (TAMU)	PANDA Workshop	Workshop on PANDA Models and Validation Results	8/11	4/13	Waiting for full calibration and validation of PANDA
	Draft Report	Documentation of PANDA Models and Validation	11/11	12/31/12	Validation against ARC testing
	Final Report (M5, M4c, F1b-1, F1c, F1d-8, F3c, and V3c)	Documentation of PANDA Models and Validation	3/12	3/31/13	N/A
	UMAT Material	PANDA Implemented in Abaqus	3/12	3/31/13	N/A
	Software	Standalone Software to support the use of and future utility and flexibility of PANDA	3/12	3/13	Creating user friendly interface for PANDA

Validation Year 5

Task	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							
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										
V3a-5: Interviews and surveys for soliciting feedback on binder tests and specifications		P											
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													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													
V3c: Validation of PANDA													TAMU
V3d: Engineered Properties Testing Plan	JP		JP	P(4)									

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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			
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				
V3a-5: Interviews and surveys for soliciting feedback on binder tests and specifications									P		JP		P				
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																	
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																	
V3c: Validation of PANDA																	**TAMU**
V3d: Engineered Properties Testing Plan										P(2)	JP	P(3), JP					

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Work planned
Work completed
Parallel topic

PROGRAM AREA: TECHNOLOGY DEVELOPMENT

Work element TD1: Prioritize and Select Products for Early Development (Year 1) (AAT, WRI)

This work element has been completed. Six early development products were identified.

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

Work Done This Quarter

Table TD2.1 summarizes the progress on the Products for Early Development. The test method for Automated Flocculation Titrimetric Analysis has been published as an ASTM standard method of test, ASTM D6703 – 07. Draft AASHTO Standards have been completed for other 5 products; however, the Draft AASHTO Standard for simplified continuum damage fatigue analysis for the Asphalt Mixture Performance Tester is being revised significantly based on the findings of the analyses being conducted in the continuum damage fatigue model refinement in Work Element E2e. The Draft AASHTO Standard for Determination of Polymer in Modified Asphalt is available on the outreach portion of the ARC website at: http://www.arc.unr.edu/Outreach.html#TechDevelopmentProducts.

Table TD2.1. Summary of progress on early development products.

No.	Product	ARC Research Program	Format	Estimated Completion Data	ARC Partner	Draft AASHTO Standard?
1	Simplified Continuum Damage Fatigue Analysis for the Asphalt Mixture Performance Tester	Prior	Test Method	6/30/2012	AAT	Yes
2	Wilhelmy Plate Test	Prior	Test Method	Completed	TTI	Yes
3	Universal Sorption Device	Prior	Test Method	Completed	TTI	Yes
4	Dynamic Mechanical Analysis	Prior	Test Method	Completed	TTI	Yes
5	Automated Flocculation Titrimetric Analysis	Prior	Test Method	Completed	WRI	No (ASTM)
6	Determination of Polymer in Asphalt	Prior	Test Method	Completed	WRI	Yes

Work Planned Next Quarter

AAT will continue revising the Draft AASHTO Standard for simplified continuum damage fatigue analysis for the Asphalt Mixture Performance Tester based on the findings from the continuum damage fatigue model refinement in Work Element E2e. Based on the ratings from the ETGs, support will be provided for advancing the selected products through AASHTO for publication as Provisional AASHTO Standards.

Significant Problems, Issues and Potential Impact on Progress

None.

Work element TD3: Identify Products for Mid-Term and Long-Term Development (Years 2, 3, and 4) (AAT, TTI, UNR, UW-M, WRI)

This work element has been completed. A total of 38 mid- and long-term products were identified. Table TD3.1 summarizes these products.

Table TD3.1. Summary of mid- and long-term technology development products.

No.	Product	ARC Work Element	Format	Estimated Completion Date	ARC Partner
7	A Method for the Preparation of Specimens of Fine Aggregate Matrix of Asphalt Mixtures	M1c	Test Method	12/31/2010	TTI
8	Measuring intrinsic healing characteristics of asphalt binders	F1d	Test Method	12/31/2012	TTI / UT Austin
9	Lattice Micromechanical Model for Virtual Testing of Asphalt Concrete in Tension	F3b	Analysis Program	2/28/2012	NCSU
10	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
11	Pavement Analysis Using Nonlinear Damage Approach (PANDA)	F3c	Test Method	12/31/2012	TTI

Table TD3.1 continued. Summary of mid- and long-term technology development products.

12	Test Methods for Determining the Parameters of Material Models in PANDA (Pavement Analysis Using Nonlinear Damage Approach)	F3c E1a	Test Method	12/31/2011	TTI
13	Continuum Damage Permanent Deformation Analysis for Asphalt Mixtures	E1a	Test Method	9/30/2011	TTI
14	Characterization of Fatigue and Healing Properties of Asphalt Mixtures Using Repeated Direct Tension Test	E1a	Test Method & Data Analysis Program	9/30/2011	TTI
15	Nondestructive Characterization of Tensile Viscoelastic Properties of Undamaged Asphalt Mixtures	E1a	Test Method & Data Analysis Program	Completed	TTI
16	Nondestructive Characterization of Field Cores of Asphalt Pavements	E1a	Test Method & Data Analysis Program	9/30/2011	TTI
17	Self-Consistent Micromechanics Models of Asphalt Mixtures	E1a	Analytical Model & Data Analysis Program	6/30/2011	TTI
18	Nondestructive Characterization of Anisotropic Viscoelastic Properties of Undamaged Asphalt Mixtures under Compressive Loading	E1a	Test Method	Completed	TTI
19	Mix Design for Cold-In-Place Recycling (CIR)	E1c	Practice	12/31/2011	UNR
20	Mix Design for Cold Mix Asphalt	E1c	Practice	3/31/2012	UNR
21	Evaluation of RAP Aggregates	E2b	Practice	4/30/2011	UNR
22	Identification of Critical Conditions for HMA mixtures	E2c	Practice	12/31/2011	UNR
23	Thermal Stress Restrained Specimen Test (TSRST)	E2d	Test Method	9/30/2011	UNR
24	HMA Thermal Stresses in the Intermountain Region	E2d	Model	3/31/2012	UNR
25	Dynamic Model for Flexible Pavements 3D-Move	VP3a	Software	3/31/2011	UNR

Table TD3.1 continued. Summary of mid- and long-term technology development products.

26	Bitumen Bond Strength Test (BBS)	M1a	Test Method	Completed	UWM
27	Elastic Recovery – DSR	F2a	Test Method	12/31/2010	UWM
28	Linear Amplitude Sweep (DSR)	F2e	Test Method	Completed	UWM
29	Binder Yield Energy Test (BYET)	F2e	Test Method	Completed	UWM
30	Rigden Voids for fillers	F2e	Test Method	9/30/2011	UWM
31	Binder Lubricity Test – DSR	E1c	Test Method	12/31/2010	UWM
32	RAP Binder PG True Grade Determination	E2b	Test Method / Software	3/31/2011	UWM
33	Single Edge Notch Bending	E2d	Test Method	5/31/2011	UWM
34	Binder Glass Transition Test	E2d	Test Method	5/31/2011	UWM
35	Asphalt Mixture Glass Transition Test	E2d	Test Method	5/31/2011	UWM
36	Planar imaging/ Aggregate Structure	E1b	Test Method/ Software	3/31/2011	UWM
37	Gyratory Pressure Distribution Analyzer (GPDA)	E1c	Test Method	Completed	UWM
38	Improved Oxygen and Thermal Transport Model of Binder Oxidation in Pavements	F1c	Methodology, Publication	3/31/2011	TAMU
39	Field Validation of an Improved Oxygen and Thermal Transport Model of Binder Oxidation in Pavements	F1c	Methodology, Publication	3/31/2011	TAMU
40	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	3/31/2011	TAMU
41	Pavement Air Voids Size Distribution Model for use in an Oxygen and Thermal Transport Model of Binder Oxidation in Pavements	F1c	Methodology, Publication	3/31/2011	TAMU
42	Improved Understanding of Fast-Rate, Constant-Rate Binder Oxidation Kinetics Mechanism through the Effects of Inhibitors	F1c	Publication	3/31/2011	TAMU

Table TD3.1 continued. Summary of mid- and long-term technology development products.

43	Improved Understanding of Fatigue Resistance Decline with Binder Oxidation	F1c	Publication	3/31/2011	TAMU
44	Micromechanical Properties of Various Structural Components in Asphalt using Atomic Force Microscopy (AFM)	F2d	Test and Analysis Method	3/31/2011	TAMU

Work Element TD4: Develop Mid-Term and Long-Term Products (Years 3, 4, and 5) (AAT, TTI, UNR, UW-M, WRI)

Work Done This Quarter

Work continued on the development of the mid-term and long-term products. Responses to the product rating request issued to the ETGs by the FHWA were compiled by the research team and included in the June 2011 progress report. These responses are being considered by the research team in selecting the effort that will be expended on each of the mid- and long-term products.

Work Planned Next Quarter

The research team will continue with the development of the mid- and long-term technology development products. A staff person from an ARC organization will be assigned to each TD product to guide the product through development and to be a point of contact.

Significant Problems, Issues and Potential Impact on Progress

None.

PROGRAM AREA: TECHNOLOGY TRANSFER

CATEGORY TT1: OUTREACH AND DATABASES

Work element TT1a: Development and Maintenance of Consortium Website (Duration: Year 1 through Year 5) (UNR)

Work Done This Quarter

The ARC website was maintained and updated. The ARC quarterly technical progress report, October 1- December 31, 2011, was uploaded to the ARC website. The following references and files were updated:

- List of Publications and Conference Proceedings under the "Publications" webpage.
- List of Presentations and Posters under the "Outreach" webpage.

The 3D-Move Discussion Group Forum and the ARC Database Forum were also maintained.

Significant Results

None

Significant Problems, Issues and Potential Impact on Progress

None

Work Planned Next Quarter

Continue maintaining and updating the ARC website. Publish the ARC newsletter. Update the list of Publications and Conference Proceedings. Update the list of Presentations and Posters and the list of Theses and White Papers. Post information and new releases for 3D-Move. Maintain the 3D-Move Discussion Group Forum and the ARC Database Forum.

Work element TT1b: Communications (Duration: Year 1 through Year 5) (UNR)

Work Done This Quarter

None.

Significant Results

None.

Significant Problems, Issues and Potential Impact on Progress

None.

Work Planned Next Quarter

Prepare and publish the eleventh ARC Newsletter.

Work element TT1c: Prepare Presentations and Publications (All)

Presentations

Alavi, E.Z., Hajj, E. Y., Hanz, A., and H., Bahia. "Evaluating Adhesion Properties and Moisture Damage Susceptibility of Warm Mix Asphalts Using Bitumen Bond Strength (BBS) and Dynamic Modulus Ratio (ESR) Tests." Presentation made at the 91st Annual Transportation Research Board Meeting, January 22-26, 2012, Washington DC.

Greenfield, M. L. 2011, Composition Models for Molecular Simulation of Asphalts (invited), American Chemical Society Spring Meeting, PETR 108, San Diego, CA, March 27, 2012.

E. Y. Hajj. FHWA Asphalt Mixture and Construction Expert Task Group, "Results and Findings of FN Test Experiment," Baton Rouge, Louisiana, Mar. 19-20, 2012.

E. Y. Hajj. FHWA Fundamental Properties and Advanced Models Expert Task Group, "3D-Move Status: Standalone Deliverable, Workshop, Access, Documentation," Baton Rouge, Louisiana, Mar. 22-23, 2012.

E. Y. Hajj. FHWA Fundamental Properties and Advanced Models Expert Task Group, "ARC Database: Database Structure, Demonstration, Near/Long Term Access," Baton Rouge, Louisiana, Mar. 22-23, 2012.

Hajj, E. Y., L. G., Loria, and P. E., Sebaaly. "Estimating Effective Performance Grade of Asphalt Binders in High-RAP Mixtures Using Different Methodologies: Case Study," Event No. 509: Hot-Mix Asphalt Mixtures with High Reclaimed Asphalt Pavement Content, Lectern Presentation at 91st Annual Meeting of the Transportation Research Board, Washington, D.C., Jan. 24, 2012.

Hajj, E. Y., P., Thushanthan, P. E., Sebaaly, and R. Siddharthan. "Influence of Tire-Pavement Stress Distribution, Shape, and Braking on Asphalt Pavement Performance Predictions," Event No. 617: Analysis of Pavement Section Response, Lectern Presentation at 91st Annual Meeting of the Transportation Research Board, Washington, D.C., Jan. 24, 2012.

Koohi, Y., J. J. Lawrence, R. Luo, and R. L. Lytton (2012). "Evaluation of Stiffness Gradient Transitions of Field-Aged Asphalt Layers Using Direct Tension Test." *The Transportation Research Board (TRB) 91st Annual Meeting*, Washington, D.C., January 22 – 26.

Luo, R., and R. L. Lytton (2012). "Selective Absorption of Asphalt Binder by Limestone Aggregates in Asphalt Mixtures." *The Transportation Research Board (TRB) 91st Annual Meeting*, Washington, D.C., January 22 – 26.

Luo, X., R. Luo, and R. L. Lytton (2012). "Dissipated and Recoverable Energy in Asphalt Mixtures under Repeated Direct Tensile Loading." *The Transportation Research Board (TRB) 91st Annual Meeting*, Washington, D.C., January 22 – 26.

Porras, J., E. Y., Hajj, P. E., Sebaaly, S., Kass, and T., Liske. "Performance Evaluation of Field-Produced Warm-Mix Asphalt Mixtures in Manitoba, Canada" Event No. 584: Warm-Mix Asphalt, Poster Presentation at 91st Annual Meeting of the Transportation Research Board, Washington, D.C., Jan. 24, 2012.

Swiertz, D., R. Velasquez, and H. Bahia, 2011, "Partnership between WCTG/RMAUPG and UW MARC." Presentation at the Rocky Mountain Asphalt User/Producer Group/Western Cooperative Testing Group Annual Meeting, Henderson, NV, March 28, 2012.

Tabatabaee, H., Velasquez, R., and Bahia, H., Modeling Thermal Stress in Asphalt Mixtures Undergoing Glass Transition and Physical Hardening, Presentation made at the 91st Annual Transportation Research Board Meeting, January 22-26, 2012, Washington DC.

Ulloa, A. C., E. Y., Hajj, R. V., Siddharthan, and P. E., Sebaaly. "Establishing Equivalent Loading Frequencies in Static Multilayer Analyses to Simulate Dynamic Responses in Asphalt Layer," Event No. 617: Analysis of Pavement Section Response, Lectern Presentation at 91st Annual Meeting of the Transportation Research Board, Washington, D.C., Jan. 24, 2012.

Velasquez, R., D. Swiertz, H. Bahia, 2012, "UW MARC and ARC Update." Presentation at the Rocky Mountain Asphalt User/Producer Group/Western Cooperative Testing Group Annual Meeting, Henderson, NV, March 28, 2012.

Zhang, Y., R. Luo, and R. L. Lytton (2012). "Characterization of Inherent Anisotropy in Asphalt Mixtures." *The Transportation Research Board (TRB) 91st Annual Meeting*, Washington, D.C., January 22 – 26.

Zhang, Y., R. Luo, and R. L. Lytton (2012). "Characterizing Permanent Deformation and Fracture of Asphalt Mixtures Using Compressive Dynamic Modulus Tests." *The Transportation Research Board (TRB) 91st Annual Meeting*, Washington, D.C., January 22 – 26.

Publications

Alvavi, M., E. Hajj, A. Hanz, and H. Bahia, "Evaluating Adhesion Properties and Moisture Damage Susceptibility of Warm Mix Asphalts Using Bitumen Bond Strength (BBS) and Dynamic Modulus Ratio (ESR) Tests." Transportation Research Board 2012 Meeting. Accepted for presentation and publication.

Koohi, Y., J. J. Lawrence, R. Luo, and R. L. Lytton (2012). "Complex Stiffness Gradient Estimation of Field-Aged Asphalt Concrete Layers Using the Direct Tension Test." Accepted for publication, *Journal of Materials in Civil Engineering*, American Society of Civil Engineers (ASCE).

Luo, X., R. Luo, and R. L. Lytton (2012). "Characterization of Asphalt Mixtures Using Controlled-Strain Repeated Direct Tension Test." Accepted for publication, *Journal of Materials in Civil Engineering*, American Society of Civil Engineers (ASCE).

Luo, X., R. Luo, and R. L. Lytton (2012). "Modeling Fatigue Crack Growth in Asphalt Mixtures Using Pseudo Strain Energy Balance." Under review, *Journal of Materials in Civil Engineering*, American Society of Civil Engineers (ASCE).

Moraes, R., R. Velasquez, and H. Bahia, 2012, The Effect of Bitumen Stiffness on the Adhesive Strength Measured by the Bitumen Bond Strength Test, 5th Eurasphalt and Eurobitume Congress, Istanbul, Turkey, June 13-15, 2012. Accepted.

Tabatabaee, H.A., R. Velasquez, and H. U. Bahia, 2012, Predicting Low Temperature Physical Hardening in Asphalt Binders. In *Journal of Construction and Building Materials*, Elsevier, Vol. 34, pp. 162–169.

Tabatabaee, H., R. Velasquez, and H. Bahia, 2012, "Modeling Thermal Stress in Asphalt Mixtures Undergoing Glass Transition and Physical Hardening." Presentation made at the 91st Annual Transportation Research Board Meeting, January 22-26, 2012, Washington DC.

Tabatabaee, H.A., and H. U. Bahia, 2012, "Life Cycle Energy and Cost Assessment Method for Modified Asphalt Pavements." Abstract accepted and full paper submitted to the 15th Euro Working Group on Transportation: Energy Efficient Transportation Systems, September 2012.

Zhang, Y., R. Luo, and R. L. Lytton (2012). "Characterizing Permanent Deformation and Fracture of Asphalt Mixtures Using Compressive Dynamic Modulus Tests." Accepted for publication, *Journal of Materials in Civil Engineering*, American Society of Civil Engineers (ASCE).

Zhang, Y., R. Luo, and R. L. Lytton (2012). "Mechanistic Modeling of Fracture in Asphalt Mixtures under Compressive Loading." Under review, *Journal of Materials in Civil Engineering*, American Society of Civil Engineers (ASCE).

Work element TT1d: Development of Materials Database (Duration: Year 2 through Year 5) (UNR)

Work Done This Quarter

UNR hosted the regular teleconferences once a month. Also, the ARC annual meeting was held in Reno, Nevada on March 6 and 7, 2012. A total of 17 people attended the meeting from various organizations: UNR (7), UWM (2), WRI (2), Texas A&M (2), UT Austin (1), NCSU (1), UNL (1) and FHWA (1). The following list describes the work items completed or in progress this quarter:

- Working on implementation of properties having three or more factors (dimensions)
- Completed assignment of material characteristics to a test run
- Enhanced public user approval forms and process
- Batch Organization of result data for QA/QC
- Summary of Bug Fixes

Significant Results

Multi-factor Selection
This discussion of multi-factor properties has two parts. The first part descirbes the multi-factor property creation process. The second describes recording user multi-factor measures. Note that the multi-factor implementation required signficant database changes.

Part 1:
The property entry page has been changed from the existing implementation as follows:

- Properties were previously limited to 2-factors (previously referred to as 'dimensions').
- The factors were only described by a name and a set of standard levels (previously referred to as 'standard values').

In the new implementation, an unrestricted number of factors can be created for a given property. In addition, factors are now described by not only a name, but also units, hard and soft limits, and standard levels. This new interface allows for factors to be created and edited as shown in figure TT1d.1.

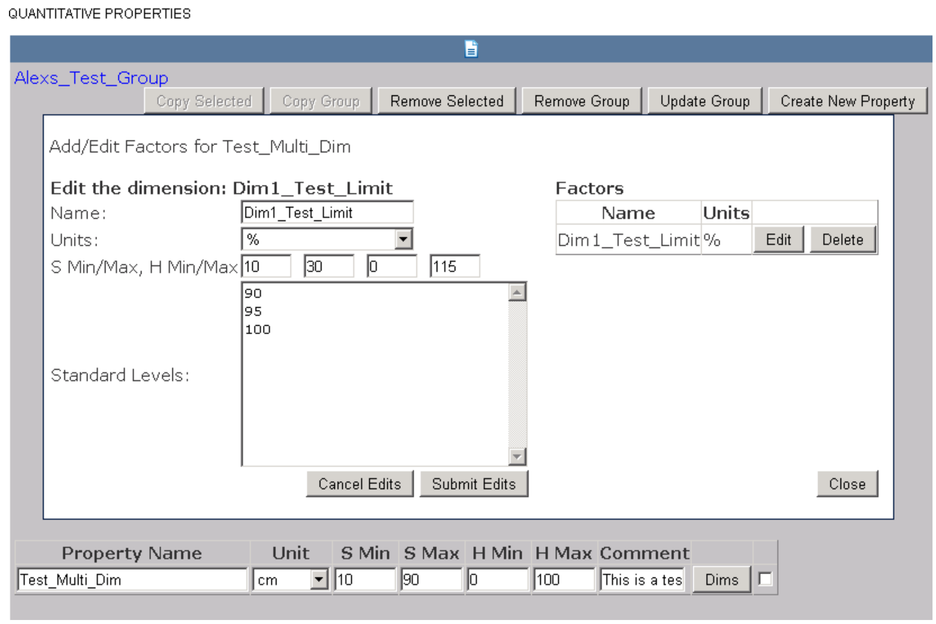

Figure TT1d.1. Factor creation/edit form.

As shown in the above figure, it is now possible to create any number of factors (dimensions). For each factor, hard and soft limits can be applied. As before, standard values can also be applied to each factor.

The following restrictions / limitations should be noted:

- While the number of factors applied to a given property is not limited, applying a large number of factors to a single property (more than 7-10) will cause the application to function perceivably slower due to a large increase in computation time.
- This form maintains the integrity of the data in the database for properties that already have measures stored. This means that if a measure already exists for a given property and then a user try to create a new factor for that property, the pre-existing measure will be deleted since a measure cannot exist if it doesn't have a value for a particular factor without introducing ambiguity into the data.

Part 2:
The Factor Editor was revised to operate on the new multi-factor properties. In order to do this, a "Measure Viewer for Multi-Factor Properties" form was created. This form allows the user to input, update, and delete measures by generating a table which is dynamically sized by the number of factors for the given property. This form also displays important information about both the factors and the property such as the hard and soft limits for the property and its factors, the units for each factor, the units for the measurement of the property, and any comments about the property. The form validates all user input so as to verify that all values entered are within the proper hard and soft limits. When the user enters a value outside of the soft limits the field in question is highlighted. Any values the user enters which are outside of the hard limits are

highlighted red and will not be persisted to the database until the user corrects them to within the hard limits. This editor also provides the ability to insert any number of blank rows for inserting new values. In addition, if the user made changes and then realized that they had made a mistake, the changes could be reversed by using the 'Remove Unsaved Rows' button. In order to save data that is entered into this editor the user must click the 'Save Data and Close Editor' button. Finally, measures can be deleted using the 'Delete Selected' button.

The following figure shows editing of a multi-factor property.

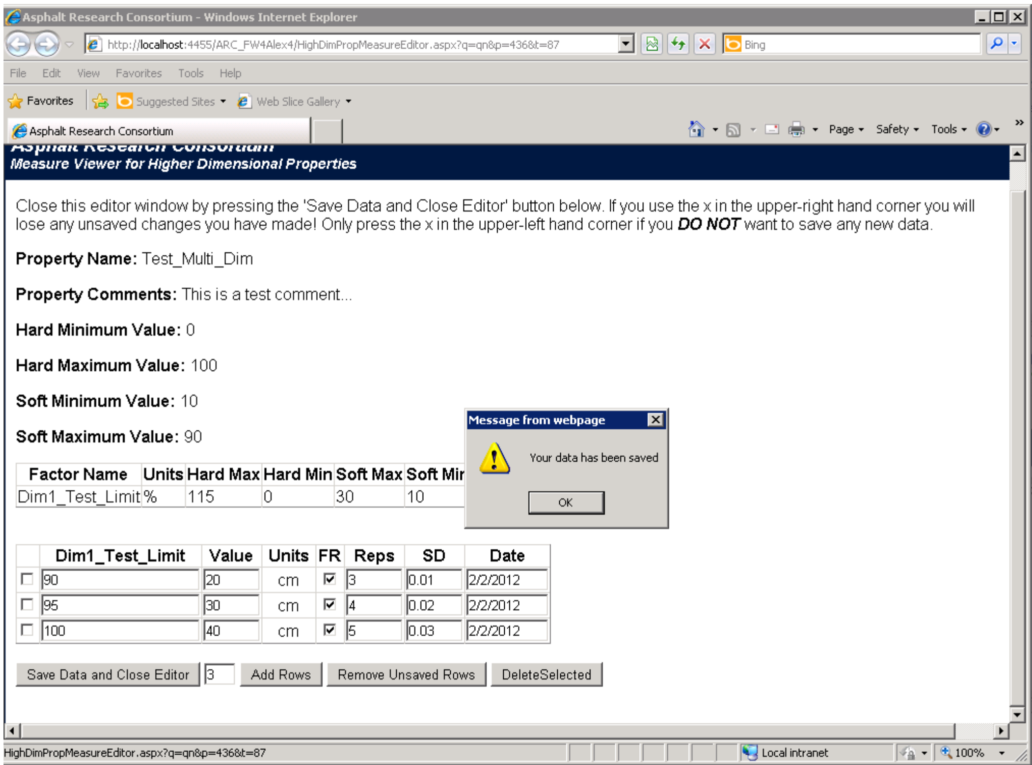

Figure TT1d.2. Multi-factor editing.

Note: Work is currently under way to decouple property entry from property groups. In other words, as it currently stands in the database, if a property such as E* exists for many different types of property groups, it has to be entered separately for each of the property groups. This can create ambiguity in the database by having multiple copies of E* input each with potential differences due to simple user error when entering them. This can be remedied by generalizing property entry and allowing for properties to be entered once and then applied to property groups. Therefore, in this example, E* would only be entered one time into the database and woud thereby standardize the property name across all property groups. (See work planned for next quarter)

Property specific Information appears in the following figure:

Property Name: Test_Multi_Dim

Property Comments: This is a test comment...

Hard Minimum Value: 0

Hard Maximum Value: 100

Soft Minimum Value: 10

Soft Maximum Value: 90

Figure TT1d.3. Multi-factor editing (property specific information).

Factor Specific Information appears in the following figure:

Factor Name	Units	Hard Max	Hard Min	Soft Max	Soft Min
Dim1_Test_Limit	%	115	0	30	10

Figure TT1d.4. Multi-factor editing (factor specific information).

When entering values for factors, hard and soft limits are enforced. The user is given visual cues to show invalid data. The following figure shows invalid data entered for a factor value. The value appears with a red background.

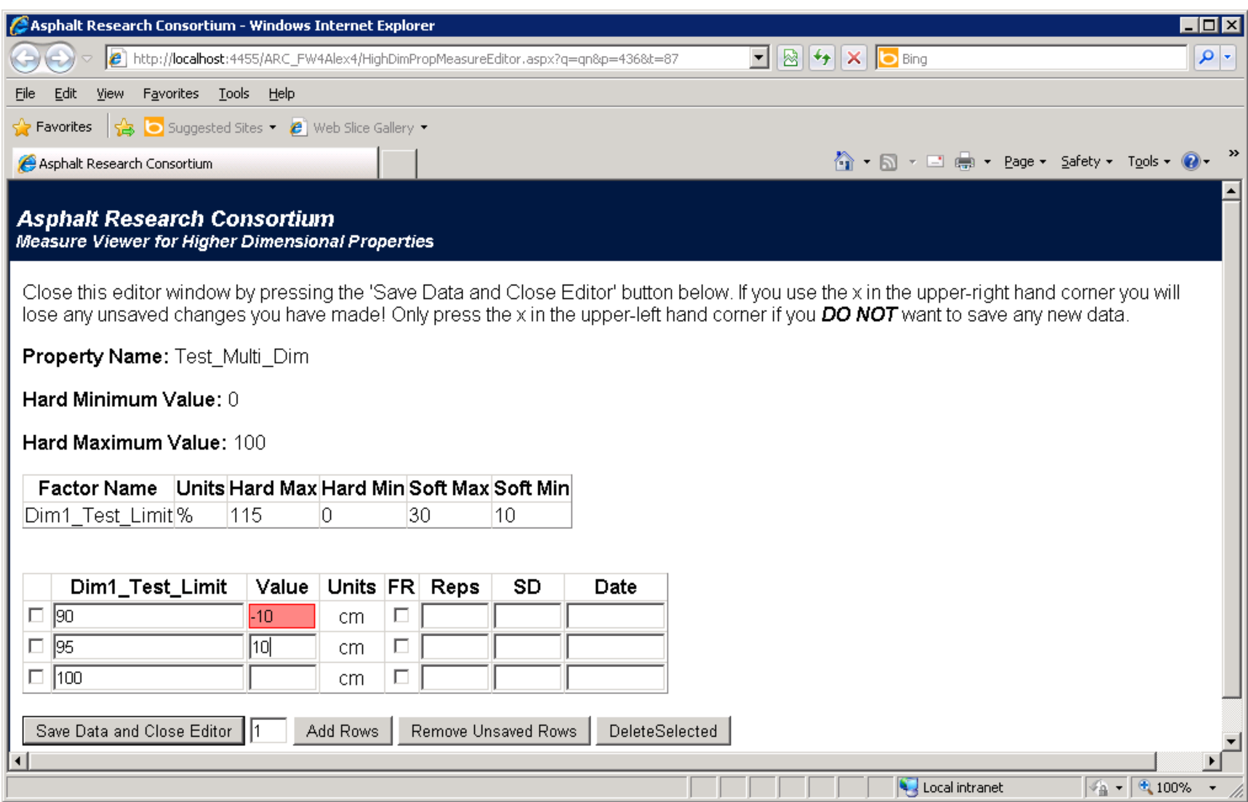

Figure TT1d.5. Multi-factor editing (error information).

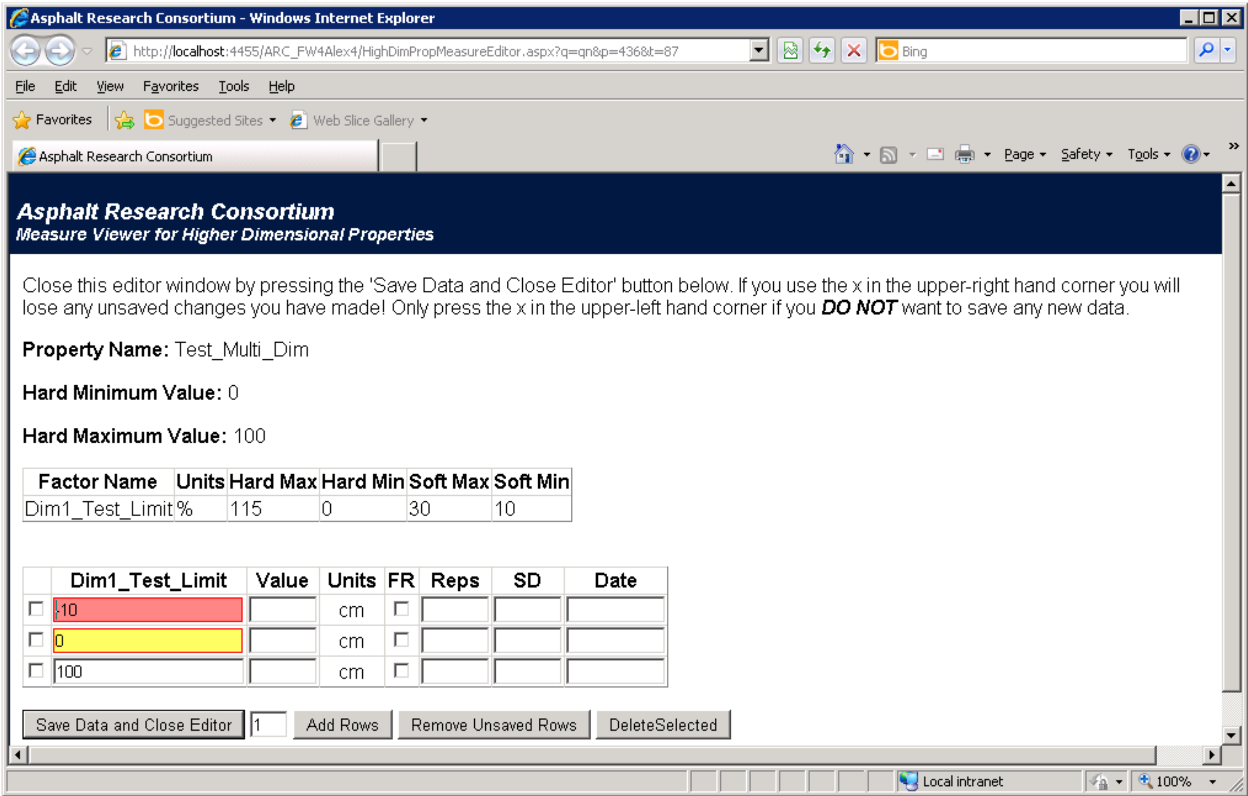

Figure TT1d.6. Multi-factor editing (error information -2).

Material Characteristic Assignment in Test Run

Last quarter, support was added to apply multiple qualitative and quantitative characteristics to materials much like characteristics were applied to properties. These material characteristics were to be applied to material test runs. This features has been completed as shown in figure TT1d.7.

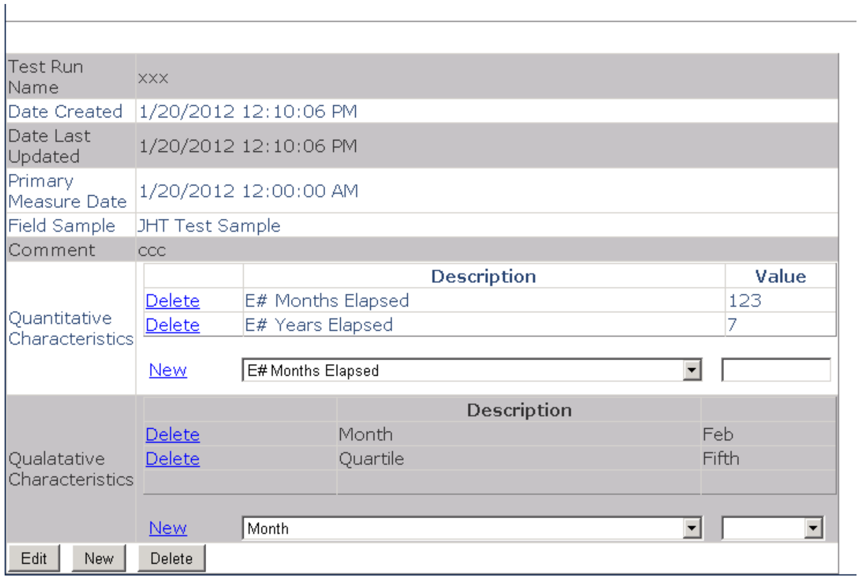

Figure TT1d.7. Qualitative and quantitative material characteristics attached to test runs.

As shown in the above figure, the quantitative and qualatative characteristics can be applied to a test run. Hard and soft limits are enforced for quantitative characteristics. Suggested values are applied to qualatative characteristics.

- Note that this enhancement required the creating of the following tables. tblQLmatChar, tblQLMatChar_Assign, tblQLMatCharValidValues, tblQNMatChar, tblQNMatChar_Assign

Approval/Rejection of Public Users
Added a field to the user table to indicate that a user was rejected. Eric Weaver suggested that we keep track of rejected users. Figure TT1d.8 shows the revised user interface:

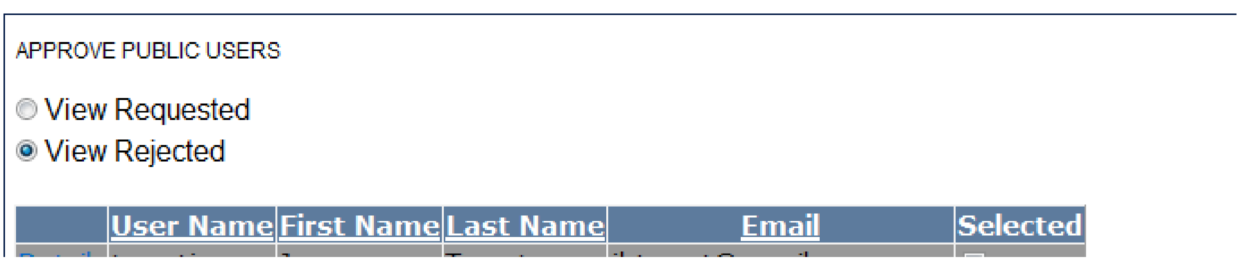

Figure TT1d.8. Rejection of public users.

In addition, depending the the status of their account, users will be redirected to a notification page indicating whether their account request is pending or has been rejected, as shown in figure TT1d.9.

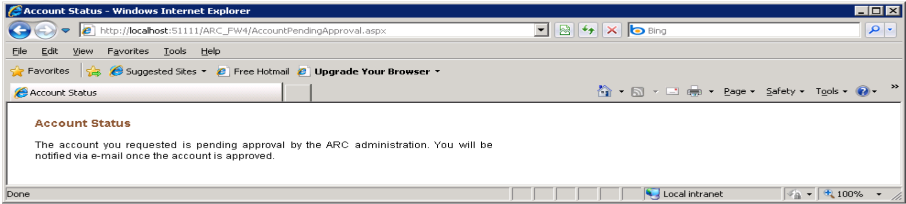

Figure TT1d.9. Account status display.

- Note also that public users now have access to the page allowing them to change their own account information.
- Secret password questions are now selected from a predefined list.
- User-entered passwords are now hidden while typing.

Changes were also made so that public users can view property groups, properties, and file metadata.

Batch Organization of result data for QA/QC
From the ARC annual meeting, a protocol is required to gather entered data into batches for the purposes of quality assurance and quality control (QA/QC). File and measure data will be grouped in to batches as the data are entered or imported. Each batch of data exists in an approval state, although as the QA/QC process is performed, selected records pertaining to a batch may have different states.
The following list discusses the status of this implementation:

- The tables and relationships to store the dynamic batch status information and the batch logs are complete.
- New fields have been added to the file-related tables to account for the batch summarization.
- The development of a user interface is underway to create batches and approve them. The form to define the batch status categories is nearly complete.
- The measures and reports forms will be need to be modified to associate current uploads with a particular batch and for the user to select specific batches.

Summary of Bug Fixes

General

- Fixed typos on MeasureViewer from. The file extensions for downloaded files appeared twice. This error was fixed.

Material Characteristics

- As you select between qualitative and quantitative characteristics, the form is reset so that the row no longer selected is hidden.
- Hard and soft limits are now optional.
- It was possible to add blank qualitative characteristics. Fixed.
- User now cannot add duplicate qualitative values for a material characteristic.
- When deleting a qualitative value, the wrong row was being deleted. Fixed.

Measures Form (Test Run)

- Unit of measure (symbol) now appears in the drop-down box that lists the characteristics (quantitative.
- Updated so that the quantitative value must exist and be numeric.
    - To do: need to check that entered value is within the valid range.
- Edit comment fixed.
- Added sentinel value [NONE] for the quantitative and qualitative characteristics. Note that users must explicitly select a qualitative or qualitative property [NONE] cannot be added.
- Move the buttons to create new test run as suggested by Elie Hajj.

<u>Significant Problems, Issues and Potential Impact on Progress</u>

None

<u>Work Planned for Next Quarter</u>

- A method is currently under development for bulk entry (import) of measures into the database. In the current implementation, each measure must be manually typed into the measure entry page or the ‘Measure Viewer for Multi-Factor Properties’. For small sets of data, this is not an issue, but for large sets of data this can hinder efficiency significantly. This system will allow for Excel files (or csv files) containing a standard structure to be uploaded to the database. This system will aso provide for uploading and associating files into the database’s file system for each particular measure in the bulk data set.
- For convenience, the File Upload system requires that users be able to move files from one folder to another. This implementation has been completed but has not yet been deployed.
- The implementation of the prototype to import existing data and files from UWM will be in place.

- Development of an enhancement to decouple property entry from property groups. Standardized lists for property names, such as E* will be created to better support consistent property naming.
- Complete batch categorization and approval process for file and measure entry.
- From the ARC annual meeting and regular teleconferences, the public user interface will be separated into a standalone user interface. Improved security and a more unified user experience were motivating factors for this change. The following items are under discussion and design related to the public user interface.
    - Inclusion of a public domain or for purchase query tool that so support custom database queries
    - Expansion of the currently implemented "filter" mechanism
    - Addition of a possible hierarchical "drill" down interface to select data and build metadata queries.

Work element TT1e: Development of Research Database (Duration: Year 2 through Year 5) (UNR)

Work Done This Quarter

Uploaded the quarterly technical progress report and the ARC newsletter to the ARC website. Updated the "Publications" and "Outreach" web pages.

Significant Results

None.

Significant Problems, Issues and Potential Impact on Progress

None.

Work Planned Next Quarter

Upload the ARC quarterly technical progress report to the ARC website. Publish the ARC newsletter on the ARC website.

Work Element TT1f: Workshops and Training (UNR lead)

Work Done This Quarter

None

Significant Results

None

Significant Problems, Issues and Potential Impact on Progress

None

Work Planned Next Quarter

None

TABLE OF DECISION POINTS AND DELIVERABLES FOR TECHNOLOGY TRANSFER

Name of Deliverable	Type of Deliverable	Description of Deliverable	Original Delivery Date	Revised Delivery Date	Reason for Changes in Delivery Date
TT1a: Development and Maintenance of Consortium Website (UNR)	Progress report	Upload quarterly progress report and newsletter	07/11	Complete	N/A
	Newsletter	Upload newsletter	07/11	Complete	N/A
	Progress report	Upload quarterly progress report and newsletter	10/11	Complete	N/A
	Newsletter	Upload newsletter	11/11	Complete	N/A
	Progress report	Upload quarterly progress report and newsletter	01/12	Complete	N/A
	Newsletter	Upload newsletter	03/12	05/12	N/A
	Progress report	Upload quarterly progress report and newsletter	04/12	N/A	N/A
TT1b: Communications (UNR)	Newsletter	Publish newsletter	07/11	Complete	N/A
	Newsletter	Publish newsletter	11/11	Complete	N/A
	Newsletter	Publish newsletter	03/12	05/12	N/A
TT1d: Development of Materials Database (UNR and All)	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.	04/11	Complete	N/A
	Database	Materials database software	03/12	N/A	N/A
TT1f: Workshops and Training (UNR and All) (TAMU)	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.	04/11	Complete	N/A
	Workshop	PANDA software training	8/11	4/13	N/A

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

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