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QUARTERLY TECHNICAL PROGRESS REPORT

July 1 – September 30, 2007

ASPHALT RESEARCH CONSORTIUM

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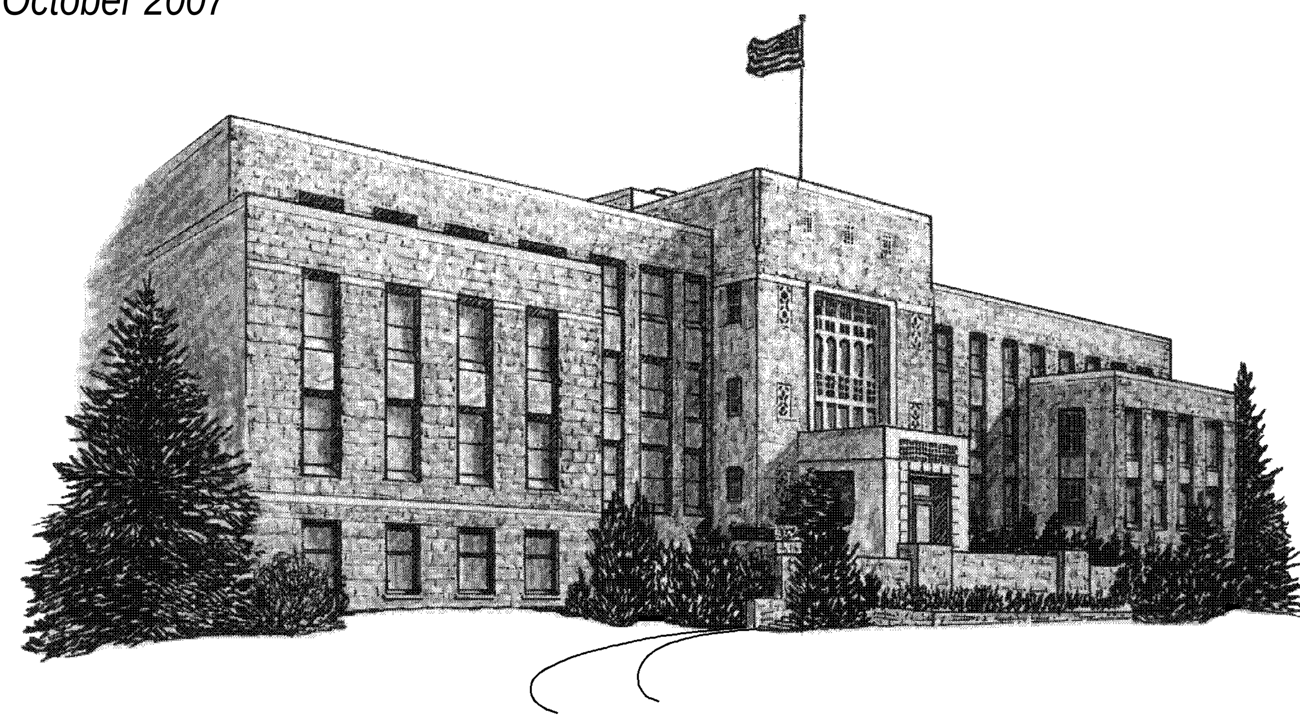
October 2007



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INTRODUCTION

This document is the Quarterly Report for the period of July 1 to September 30, 2007 for the Federal Highway Administration (FHWA) Contract DTFH61-07-H-00009, the Asphalt Research Consortium. 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 and is grouped by Work Element and Subtask. The Moisture Damage and Fatigue areas report on Work Elements and Subtasks that are interrelated and thus work together to advance the knowledge of mechanisms and models in these areas.

The research areas of Engineered Paving Materials, Vehicle-Pavement Interaction, and Validation generally report work elements that are more "stand-alone" in nature but this doesn't mean that these work elements operate independently because in most cases, at least two Consortium partners are teaming to conduct the work. These work elements also provide useful information to the other research activities in the Consortium.

Finally, the areas of Technology Development and Technology Transfer report where the research deliverables have been transmitted to the user community. The Technology Development area reports the progress to take promising research developments and refine them into useful tools for engineers and technologists involved in the design, construction, and maintenance of flexible pavement systems. The Technology Transfer area reports on the transfer of Consortium research findings to the asphalt community using the Consortium website, presentations, publications, and workshops.

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

The Asphalt Research Consortium (ARC) received approval on the First Year Work Plans from Co-AOTR's, Dr. Jack Youtcheff and Mr. Eric Weaver, on July 12, 2007. Work on many of the work elements of the program began thereafter.

Representatives of all of the Consortium members attended the Fundamental Properties and Advanced Models; Mix and Construction; and Binder Expert Task Group (ETG) meetings in Denver, Colorado during the week of July 23 – 27, 2007. The Consortium members made presentations on research work plans and the background information supporting the work plans.

In August, ARC members from Western Research Institute (WRI), University of Nevada Reno (UNR), and University of Wisconsin-Madison (UWM) along with industry representatives from Granite Construction and the National Center for Asphalt Technology (NCAT) met to develop the detailed work plan for Work Element E2b: Design System for HMA Containing a High Percentage of RAP. The collaboration of the team produced a work plan that is valuable to the construction industry and complements the activities at NCAT. The detailed work plan is presented in the Engineered Materials section, Work Element E2b.

The Consortium members also prepared a draft Materials Selection plan that includes a list of potential industrial, supplier, and academic personnel who may provide valuable input to material selection and a questionnaire to present to the selected personnel in order to obtain the needed information for the ARC to select the best materials for the research program. The draft Materials Selection plan was delivered to the Co-AOTR's and a Materials Selection meeting was scheduled for November 8, 2007 in McLean, Virginia.

WORK PLANNED FOR NEXT QUARTER

Consortium members will attend the Materials Selection meeting at the Turner-Fairbank Highway Research Center in McLean, Virginia, on November 8, 2007.

PROGRAM AREA: MOISTURE DAMAGE

CATEGORY M1: ADHESION

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

Subtask M1a-1: Select Representative Asphalt Binders and Mastics, and Aggregate Materials (Year 1 start)

Progress This Quarter

A draft Materials Selection plan was prepared for review by all Consortium members and the FHWA Co-AOTR's. After review, FHWA AOTR, Dr. Jack Youtcheff, requested a meeting at TFHRC to discuss material requirements, quantities, and storage.

Work Planned Next Quarter

Consortium members will prepare material requirements and any other additional information needed for presentation and review and the Materials Selection meeting at TFHRC on November 8, 2007.

Subtask M1a-2: Use the Modified DSR Tests to Evaluate Various Moisture Testing Conditions Including Control of Rate and Temperature and to Measure Affinity of Asphalts to Aggregates and also Cohesion of Binders (Year 1 start)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Subtask M1a-3: Evaluate the Moisture Damage of Asphalt Mixtures with Selected Material Combinations by the TSR Test or an Alternative Test System

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Subtask M1a-4: Correlate Moisture Damage as Measured by the Modified DSR Test with the Mixture Test Results - Analyze Results on Each Combination and Material

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Subtask M1a-5: Propose a Novel Testing Protocol

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

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 (Year 1 start) (TAMU)

Progress This Quarter

A test protocol to determine the enthalpy of adhesion between the aggregate and asphalt binder using a micro calorimeter at room temperatures was developed. The micro calorimeter can be used as a surrogate to other surface energy measurement methods in order to obtain rapid estimates for the energy of adhesion between the aggregate and the asphalt binder. Also, this methodology can be applied to determine the effect of active fillers on the interfacial bond strength at the binder-aggregate interface. The methodology is briefly described below and illustrated in figure M1b-1.1.

- A sample of clean aggregates (passing the ASTM #100 and retained on the ASTM #200 sieves) is obtained.
- A stock solution of the asphalt binder is prepared using 1.5 g of the binder dissolved in 11 mL of high-performance liquid chromatography (HPLC) – grade toluene. The use of other solvents is being investigated.
- A 16 mL glass vial is used as a reaction cell for the micro calorimeter. The vials have open top polypropylene caps with a PTFE-silicone septa to provide an air tight seal. A known mass (8 g) of the aggregate sample is placed in the reaction vial and sealed.

- A syringe with a 27 gauge needle is passed through the septum that seals the vial and a vacuum is drawn on the vial by connecting the syringe to a vacuum pump at 150°C for four hours. An empty vial is preconditioned in a similar manner to serve as a reference in the differential cell micro calorimeter.
- The reaction and reference vials are allowed to cool to the test temperature (25°C) and come to thermal equilibrium in the micro calorimeter.
- Two syringes of 2 mL capacity each with the asphalt binder solution are positioned on top of the reaction vial and the reference vial, each. After thermal equilibrium is reached, the asphalt binder solutions are simultaneously injected into the reaction and reference vials. The two vials are allowed to return to thermal equilibrium. This process typically takes about 30 to 45 minutes.
- The energy or enthalpy of immersion is measured as the area under the heat flow vs. time.

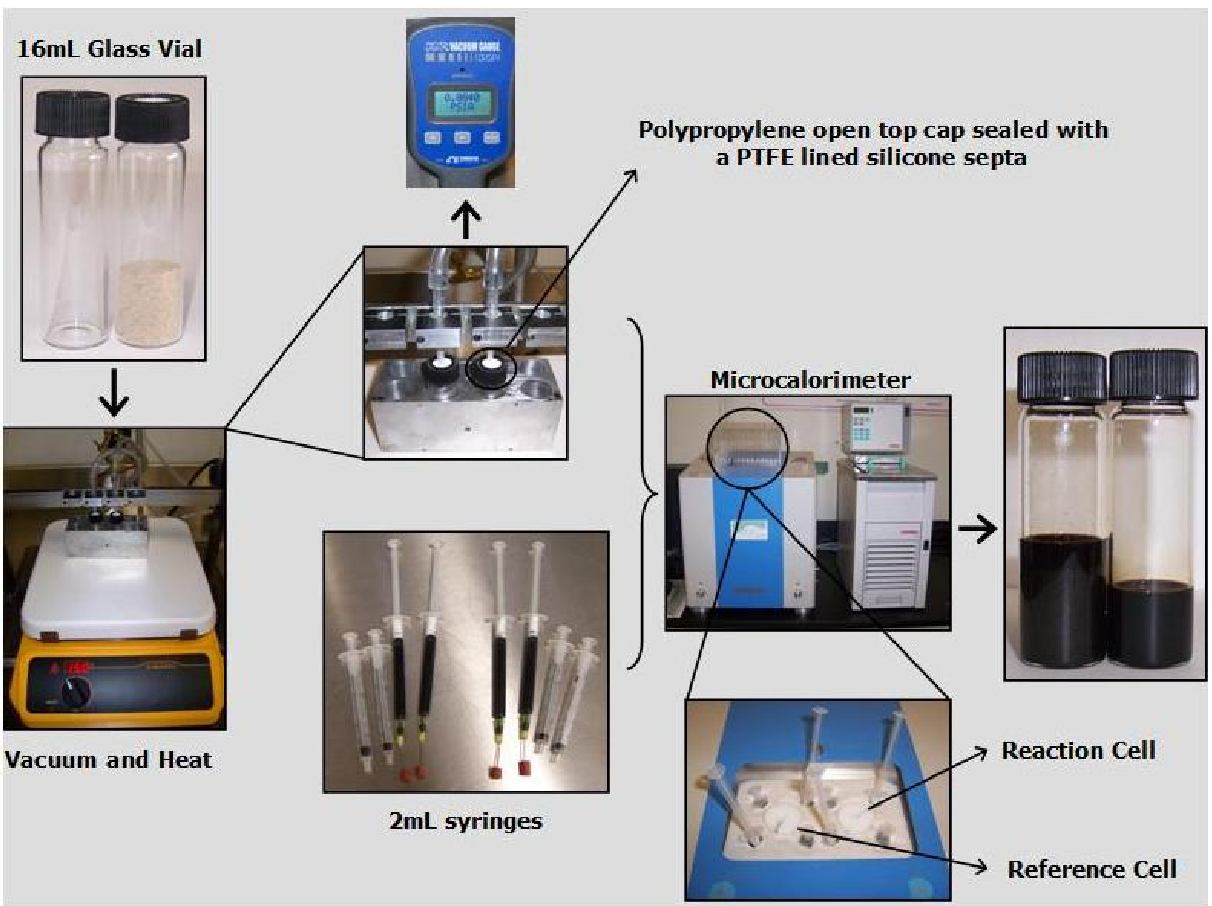


Figure M1b-1.1. Schematic showing the various steps to measure energy of adhesion between the asphalt binder and aggregate.

Figure M1b-1.2 illustrates the typical heat flow from the reaction to the reference cell just before, during, and immediately after the completion of an immersion test. The figure shows the initial and final datum for the steady state heat flow and the point at which heat flow increases due to the surface interactions between the solid (aggregate) and the probe liquid (asphalt binder in solution). The area under the heat flow curve between the two equilibrium points is integrated to obtain the enthalpy of immersion or total energy of adhesion (TEA) between the aggregate and the asphalt binder solution.

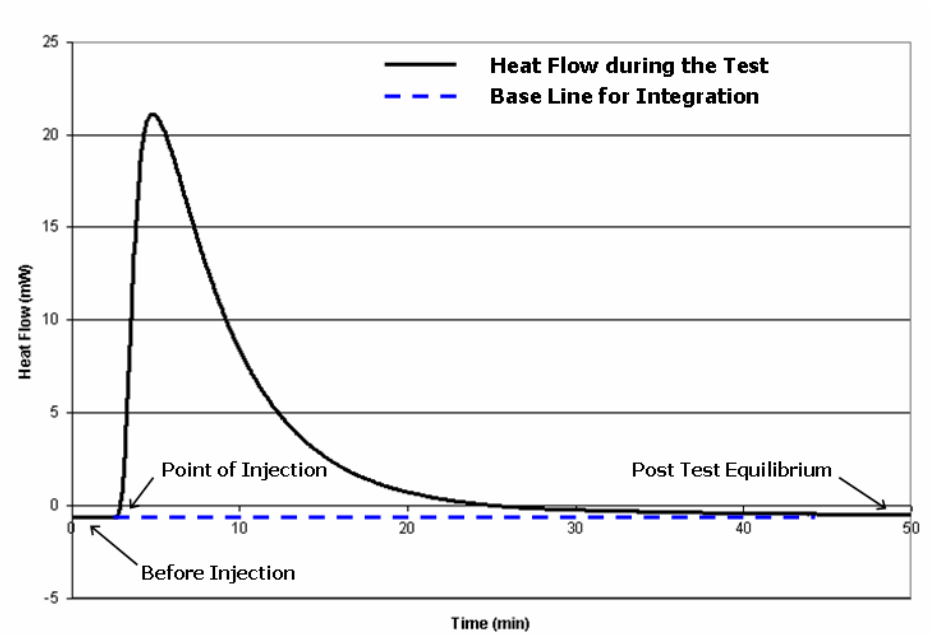


Figure M1b-1.2. Typical heat flow curve recorded with the micro calorimeter.

The net differential heat measured by the micro calorimeter during the process of immersion, ΔH_{meas}, is due to: (1) enthalpy of immersion in the reaction cell, ΔH_{imm}, and (2) difference in heat of vaporization of the solvent (toluene) due to the difference in free volumes inside the vacuum sealed reaction and reference cells, $\Delta H_{\delta v}$. Therefore, the corrected enthalpy of immersion is determined from the heat of immersion as follows:

$$\Delta H_{imm} = \Delta H_{meas} - \Delta H_{\delta v} = \Delta H_{vap} \frac{v_s p_0}{RT} \qquad \text{(M1b-1.1)}$$

where, v_s is the volume occupied by aggregates in the vacuum sealed reaction cell, p_0 is the saturation vapor pressure of the toluene at the test temperature, R is the universal gas constant, T is the test temperature, and ΔH_{vap} is the change in enthalpy due to vaporization or heat of vaporization per mole of the solvent (toluene).

Figure M1b-1.3 illustrates typical results from this test for two replicates of three different types of aggregates (RA, RK, and RL) immersed in one type of asphalt binder (AAD). The results indicate that this test method is repeatable with good precision and is sensitive to the type of aggregate. Tests with different types of asphalt binders and non polar solutions to evaluate sensitivity of the test method to the type of asphalt binder are in progress.

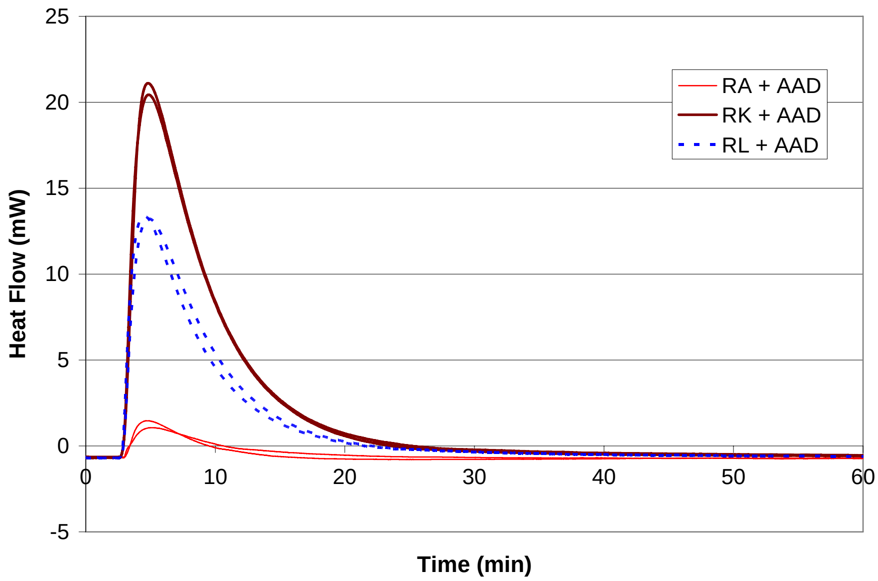


Figure M1b-1.3. Sensitivity and precision of measurements made using the micro calorimeter.

<u>Work Planned Next Quarter</u>

The planned activity for the next quarter is to continue development of this methodology with emphasis on the sensitivity of the test method to different types of asphalt binders. Solvents other than toluene will also be evaluated. A methodology to evaluate the effect of active and inactive fillers on the energy of adhesion between the binder and aggregate will also be addressed in the next quarter.

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

<u>Progress This Quarter</u>

No activity this quarter.

<u>Work Planned Next Quarter</u>

No work planned.

Subtask M1b-3: Identify Mechanisms of Competition between Water and Organic Molecules for Aggregate Surface (Year 1 start) (TAMU)

The work of adhesion between asphalt binders and aggregates determined using thermodynamics is based on the average properties of these two materials. Asphalt binders as well as aggregates are highly heterogeneous in terms of their chemical or mineralogical composition. This sub task will investigate mechanisms responsible for adhesion and debonding using pure minerals and rocks (representing common aggregates) and model organic compounds (representing functional groups in asphalt binder). This information is extremely important in order to: (i) provide knowledge by which to make informed modifications to the asphalt binders and/or aggregates that will improve the mixtures resistance to moisture damage, and (ii) refine the existing methods used to measure material properties such as surface free energy.

Work at TTI-WRI under funding administered by the FHWA has demonstrated that electrostatic interactions, one component of surface energy that describe the complex interactions between asphalt and aggregate surfaces, are small but important molecular interactions affecting the impact of moisture on the strength of the aggregate-bitumen interaction. Other molecular-scale interactions likely important include electron-donor acceptor reactions between aromatic organics and specific surface functional groups on the aggregate surface, organic hydrolysis reactions, and secondary precipitation reactions between inorganic salts and organic molecules.

<u>Progress This Quarter</u>

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

The dual-mode flow adsorption calorimeter is capable of operating in both injection and/or flow-through modes and is currently being tested and optimized (figure M1b-3.2). The sensing unit of the calorimeter is thermistor based and consists of: (i) a reference thermistor (Thermistor 1), which senses the temperature of the incoming adsorbate; (ii) a calibrating resistor, for calibrating calorimetric response to known heat input; (iii) a column, containing the adsorbent of interest; and (iv) a column thermistor (Thermistor 2), which senses the temperature of the absorbate after interacting with the absorbent. The difference in temperature between Thermistor 1 and 2 is amplified and recorded as a voltage output over time, with a return to baseline (or zero difference) considered to be the end of the reaction. The output is attributed to absorbent-absorbate interaction and can be used along with calibration data and the difference between initial absorbate and effluent concentrations to directly determine molar heats of reaction.

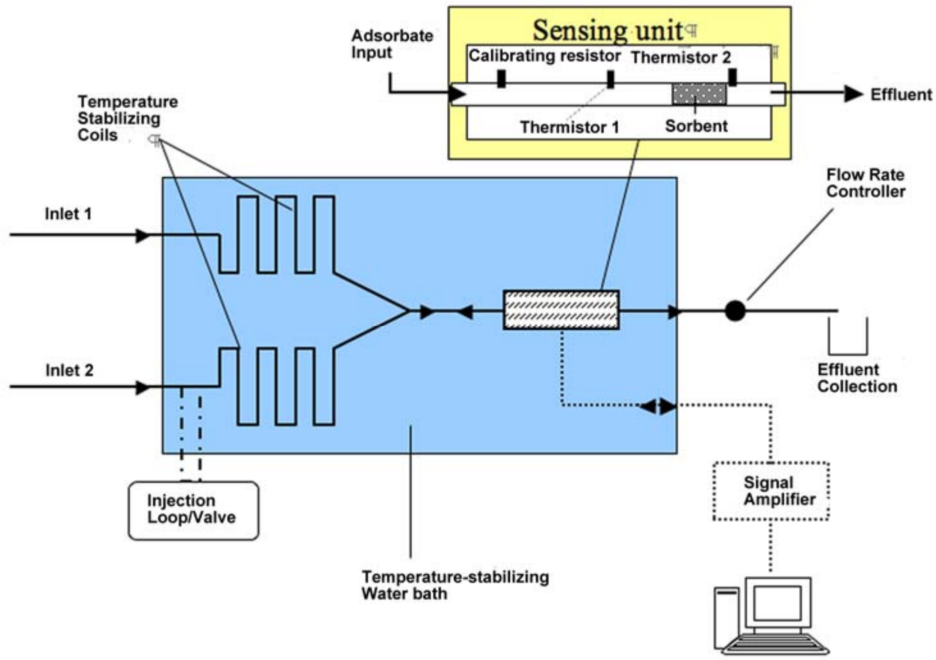


Figure M1b-3.1. Schematic of dual mode flow adsorption calorimeter.

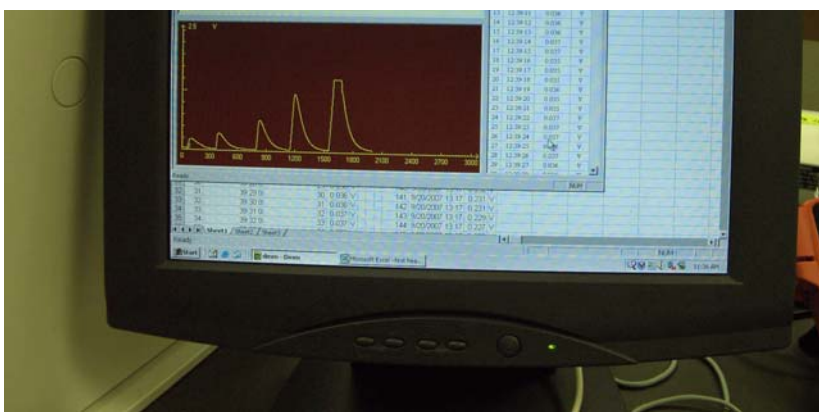


Figure M1b-3.2. Calorimetric response of recently built flow calorimeter to increasing heat input. Peaks (from left to right) represent response to heat inputs of 35, 70, 140, 280 and 420 mJ, respectively.

Work Planned Next Quarter

We are in the process of selecting model organic compounds and mineral phases.

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

Minerals and organic compounds to be used for this study will be purchased and characterized. Physico-chemical properties of the minerals selected for use will be characterized using different methods including x-ray diffraction, scanning electron microscopy and particle size analysis, elemental analysis and surface area analysis. In addition, to flow calorimetry other test methods, commonly used to investigate interfacial interaction processes, will also be investigated. Mineral-organic interactions experiments will be conducted at several levels: (i) Single mineral-single functional group interactions; (ii) Single mineral-multiple functional group interactions; (iii) Multi-mineral-single functional group interactions; and (iv) Multi-mineral-multiple functional group interactions.

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

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

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

Progress This Quarter

The experimental and analytical methods to determine the fatigue cracking life of moisture conditioned specimens of the fine aggregate matrix (FAM) using the DMA will follow the methodologies for the testing and analysis of dry specimens developed in work elements F1b and F2b. In addition, we have evaluated the use of a probabilistic model to compare the fatigue cracking life of dry specimens versus moisture conditioned specimens for a given type of material. The probabilistic model has two key advantages: (1) it can be applied to a fracture mechanics based model that is used to quantify fatigue cracking life of FAM specimens and (2) it accommodates the inherent variability associated with experimental data obtained from replicate tests. The following is one example for the use of this model to quantify the effect of moisture damage on the crack growth characteristics of four different types of materials.

The effect of moisture induced damage on the fatigue cracking life of a FAM matrix can be quantified by comparing the crack growth index in dry and moisture conditioned states represented by ΔR_{dry} and ΔR_{wet}, respectively. Typically, this would be done by obtaining the ratio of the average value of these two parameters for a given number of replicates at a given number of load cycles. However, an alternative approach is to compare the ratio of these two parameters at different load cycles using a probabilistic model that accommodates the variability in the measured data. A more detailed description of this methodology is documented in a recent paper submitted for possible publication in the Transportation Research Record authored by Silvia Caro, Eyad Masad, Gordon Airey, Amit Bhasin, and Dallas Little.

The probability that $\Delta R_{dry}(N)$ is greater than $\Delta R_{wet}(N)$ at any load cycle, N, is:

$$p\left(\Delta R_{wet} > \Delta R_{wet} \middle| N\right) \qquad \text{(M1c.1)}$$

The probability, p, at any given load cycle, N, can be computed using a point-in-time approach, which implies that the probability at each load cycle is independent of the past damage and loading history. The following log normal fit was found to be the most appropriate based on a best-fit density distribution analysis. Therefore, the probability can be computed as:

$$p\left(\Delta R_{wet} > \Delta R_{wet} \middle| N\right) = \Phi\left(\frac{-\ln\left(\frac{\mu_{\Delta R(wet)}}{\mu_{\Delta R(dry)}} \left(\frac{1+V^2_{\Delta R(wet)}}{1+V^2_{\Delta R(dry)}} \right)^{\frac{1}{2}} \right)_N}{\left[\ln\left(\left(1+V^2_{\Delta R(wet)}\right)\left(1+V^2_{\Delta R(dry)}\right)\right)\right]^{1/2}_N} \right) \qquad \text{(M1c.2)}$$

where $\mu_{RN(dry)}$ and $\mu_{RN(wet)}$ are the mean values of $\Delta R(N)$ in dry and wet conditions; and $V_{RN(dry)}$ and $V_{RN(wet)}$ are the corresponding coefficients of variation obtained from replicate measurements. The sub-index N indicates that both, mean values and V, are computed for each load cycle separately. Figure M1c.1 shows the results obtained from this analysis for four different type of FAM, labeled NP2 through NP5. The four FAM utilize the same asphalt binder but different fillers. Mixtures that incorporate these four materials were rigorously examined for their moisture sensitivity in another study conducted by the University of Nottingham, UK. Therefore, these materials were an ideal choice for the preliminary evaluation of this probabilistic model. It is envisaged that in the future this methodology can be adopted for the suite of materials that will be selected as part of the experiment design in the moisture damage work area.

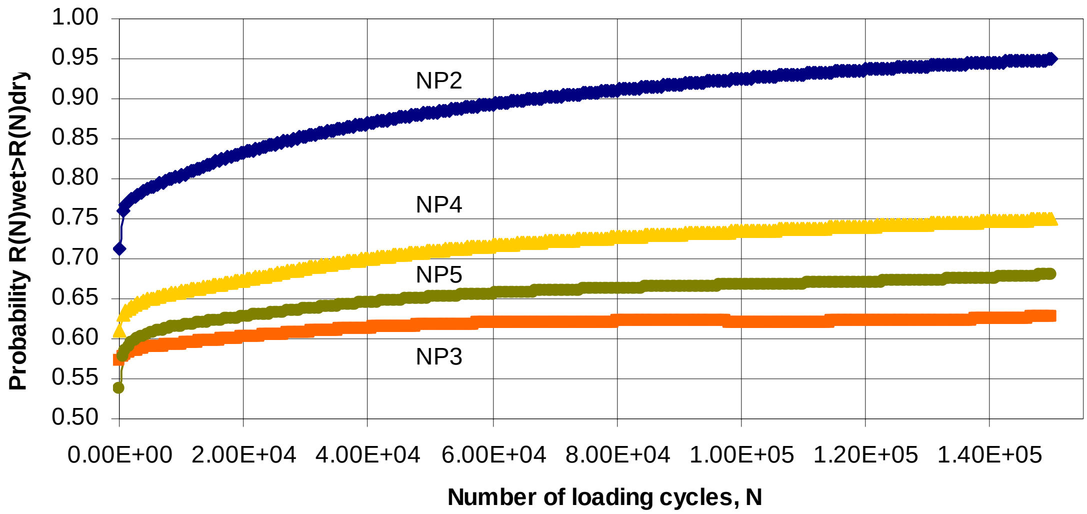


Figure M1c.1. Probability that ΔR(N)[wet]>ΔR(N)[dry] vs. number of load applications for all mixtures.

Work Planned Next Quarter

Fatigue test and analysis methods will continue to be developed for dry specimens. The finalized methodology for dry specimens will then be extended for moisture conditioned specimens at a later time in this task.

Reference

Caro, S., E. Masad, G. Airey, A. Bhasin, and D. N. Little. "Probabilistic Analysis of Fracture in Asphalt Mixtures Caused by Moisture Damage." Submitted for consideration in the *Transportation Research Record,* TRB, National Research Council, Washington D.C.

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 (Year 1 start) (TAMU)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

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

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Work Element M2b: Impact of Moisture Diffusion in Asphalt Mixtures

Subtask M2b-1: Measurements of Diffusion in Asphalt Mixtures (Year 1 start) (TAMU)

Progress This Quarter

Two methodologies were found to be most commonly reported in the literature for use with polymeric films and materials similar to asphalt binder. The first methodology is based on the use of Fourier Transform Infrared Spectroscopy (FTIR) and the second is based on gravimetric measurements.

We began the development of a methodology to determine the rate of moisture diffusion through thin films of asphalt binders using FTIR spectroscopy. We have also started tests based on gravimetric measurements to determine the diffusivity of water in fine aggregate matrix (FAM) specimens. Although, the use of the gravimetric method requires significant amount of time, the measurements are relatively easy to obtain and can provide an initial estimate for the range of expected diffusivity in FAM specimens. The following is a summary of the progress that was made in determining the diffusivity using FTIR spectroscopy.

An attenuated total reflectance (ATR) cell was used to determine the diffusivity of water through thin films of asphalt binders. An enclosure for the ATR cell was specifically designed for and fabricated for this and future tests involving moisture diffusion. This enclosure makes it possible to immerse the ATR window coated with the thin asphalt binder film under water. The air tight enclosure is also designed to conduct experiments by passing air at different relative humidity through the cell (dry to 95% saturated). This enclosure will allow the measurement of hysteresis in the rate of moisture diffusion through asphalt binders. The various steps followed to determine the rate of moisture diffusion through the asphalt binder are briefly described below and illustrated in figure M2b-1.1.

- A stock solution of the asphalt binder in toluene is prepared. About 0.2 mL of the stock solution are poured inside the ATR chamber to obtain an asphalt film approximately 50 μm thick after solvent evaporation.
- Solvent evaporation is facilitated by passing dry nitrogen through the chamber for 12 hours. The ATR cell with the binder film is heated for 1 hour at 60°C to eliminate any micro capillaries created during solvent evaporation.

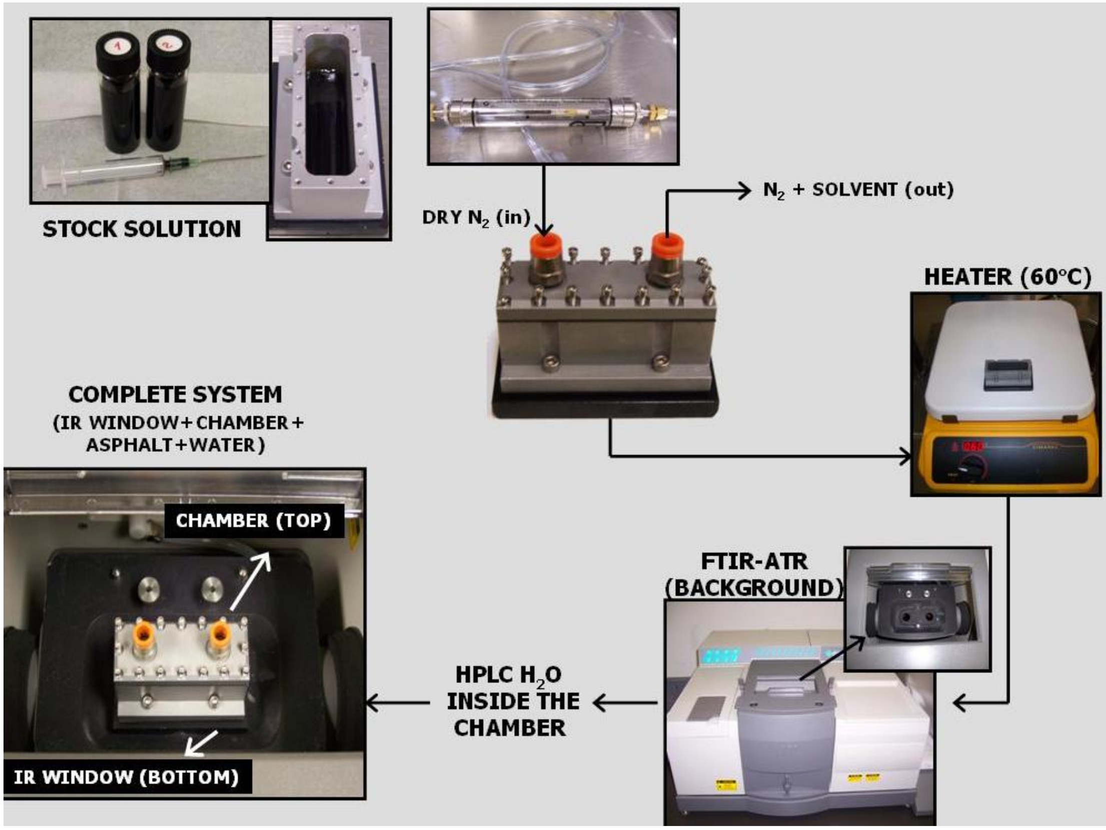


Figure M2b-1.1. Schematic showing the various steps followed to determine the rate of moisture diffusion through asphalt binder using ATR-FTIR spectroscopy.

- The background spectrum for the cell is obtained. The film is then immersed under water by injecting 2 mL of HPLC grade water. The FTIR spectrum is recorded at predetermined intervals.

The increase in the absorbance peak for the O-H bond in water (3400 cm^{-1}) was plotted over time to record the diffusion of water through the film (figure M2b-1.2). The preliminary experiments to develop this test method were conducted for a relatively short duration of time. We are currently evaluating the diffusion process for relatively longer time durations. We are also evaluating the use of Fick's second law to model the diffusion process through the thin film of the asphalt binder. The coefficient of diffusion of moisture through the thickness of a thin film following Fick's second law can be obtained from the following form (Crank 1975):

$$\frac{A_t}{A_\infty} = 1 - \frac{8\gamma}{\pi\left[1-\exp(-2\lambda L)\right]} \times \sum_{n=0}^{\infty} \left[\frac{\exp\dfrac{-D(2n+1)^2\pi^2 t}{4L^2}\left[\dfrac{(2n+1)\pi}{2L}\exp(-2\gamma L)+(-1)^n(2\gamma)\right]}{(2n+1)\left(4\gamma^2+\dfrac{(2n+1)\pi}{2L}\right)} \right]$$

where,

$$d_p = \frac{\lambda}{2\pi n_1 (n_1^2 \sin^2 \phi - n_2^2)^{1/2}};$$

$$\gamma = \frac{1}{d_p};$$

A_t and A_∞	–	spectral absorptions at a time t and equilibrium, respectively;
d_p	–	penetration depth;
L	–	film thickness;
D	–	diffusivity coefficient;
Λ	–	wavelength of radiant energy;
n_1 and n_2	–	index of refraction of the IRE and of the sample, respectively;
ϕ	–	angle of incidence radiation on the interface.

We expect to have preliminary results for few different types of asphalt binders by the end of the next quarter.

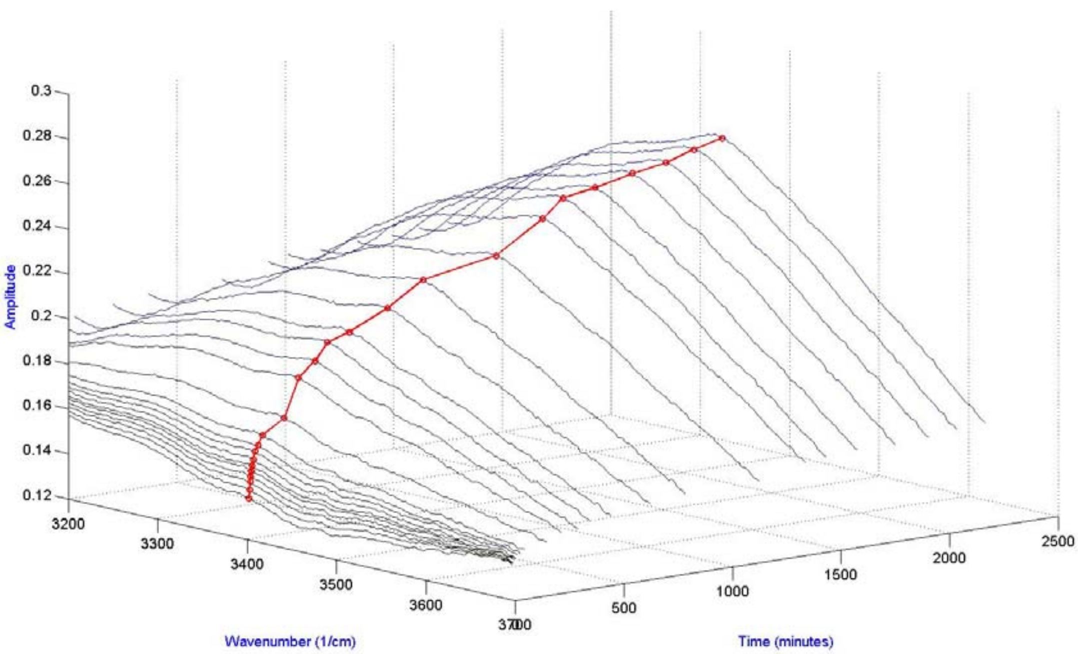


Figure M2b-1.2. The increase in the amplitude of the signal corresponding to the –OH peak from water over time.

Work Planned Next Quarter

In the next quarter, we plan to continue the experiments described above using different asphalt binders. A second setup is being prepared for the FTIR which will allow humid air flow through the chamber (controlled relative humidity) in order to compare with the steady water results. Beside the FTIR experiment, measurements of the refractive indexes (ellipsometer), and of the thickness of the asphalt film (profilometer) also need to be addressed in the next quarter.

Reference

Crank, J., 1975, *The Mathematics of Diffusion,* 2nd ed., Oxford University Press, NY.

Subtask M2b-2: Kinetics of Debonding at the Binder-Aggregate Interface (TAMU)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

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

Subtask M2c-1: Evaluate Load and Deflection Measurements using the Modified PATTI Test (Year 1 start) (UWM)

Subtask Lead: Codrin Daranga

Progress This Quarter

The Pull-Off Strength of Coatings test is a methodology originally developed by the painting/adhesive industry to measure the adhesion or pull-off strength of a coating on solid surfaces (e.g., metal, concrete, etc.) per ASTM D4541. This testing method measures the greatest perpendicular force that a solid surface-coating can take before the adhesive is detached from the solid surface. The test also allows for the evaluation of the type or failure: adhesive (at the coating-solid interface) or cohesive (within the coating) by inspecting the failure surface after the detachment has occurred.

However, the methodology presented in the ASTM standard does not provide data to evaluate the deformation behavior of the coating (i.e., binder), nor does it allow for the conditioning of the surface and/or binder to evaluate moisture damage in asphalt binders. These limitations are addressed in a proposed modification of the PATTI test for its application in the evaluation of pull-off strength of asphalt binders.

During this quarter, a modified PATTI test setup and methodology was developed. This new test is designed to enhance the parameters measured during the pullout test and to allow an improved evaluation of the mineral-binder adhesive and binder cohesive properties and of the effects of moisture damage within the binder and at the mineral-binder interface. This methodology also addresses the ETG’s comments and suggestions presented during the July 23–27, 2007 meeting in Denver, Colorado.

Figures M2c-1.1 and M2c-1.2 present the design components for the modified PATTI test.

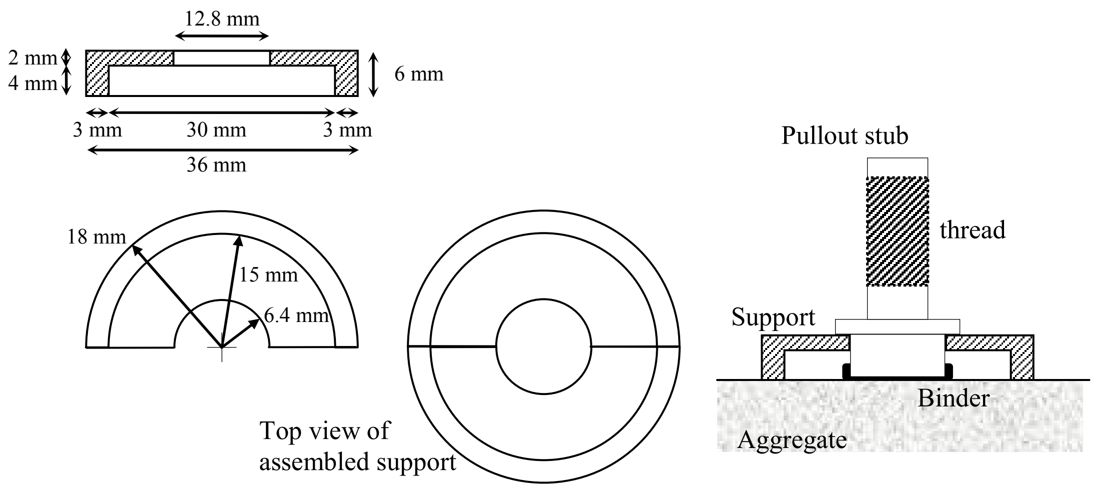


Figure M2c-1.1. Details of the split pullout stub support and assembled aggregate, binder, support and pullout stub.

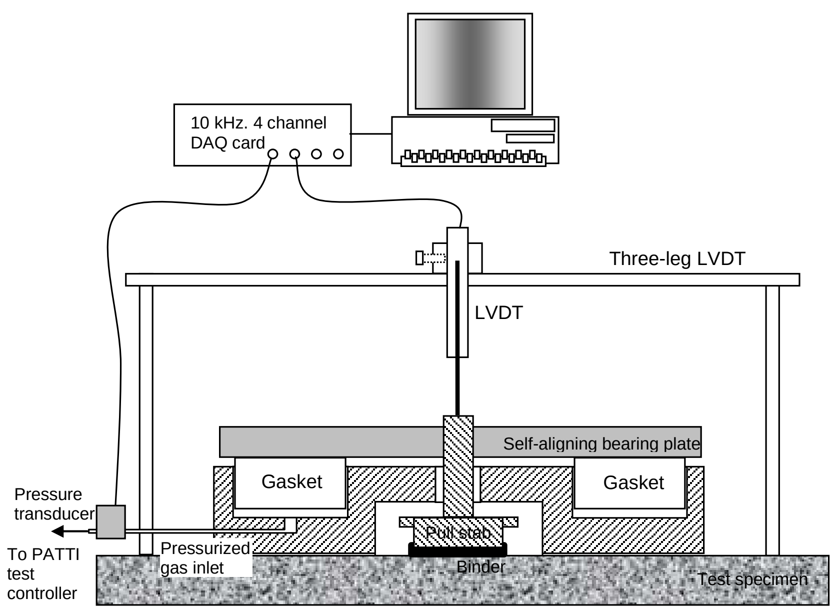


Figure M2c-1.2. Schematic of the complete ensemble modified PATTI test.

Problems Encountered and Solutions

None.

Work Planned Next Quarter

Start using the modified procedure for the PATTI test. The testing program will include:

- Mineral rocks (2): granite and limestone
- Binders (3): neat PG58-22 binder, PG64-22 SBS-modified binder, and PG64-22 Elvaloy-modified binder
- Conditioning temperatures (1): 60°C
- Conditioning times (1): 24 hours
- Conditioning environment (4): unconditioned, de-ionized water, 0.5 M NaCl solution and 0.5 M $CaCl_2$ solution
- Testing temperatures (2): 10°C (inside an environmental chamber) and 25°C (room temperature)
- Pullout rates (2): one slow and one fast (as determined from a parametric pullout rate study)

Total number of tests: 96 tests (plus duplicates)

Subtask M2c-2: Evaluate Effectiveness of the Modified PATTI Test for Detecting Modification Effects (Year 1 start) (UWM)

Progress This Quarter

Baseline properties of the selected materials have been measured using typical SHRP test methods. Both modified and unmodified binders have been selected and tested. For consistency, the materials included in this subtask are chosen such that they are similar to those employed in other work plans, such as fatigue testing or thermal cracking. Also, the tooling required for rock sample preparation has been acquired. We have also secured access to the geological lab and tool training for sample preparation.

Problems Encountered and Solutions

None.

Work Planned Next Quarter

Begin testing using the modified DSR method to measure cohesive strength and adhesive strength. Finish the building of the modified PATTI test so that comparative testing can begin. Start data analysis and comparison with the modified PATTI test. Same experimental variables listed in Task M2c-1 will be used in this task.

Subtask M2c-3: Validation of the Modified PATTI Test using Results from DSR Testing (UWM)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Subtask M2c-4: Testing of Mastics Using Modified PATTI and DSR Tests (UWM)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Subtask M2c-5: Commercialization and Practicality Evaluation of the Modified PATTI Test (UWM)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Subtask M2c-6: Analysis and Recommendations for the Modified PATTI Test (UWM)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

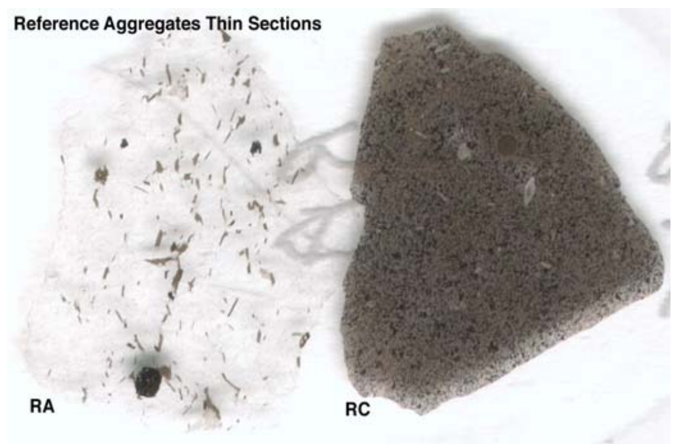
No work planned.

CATEGORY M3: AGGREGATE SURFACE

Work Element M3a: Aggregate Surface Characterization (Year 1 start) (TAMU)

Physical and chemical properties of aggregates at the macro and molecular scale influence the performance of asphalt mixes. These properties control the nature and durability of the bond between the aggregates and the bitumen in wet and dry conditions and its resistance to moisture induced damage and fatigue cracking.

Recent research by Little and colleagues has shown that surface energy of the aggregate-bitumen interface is a reliable predictor of engineering properties of the asphalt mixture. Current understanding of the aggregate and bitumen properties that control and shape surface energy is limited, limiting our ability to *a priori* predict surface energy of any given aggregate-bitumen combination.



We propose to develop a predictive model of aggregate surface energy based upon a linear additive model of the surface energies of individual minerals that compose the aggregates. While aggregate properties are very heterogeneous, most aggregates are composed of a relatively few minerals. The image to the right shows thin sections of two common aggregates. The images clearly illustrate the mineralogical heterogeneity of the aggregates.

The tasks are organized around the (1) characterization of the chemical composition of the surfaces of reference minerals and aggregates through electron beam spectroscopes, including electron microprobe, backscatter electrons and electron-dispersive spectroscopy (EDS), (2) characterization of the bonding between water and representative organics and aggregate surfaces using infrared spectroscopy, particularly sum-frequency generation (SFG) which directly probes the infrared adsorption at an interface, and (3) characterize the surface energies of reference minerals and aggregates through the universal sorption device and microcalorimetry. The results from these three tasks will be used to develop a predictive model of aggregate surface energies based upon the surface energies of the minerals that compose the aggregate.

Progress This Quarter

Our efforts this quarter focused on identifying a set of mineral that are representative of the mineralogy of common aggregates as found in the Strategic Highway Research Program's (SHRP) Materials reference library (table M3a.1). The following major mineral groups comprise the abundant constituents of rocks used as aggregate material. Therefore, a reference suite of these minerals must be acquired and characterized to provide starting material for experimental work:

- Feldspars: (1) plagioclase (sodic to calcic), and (2) potassium feldspar

- Amphiboles: most common: Hornblende
- Pyroxenes: most common: Augite
- Olivines: most common: Forsterite
- Carbonates: most common: Calcite and Dolomite
- Micas: most common: Muscovite and Biotite
- Iron-Titanium Oxides: most common: Hematite, Magnetite, Ilmenite, Goethite
- Quartz

Table M3a.1. Representative minerals commonly found in aggregates.

Mineral	Group	Chemical Formula	Occurrence
Microcline	Feldspar	$KAlSi_3O_8$	
Na-Plagioclase	Plagioclase Feldspar[1]	$NaAlSi_3O_8$	Dominant feldspar in andesite, an igneous rocks. Minor component in granite and metamorphic rocks.
Labradorite	Plagioclase Feldspar[1]	$Ca_{(0.5\text{-}0.7)}Na_{(0.3\text{-}0.5)}(Al,Si)AlSi_2O_8$	
Andesine	Plagioclase Feldspar[1]	$Na_{(0.5\text{-}0.7)}Ca_{(0.3\text{-}0.5)}(Al,Si)AlSi_2O_8$	Dominant feldspar in andesite, an igneous rocks. Minor component in granite and metamorphic rocks.
Olivine[2]	Nesosilicates	$(Mg,Fe)_2SiO_4$	Olivine is found in ultramafic igneous rocks and marbles that formed from metamorphosed impure limestones.
Augite	Pyroxene	$(Ca,Na)(Mg,Fe,Al)(Al,Si)_2O_6$	An important rock-forming mineral in many igneous rocks, especially in gabbros and basalts. Augite is also found in some hydrothermal metamorphic rocks.
Hornblende[3]	Amphibole	$Ca_2(Mg,Fe,Al)_5(Al, Si)_8O_{22}(OH)_2$	An important rock-forming mineral in many igneous rocks, especially in gabbros and basalts.
Ilmenite	Oxyhydroxides	$FeTiO_3$	Ilmenite forms as a primary mineral in mafic igneous rocks
Magnetite	Oxyhydroxides	Fe_3O_4	
Dolomite	Carbonates	$CaMg(CO_3)_2$	A common sedimentary rock-forming mineral, dolomitic limestone.

[1] The plagioclase series comprises minerals that range in chemical composition from pure NaAlSi3 O8, Albite to pure CaAl2 Si2 O8 , anorthite. Andesine by definition must contain 70-50% sodium to 30-50% calcium in the sodium/calcium position of the crystal structure.

[2] Olivine is actually a name for a series between two end members, fayalite and forsterite. Fayalite is the iron rich member with a pure formula of Fe2SiO4. Forsterite is the magnesium rich member with a pure formula of Mg2SiO4.

[3] Hornblende is actually the name given to a series of minerals that are rather difficult to distinguish by ordinary means. The iron, magnesium and aluminum ions can freely substitute for each other and form what have been distinguished as separate minerals. The minerals are given the names Magnesio-hornblende, Ferrohornblende, Alumino-ferro-hornblende and Alumino-magnesio-hornblende.

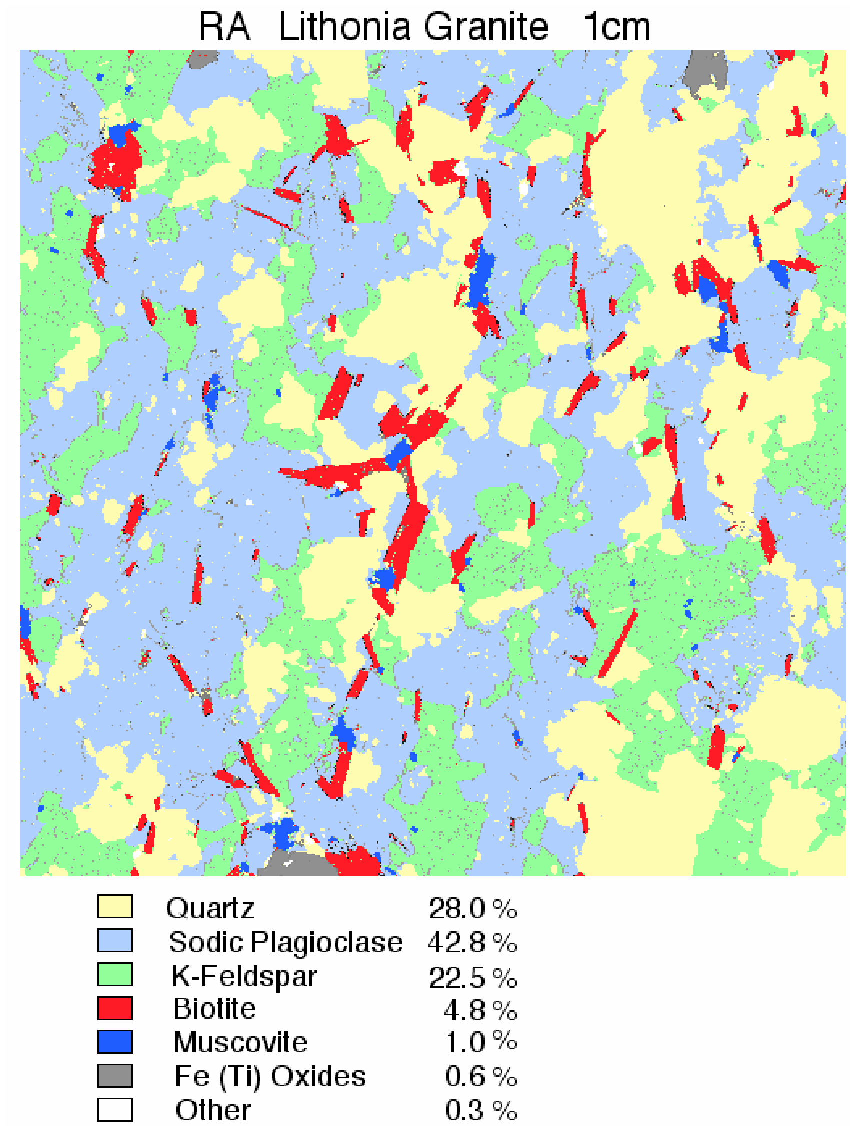
Preliminary examination of representative samples from some of these mineral groups indicates that considerable care will have to be taken to ensure that the selected samples are monomineralic and not contaminated with significant quantities of other mineral phases that would complicate the interpretation of experimental results in the later phases of this asphalt adhesion study.

Thin sections of representative 1 to 3 cm fragments of the following SHRP aggregates have been prepared: RA: Lithonia Granite; RC: Limestone (higher absorption); RD: Limestone (low absorption); RK: Basalt; and RL: Gulf Coast Gravel. Preliminary examination indicates some discrepancies between the modal mineralogy observed in thin section compared to that reported in the SHRP-A-645 publication (SHRP Materials Reference Library: Asphalt Cements: A Concise Data Compilation, by David R. Jones, IV, 1993). For example, quartz and clays are not reported for the RC Limestone in SHRP-A-645, but were observed as major constituents (>10%) in our thin section. Calcite is also reported as the only carbonate, while we observed that about 25% of the carbonate is dolomite rather than calcite using Xray elemental mapping on the electron microprobe. For the RA Lithonia Granite, plagioclase feldspar was reported in SHRP-A-645 as comprising 10% of the rock, while our thin section Xray elemental mapping analysis indicated it to be the dominant mineral, making up 40% of the rock in thin section (figure M3a.1).

Work Planned Next Quarter

Our task in the next quarter will be to characterize the chemical properties of representative minerals given in table M3a.1 using elemental mapping by electron microprobe, backscatter electron spectroscopy and X-ray dispersive spectroscopy. Specific objectives include:

1. Continue modal mineral analysis (volume % mineral in rock) and chemical compositional mineral analysis (wt % elements in each mineral) using the electron microprobe for the SHRP aggregate materials used in this study and compare our results with those reported in SHRP-A-645.
2. Begin analysis of pure mineral standards to be used in this study. Methodology to be used in the selection of representative members of the mineral groups listed above:
3. Include all major minerals present in the SHRP aggregate rock standards
4. Select monomineralic specimens to simplify measurement of surface characteristics
5. Characterize the chemical composition of each mineral using electron microprobe analysis
6. Insure that a sufficient quantity of each mineral can be obtained for the required adhesion tests.



M3a.1. Typical thin section X-Ray elemental map.

Steps involved in the detailed characterization of the aggregates include:

1. Examination of a comprehensive range of representative aggregate materials to determine mineralogical content, grain size and texture. This will initially be done by optical petrography techniques (polished thin sections), followed by elemental distribution maps acquired on an electron microprobe using wavelength-dispersive (WDS) X-ray as well as backscattered electron (BSE) signals. The compositions of the individual aggregate minerals will then be determined by quantitative individual-point X-ray WDS analyses on the electron microprobe.
2. Based on the mineralogy of the aggregates, suitable individual mineral reference materials will be acquired for further testing. These minerals will include both

compositional end-members and intermediate members of the common rock forming minerals found in the aggregate materials. For example, in the plagioclase feldspar series, nearly pure Na plagioclase (albite), Ca plagioclase (anorthite) and intermediate Na-Ca plagioclase compositions (andesine, and/or labradorite, etc) will be acquired and analyzed so that these individual well-characterized mineral components can be used in some of the aggregate-asphalt experiments.

Examples of properties of aggregates that will be characterized include: (1) specific surface area for different size fractions, (2) major mineralogical composition, (3) chemical composition (major oxide) of minerals, (concentration of major surface function groups, and (5) concentration of water and acid solubles.

CATEGORY M4: MODELING

Work Element M4a: Micromechanics Model (TAMU)

Progress This Quarter

A detailed literature review was conducted to identify the modeling aspects related to moisture induced damage at adhesive interfaces. The review focused on research conducted in areas other than bituminous materials such as adhesives, thin film packaging, and electronics industries. Key findings from this review are briefly summarized below.

General: Environmental deterioration of adhesive joints accounts for the deleterious processes occurring within the bulk of the adhesive material and at the substrate-adhesive interface. The degradation within the bulk of the adhesive, generally referred to as cohesive deterioration, includes creep, swelling, thermal degradation, post-cure effects, cracking, plasticization by water and hydrolysis, among others (Zewi et al. 1984). The degradation of the interface is mainly the result of the breakage of secondary or covalent bonds due to the action of water and temperature (Zewi et al. 1984).

Water-induced adhesive failure depends on the physio-chemical and mechanical properties of the substrate and adhesive, as well as on the external conditions to which the interface is exposed. Failure of adhesive interfaces can be modeled using two different approaches. The first approach is to model interfacial damage as a water-assisted mechanical deterioration process, i.e. water participates in the process but external stresses are the major contributors to damage. The second approach is to model interfacial damage as a stress-enhanced debonding process, i.e., hydrolysis and other water-induced processes are the main source of damage and presence of stresses only acts as a catalyst in the process (Lam et al. 1999; Lam and Wang 2007). Most of the experimental and numerical modeling work cited in the literature is related to the first approach. This work typically involves experimental testing and mechanical analysis of the performance of adhesive joints under different environmental conditions. Regardless of the approach, moisture degradation is a complex process including physical, mechanical, chemical and thermodynamic aspects. Interfacial chemistry, cathodic delamination, and electro-chemical corrosion, among others, have been used to explain, analyze and model the debonding process in the presence of water (Lam et al. 1999; Lam and Wang 2007).

<u>Thermodynamics</u>: Principles of thermodynamics have been used in the literature to explain the effect of water on adhesion (Kinloch 1980; Clint and Wicks 2001; Liljedahl et al. 2006; Bhasin et al. 2006). It has been observed that the change in free energy when water displaces an adhesive interface is negative, suggesting that delamination by water (i.e., displacement of the substrate by water) is a thermodynamically favorable process. Tasks M1a and M2a of this research project emphasize this aspect of moisture induced damage. However, the limitation of any thermodynamics based approach is that although the potential to reach a new equilibrium state of damage is well quantified, the time required to reach this state is not addressed. This shortcoming is often addressed by combining principles of thermodynamics with reaction kinetics.

<u>Rate of Moisture Damage</u>: Crocombre (1997) has proposed that the rate of moisture deterioration in adhesive joints is dependent on two processes: (1) the rate at which the moisture is delivered to the interface, and (2) the rate at which subsequent degradation processes occur at the interface. The first stage is mainly a diffusion process driven by the moisture concentration gradient and controlled by the diffusivity properties of the material. The second stage involves loss of interfacial adhesion due to displacement by water. This stage is driven by the thermodynamic potential and controlled by the absolute rate of reaction (displacement of interfacial bonds by water molecules) at the interface. Task M2b of this research project emphasizes these time dependent aspects of moisture induced damage. Gledhill et al. (1980) have identified a final stage conformed by the ultimate failure of the adhesive bond. At this point, the authors suggested that ultimate failure occurs when the interface reaches a critical moisture content.

In some cases, it is assumed that damage occurs instantaneously right after water reaches the interface. In such cases, moisture induced damage is modeled as a function of water concentration at the interface. As a result, the rate of interfacial damage is dependent exclusively on the rate of diffusion (Gledhill et al. 1980; Hua et al. 2006). Also, in such cases the loss of structural strength of the joint is directly modeled based upon the concentration of water at the interface (Hua et al. 2006).

Leung et al. (2004) developed an analytical model based on the principles of chemical kinetics that utilizes results from shear fracture tests at different relative humidity and temperature conditions to delineate the material parameters that govern the deterioration process at the interface. The authors concluded that the effect of temperature in the moisture-degradation of interfacial bonds follows a chemical kinetics model with Arrhenius form. They also concluded that the rate of degradation is highly influenced by the hydrogen ion concentration at low acidity and that the influence of the applied stresses on this rate can be characterized by the activated area coefficient of the activated state divided by the overall bond density.

In another study, Lam et al. (1999) used principles of chemical kinetics to describe interfacial degradation of adhesive joints commonly used in electronic packages. The authors concluded that the mechanism of debonding at these joints was dominated by water and not by external stresses (i.e., stress-enhanced process).

Fracture Mechanics Approach: An alternative methodology to quantify the effect of moisture on the rate of crack growth is by direct measurement of the crack propagation speed at the interface under different moisture conditions (different relative humidity). Several examples of this methodology are available in the literature (Mostovoy and Ripling 1969; Weiderhorn et al. 1980; Ritter and Conley 1992; Fernando et al. 1996; Kinloch et al. 2000; Kook and Dauskardt 2002; Leung et al. 2004; Lane et al. 2004; Liljedahl et al. 2006; O'Brien et al. 2006; Ferguson and Qu 2006). In most cases, principles of elastic fracture mechanics are applied to quantify the energy release rate (*G*) associated with the crack growth process.

Figure M4a.1 illustrates the three main zones that are typically observed in the relationship between the crack growth rate and the energy released rate of adhesive joints in humid environments. The crack growth rate in the first zone (zone I) is highly dependent on the energy release rate, in the second (zone II) it seems to be less sensitive to the energy released rate, and the last zone (zone III) represents the ultimate failure condition (Gdoutus 2005). This behavior was first observed in adhesive joints with ceramics (Weiderhorn et al. 1980, Ritter and Conley 1992), and it has been also verified for metal-epoxy joints (Lane et al. 2004). Figures M4a.2 and M4a.3 illustrate typical test results from this relationship in metal-epoxy adhesive joints.

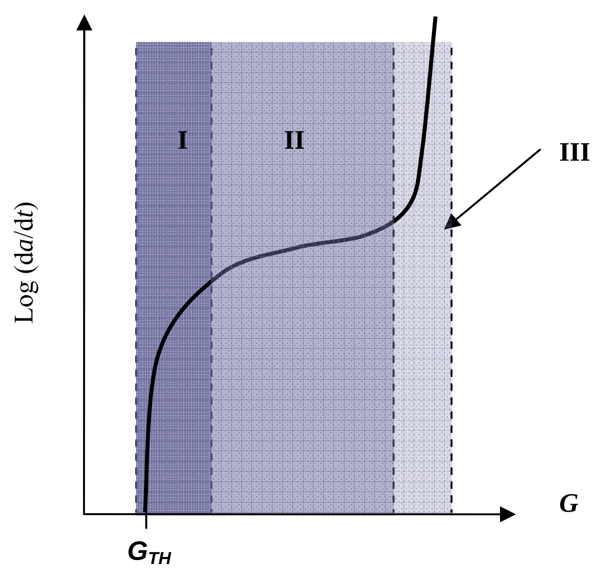


Figure M4a.1. General relationship between crack growth rate (da/dt) and energy released rate (G). G_{TH} is the threshold value of G bellow which no crack growth is observed (adapted from Lane et al. 2004).

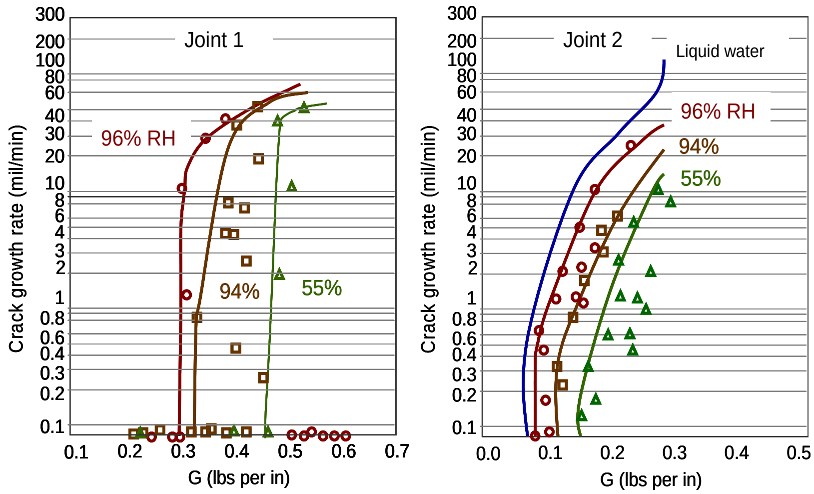


Figure M4a.2. Results for two different metal-epoxy adhesive joints subjected to mode I test (adapted from Mostovoy and Ripling, 1969).

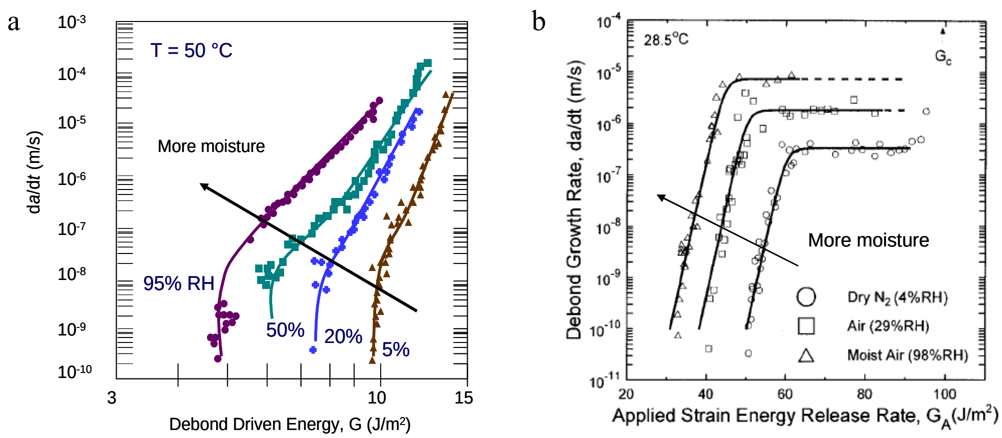


Figure M4a.3. Results for two metal-cooper adhesive joint subjected to mode I test (a) adapted from Lane at al. (2001), and (b) adapted from Hook and Dauskardt (2002).
Note: the moisture conditioning process of the specimens was different for each work.

The main conclusions from the review of literature pertaining to the fracture mechanics framework are:

- The threshold value of energy release rate for a crack propagating at the interface (or stress intensity factor) increases with increase in relative humidity (G_{TH} in figure M4a.1, Lam et al. 1999; Gdoutos 2005).
- High relative humidity reduces the fracture toughness of an adhesive joint (Ripling 1971; Ferguson and Qu 2006).

- The fracture locus under humid conditions is adhesive in most cases (Kinloch et al. 1980) and switches to cohesive in the absence of moisture (Ferguson and Qu 2006).

Numerical Modeling: There is limited work in the literature related to numerical modeling of interfacial damage. Hua et al. (2006) and Liljedahl et al. (2006) have successfully used a commercial finite element package to model the debonding of metal-epoxy adhesive joints under humid environments. In both cases, the authors used a physical-mechanical coupled scheme in combination with de-cohesive elements to model the behavior at the interface. The model simulates the diffusion of moisture through the adhesive and the loss of strength at the interface. A traction-separation constitutive law that is a function of the level of stress and water concentration determines the behavior of the cohesive elements. When an element reaches a maximum allowable strength condition it is eliminated and its stresses are distributed in the surrounding elements. Figure M4a.4 presents the debonding process by the combined action of load and moisture of a three dimensional metal-epoxy adhesive joint at four different periods of time.

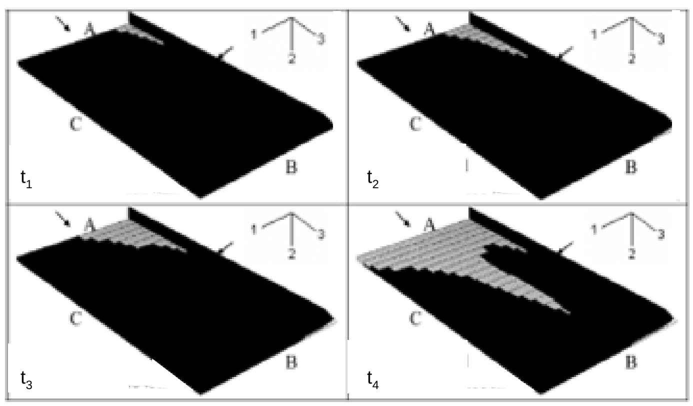


Figure M4a.4. A 3-dimensional model of the debonding process of a metal-epoxy adhesive joint by the combined action of external load and moisture (adapted from Hua et al. 2006).

In October, Professors Little and Masad traveled to the University of Nottingham and to Imperial College in London to visit with Drs. Gordon Airey, Andrew Collup, Ambrose Taylor, and Anthony McKintoch to discuss their work on applying surface energy to evaluate bond strength in the presence of water. The work at Imperial College is fundamentally based in the area of adhesion mechanics. The work at Nottingham is more applied. A collaborative effort among Texas A&M, Nottingham, and Imperial College to study the application of surface energy on bond strength determinations is currently being funded by the Engineering and Physical Science Foundation, which is essentially the equivalent of NSF in Europe.

Work Planned Next Quarter

A computational model will be developed to represent the moisture damage process at the binder-aggregate interface based on fundamental material properties. It is envisioned that this model will later be integrated with other computational models that represent other mechanisms of the moisture damage process in an asphalt mixture.

Collaboration with Nottingham and Imperial College will continue.

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

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Work Element M4c: Unified Continuum Model (TAMU)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

CATEGORY M5: MOISTURE DAMAGE PREDICTION SYSTEM (Later start) (AAT, TAMU, UNR, UWM, WRI)

Progress This Quarter

Later start.

Work Planned Next Quarter

No work planned.

PROGRAM AREA: FATIGUE

CATEGORY F1: MATERIAL AND MIXTURE PROPERTIES

Work Element F1a: Cohesive and Adhesive Properties

Subtask F1a-1: Critical Review of Measurement and Application of Cohesive and Adhesive Bond Strengths (Year 1 start) (TAMU)

<u>Progress This Quarter</u>

A critical review of the literature related to the experimental and analytical methods that are used to determine the practical work of cohesion and adhesion was conducted. This literature review is nearing completion.

The test equipment required to conduct transverse tensile tests on thin films of asphalt binders using various geometries was also fabricated. Preliminary experiments to develop a test procedure are in progress.

<u>Work Planned Next Quarter</u>

The literature review will be completed and summarized in the next quarterly report. Some preliminary tests on thin films of asphalt binders will also be conducted and reported in the next quarter.

Subtask F1a-2: Develop Experiment Design (Year 1 start) (TAMU)

<u>Progress This Quarter</u>

No activity this quarter.

<u>Work Planned Next Quarter</u>

No work planned.

Subtask F1a-3: Thermodynamic Work of Cohesion and Adhesion (Year 1 start) (TAMU)

<u>Progress This Quarter</u>

No activity this quarter.

<u>Work Planned Next Quarter</u>

No work planned.

Subtask F1a-4: Mechanical Work of Adhesion and Cohesion (TAMU)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Subtask F1a-5: Evaluate Acid-Base Scale for Surface Energy Calculations (TAMU)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Work Element F1b: Viscoelastic Properties (Year 1 start)

Subtask F1b-1: Separation of Nonlinear Viscoelastic Deformation from Fracture Energy under Cyclic Loading (TAMU)

Progress This Quarter

Literature from previous TxDOT Projects 0-4468, "Evaluate the Fatigue Resistance of Rut Resistant Mixes" and 0-4688, "Development of a Long Term Durability Specification for Modified Asphalt" was gathered for review in terms of the required laboratory testing and analysis for mixtures tested in direct tension and evaluated in terms of fatigue life predicted by the calibrated mechanistic with surface energy (CMSE) approach. The repeated direct tension test and the monitoring of dissipated pseudo-strain energy was the focus of this review to facilitate extension of the DMA fatigue analysis to mixtures.

In this quarter, we also have developed a method to calculate the nonlinear viscoelastic and damage parameters based on Schapery's nonlinear viscoelastic model. This method was extended to dynamic loading in a fatigue test by considering the nonlinear parameters as a function of stress or strain amplitudes applied in the DMA. Damage is quantified by changes in the nonlinear parameters at an applied stress or strain level. This analysis method was used to analyze DMA test results at various stress amplitudes, strain amplitudes and frequencies. We have also derived a more comprehensive model in which the non linear parameters are formulated as functions of the stress or strain magnitude at any given time within each load cycle. Using this new derivation, we will be able to determine the model's parameters for the stress-strain constitutive relationship and use it in modeling the material response under various loading conditions. Table F1b-1.1 summarizes the three important components of this methodology.

Table F1b-1.1. Methodology to characterize fatigue damage by incorporating the non linear viscoelastic response of the material.

	Procedure	**Purpose**
Step 1	Identify the limiting stress or strain amplitude that generates nonlinear viscoelastic response without causing damage	This information will also be used to select a suitable magnitude of stress or strain amplitude for the specific material to ensure that incremental crack growth occurs with each consecutive cycle
Step 2	Model and monitor **the change in** the nonlinear viscoelastic **parameters with increasing number of load cycles** during the fatigue test	A change in the nonlinear viscoelastic parameters with increasing number of load cycles indicates accumulation of damage. Therefore, this change can be used to quantify the accumulated fatigue damage in the test specimen
Step 3	Model and monitor **the change in** the nonlinear viscoelastic **parameters within each cycle** during the fatigue test	A change in the nonlinear parameters within each cycle can be modeled and monitored to determine the type of damage that is being accumulated during the fatigue load test and also to accurately partition the dissipated energy due to damage versus nonlinear viscoelastic dissipated energy

Step 1: The limiting stress or strain amplitude that generates nonlinear viscoelastic response without causing damage can be determined by conducting stress or strain sweeps and following the procedure described next. The stress or strain sweeps are conducted by subjecting the specimen to a minimum number of load cycles at each increment of the strain or stress amplitude. The optimal parameters for increments and the minimum number of load cycles that are required to obtain the desired information were determined by conducting several trials. For a strain amplitude sweep, the slope or change in the torque amplitude versus number of load cycles was recorded at each strain amplitude. Similarly, for a stress amplitude sweep, the slope or change in the displacement amplitude versus number of load cycles is recorded at each stress amplitude.

In the case of a strain sweep test, if the applied strain amplitude does not exceed the nonlinear viscoelastic limit, the torque response will not change with increasing number of load cycles. However, a decrease in the response torque amplitude with increasing number of load cycles indicates that the material is accumulating damage. Based on this reasoning, the maximum strain amplitude that does not cause the torque to decrease with number of load cycles corresponds to the limiting value for nonlinear behavior without damage. The same process can be repeated for a stress sweep test. Figure F1b-1.1 illustrates the results from stress sweep tests in which three replicates were used. From figure F1b-1.1, the limiting stress amplitude that generates nonlinear viscoelastic response without cause damage is close to 4.5E+04 Pa.

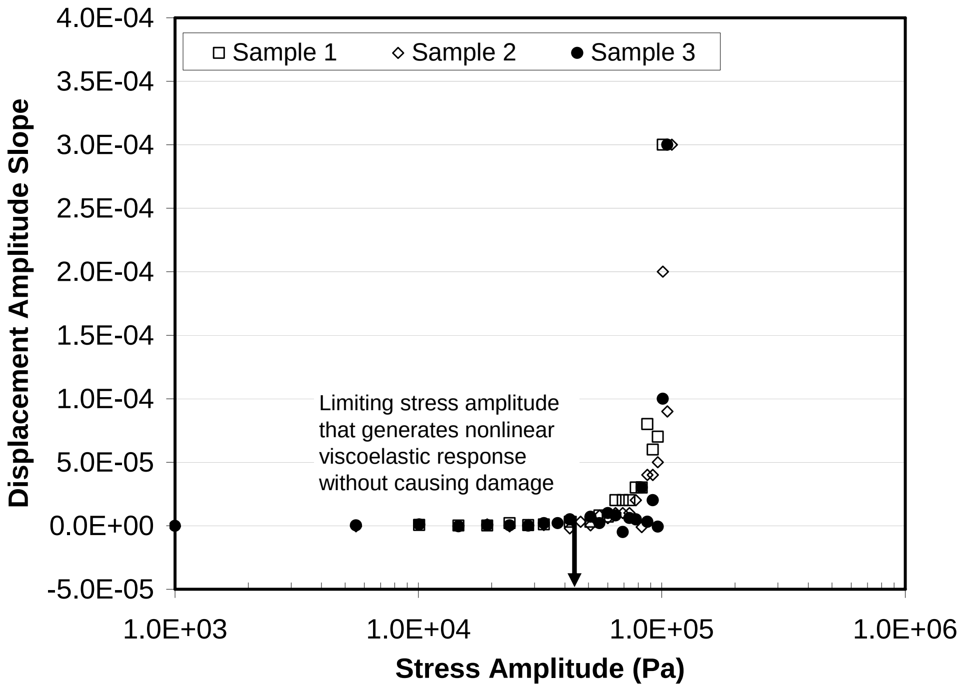


Figure F1b-1.1. Displacement Amplitude Slopes

Step 2: Schapery developed a model for the nonlinear viscoelastic behavior that could be used with the Boltzmann superposition integral to characterize the response of the material under a variety of stress states (Schapery 1969; Golden et al. 1996). The strain response (ε) for a given stress (σ) history can be represented using equation F1b-1.1.

$$\varepsilon = g_0 D_0 \sigma + g_1 \int_0^t \hat{D}(t-\tau)\frac{\partial g_2 \sigma}{\partial t} d\tau \qquad \text{(F1b-1.1)}$$

The nonlinear viscoelastic parameters can be defined as follows: (i) g_0 is related to the nonlinear instantaneous elastic compliance and quantifies the reduction in stiffness as a function of the stress level, (ii) g_1 is the transient creep parameter and measures the nonlinearity effect on the transient compliance, and (iii) g_2 is the parameter that accounts for the load rate effect on the transient compliance, and t and τ are present and previous times, respectively.

To account for oscillatory contributions, the function described on equation F1b.1 was expanded as shown in equation F1b-1.2.

$$\Delta\varepsilon = D_0(g_{0,t} + \Delta g_0)(\sigma) + (g_{1,t} + \Delta g_1)\int_{-\infty}^{t} D(t-\tau)\frac{\partial}{\partial \tau}(g_{2,t} + \Delta g_2)(\sigma)\partial\tau \qquad \text{(F1b-1.2)}$$

where, $\sigma = \sigma_t + \Delta\sigma e^{iwt}$, w is the angular frequency defined as $w = 2\pi f$, and σ_t is the preload prior to applying the oscillatory stress.

For the current study, no preload was used. Therefore, the terms with subscript *t* in equation F1b-1.2 were dropped to yield equation F1b-1.3.

$$\Delta\varepsilon = D_0 \Delta g_0(\sigma) + (\Delta g_1)\int_{-\infty}^{t} D(t-\tau)\frac{\partial}{\partial\tau}(\Delta g_2)(\sigma)\partial\tau \qquad \text{(F1b-1.3)}$$

The terms with the symbol Δ represent the nonlinear parameters due to the magnitude of the amplitude of the oscillatory stress. After some mathematical manipulations, equation F1b-1.3 can be rewritten as:

$$\Delta\varepsilon = D_0 \Delta g_0(\Delta\sigma) + (\Delta g_1)(\Delta g_2)(\Delta\sigma)(\hat{D}' + i\hat{D}'') \qquad \text{(F1b-1.4)}$$

Creep compliance for linear response can be represented by equation F1b-1.5:

$$D^* = \frac{\Delta\varepsilon}{\Delta\sigma} = \frac{\varepsilon_0}{\sigma_0}\cos\delta + i\frac{\varepsilon_0}{\sigma_0}\sin\delta \qquad \text{(F1b-1.5)}$$

where, ε_0, σ_0, and δ are strain, stress amplitude and phase angle, respectively.

The real and imaginary parts of the compliance can be written as in equations F1b-1.6 and F1b-1.7 for controlled-stress analysis.

$$\frac{\varepsilon_0}{\sigma_0}\cos\delta = D_0(\Delta g_0) + (\Delta g_1)(\Delta g_2)\hat{D}' \qquad \text{(F1b-1.6)}$$

$$\frac{\varepsilon_0}{\sigma_0}\sin\delta = (\Delta g_1)(\Delta g_2)\hat{D}'' \qquad \text{(F1b-1.7)}$$

For controlled strain loading, the real and imaginary parts are presented by equations F1b-1.8 and F1b-1.9, respectively.

$$\frac{\sigma_0}{\varepsilon_0}\cos\delta = E_e(\Delta h_e) + (\Delta h_1)(\Delta h_2)\hat{E}' \qquad \text{(F1b-1.8)}$$

$$\frac{\sigma_0}{\varepsilon_0}\sin\delta = (\Delta h_1)(\Delta h_2)\hat{E}'' \qquad \text{(F1b-1.9)}$$

In order to add damage analysis, two damage parameters were considered: (i) *V* (damage parameter for controlled-stress analysis), and (ii) *W* (damage parameter for controlled-strain analysis). Equations F1b-1.6- F1b-1.9 can be rewritten as in equations F1b-1.10-13 to account for damage. If there is no damage (linear or nonlinear viscoelastic behaviors only), damage parameters (*V* and *W*) should be equal to one.

$$\frac{\varepsilon_0}{\sigma_0}\cos\delta = D_0(\Delta g_0) + (\Delta g_1)(\Delta g_2)(V)\hat{D}' \qquad \text{(F1b-1.10)}$$

$$\frac{\varepsilon_0}{\sigma_0}\sin\delta = (\Delta g_1)(\Delta g_2)(V)\hat{D}'' \qquad \text{(F1b-1.11)}$$

$$\frac{\sigma_0}{\varepsilon_0}\cos\delta = E_e(\Delta h_e) + (\Delta h_1)(\Delta h_2)(W)\hat{E}' \qquad \text{(F1b-1.12)}$$

$$\frac{\sigma_0}{\varepsilon_0}\sin\delta = (\Delta h_1)(\Delta h_2)(W)\hat{E}'' \qquad \text{(F1b-1.13)}$$

<u>Preliminary Tests and Results:</u> The methodology described above was evaluated on selected types of fine aggregate matrix (FAM) using the dynamic mechanical analyzer (DMA). Relaxation modulus at constant strain amplitude within the linear viscoelastic region (0.0065%) was determined for the FAM. The total time for the load step function was 100 seconds. Results for the relaxation modulus (*E(t)*) are shown in figure F1b-1.2. The experimental data were described using a power law relationship ($E(t) = E_e + E_1 t^{-n}$). Values found for E_e, E_1 and *n* were 3.47E+02 Pa, 5.00E+07 and -0.55, respectively.

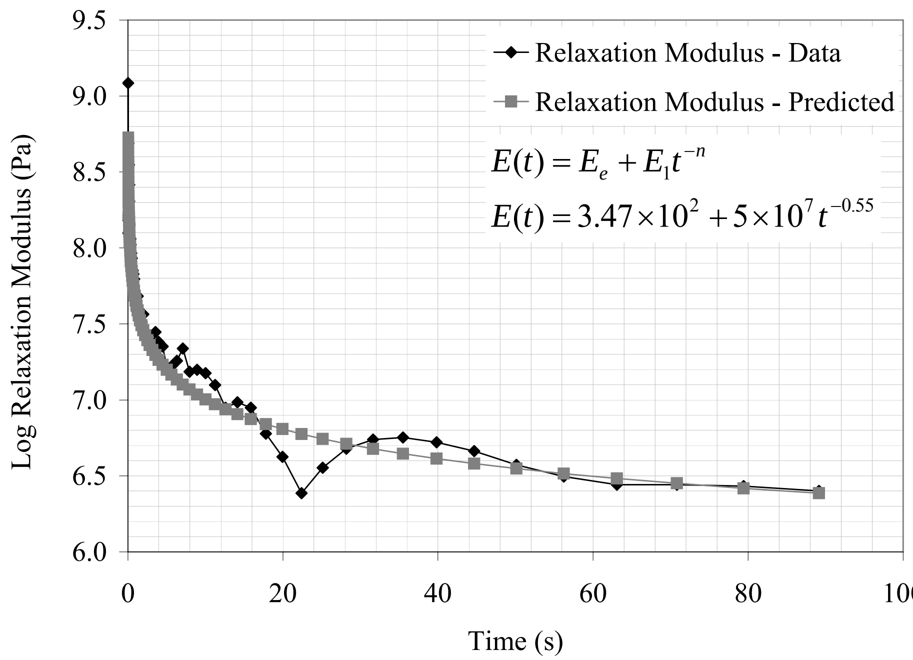


Figure F1b-1.2. Relaxation Modulus for FAM.

Based on the work of Park and Kim (1999), the relaxation modulus was converted to creep compliance (*D(t)*) (figure F1b-1.3). Two inter conversions were used: (i) quasi-elastic interrelationship ($E(t)D(t) \cong 1$), and (ii) power-law-based interrelationship ($E(t)D(t) = \frac{\sin n\pi}{n\pi}$). The results from both interrelationships were very close. Creep compliance was predicted using a power law relationship ($D(t) = D_0 + D_1 t^m$). The values found for D_0, D_1, and *m* were 9.80E-10 1/Pa, 1.00E-08 1/Pa and 0.67, respectively.

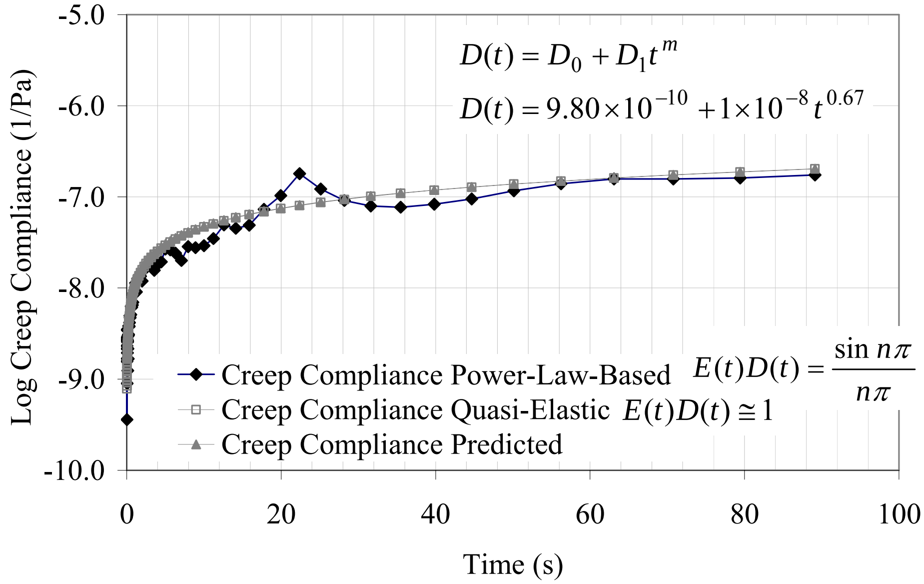


Figure F1b-1.3. Creep compliance for FAM.

Oscillation tests conducted within the linear viscoelastic (LVE) region were used to determine $\hat{D}'$ and $\hat{D}''$ in equations F1b-1.6 and F1b-1.7, and $\hat{E}'$ and $\hat{E}''$ in equations F1b-1.8 and F1b-1.9. $\hat{D}'$ and $\hat{D}''$ can be defined using equations F1b-1.14 and F1b-1.15, respectively, and $\hat{E}'$ and $\hat{E}''$ can be defined using equations F1b-1.16 and F1b-1.17, respectively.

$$\left|D^*\right|_{LVE} \cos\delta_{LVE} = D_0 + \hat{D}^*_{LVE}\cos\hat{\delta}_{LVE} = D_0 + \hat{D}' \qquad \text{(F1b-1.14)}$$

$$\left|D^*\right|_{LVE} \sin\delta_{LVE} = \hat{D}^*_{LVE}\sin\hat{\delta}_{LVE} = \hat{D}'' \qquad \text{(F1b-1.15)}$$

$$\left|E^*\right|_{LVE} \cos\delta_{LVE} = E_e + \hat{E}^*_{LVE}\cos\hat{\delta}_{LVE} = E_e + \hat{E}' \qquad \text{(F1b-1.16)}$$

$$\left|E^*\right|_{LVE} \sin\delta_{LVE} = \hat{E}^*_{LVE}\sin\hat{\delta}_{LVE} = \hat{E}'' \qquad \text{(F1b-1.17)}$$

where, the subscript *LVE* stands for the property within the linear viscoelastic region (using low strain/stress amplitudes). Since very low strain (0.0065%) or stress (3.2E+03 Pa) amplitudes were used, the phase angle and dynamic modulus should be constant throughout the test. Creep compliance was calculated using the relationship $D^* = \frac{1}{E^*}$, and the creep storage compliance (*D'*) and creep loss compliance (*D"*) were calculated using D^* and δ. The creep compliance, as well as dynamic modulus, are almost constant within the linear viscoelastic region. $\Delta h_1 \Delta h_2$ and $\Delta g_1 \Delta g_2$ parameters were calculated using equations F1b-1.10- F1b-1.13. As expected, these parameters are very close to one for the linear viscoelastic region (figure F1b-1.4). According to Golden et al. (1996), g_0 can be identified as the deviation from linearity of the initial elastic response due to changes in the mean stress. For the current study, the instantaneous compliance

D_0 was found to be negligible compared with the $\hat{D}'$. Therefore, the terms in equations F1b-1.10 and F1b-1.12 with D_0 and E_e, respectively, were neglected.

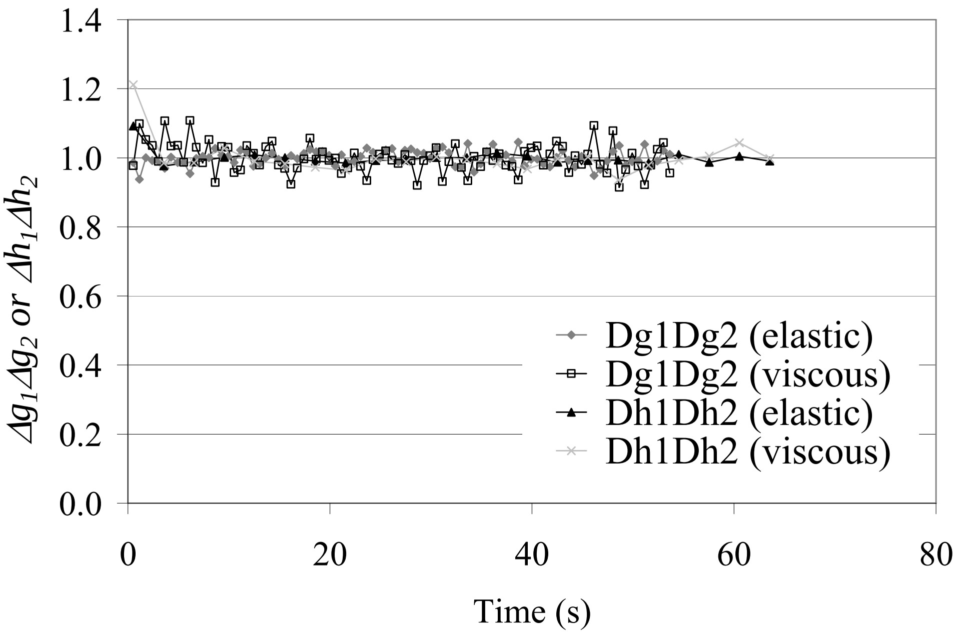
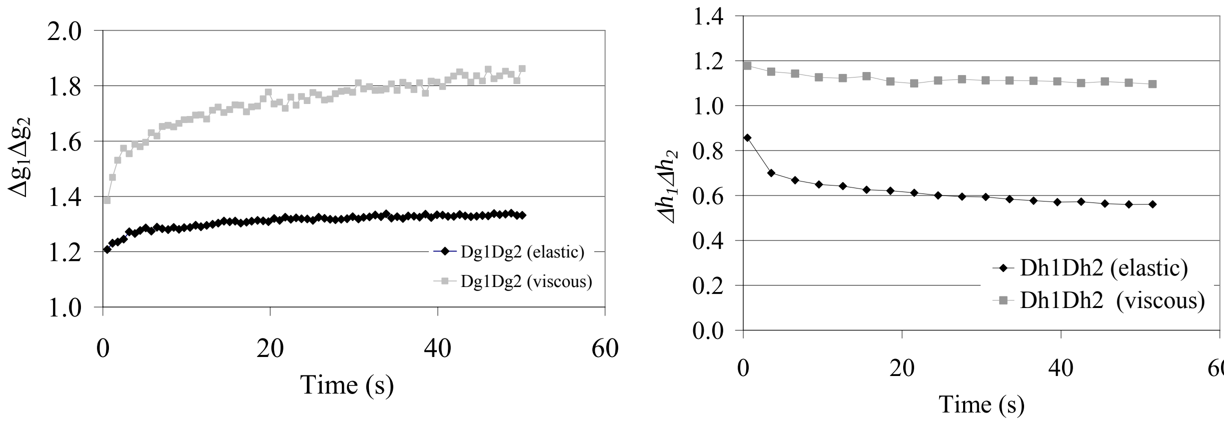


Figure F1b-1.4. $\Delta g_1 \Delta g_2$ or $\Delta h_1 \Delta h_2$ versus Time, Linear Viscoelastic Region.

The nonlinear viscoelastic and damage responses were characterized using high strain/stress oscillation data. The methodology adopted for nonlinear viscoelastic and damage parameters characterization was as follows:

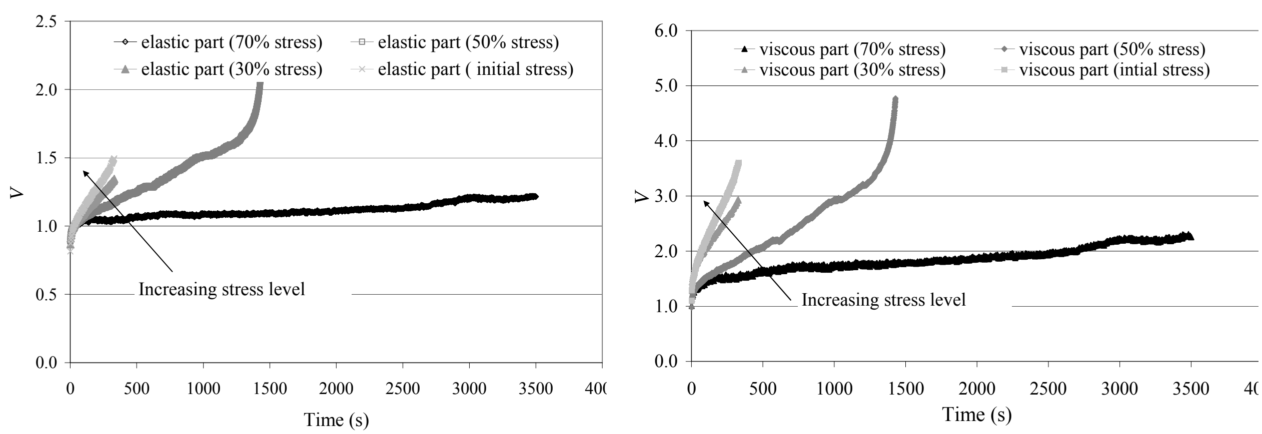
- During the first 50 seconds of the high strain/stress test, the material was considered to be within the nonlinear viscoelastic region, and no damage had accumulated ($V=W=1$). Equations F1b-1.10 and F1b-1.11 for controlled-stress analysis and equations F1b-1.12 and F1b-1.13 for controlled-strain analysis were applied and $\Delta g_1 \Delta g_2$ and $\Delta h_1 \Delta h_2$ were calculated for both elastic and viscous parts (figure F1b-1.5); as a part of a more comprehensive analysis that will be conducted in future, these nonlinear parameters will be determined up to the limiting value of stress or strain amplitude determined from step 1.
- $\Delta g_1 \Delta g_2$ and $\Delta h_1 \Delta h_2$ were found to be different than one as expected for nonlinear viscoelastic behavior. $\Delta g_1 \Delta g_2$ and $\Delta h_1 \Delta h_2$ were calculated from elastic parts (equation F1b-1.10 for controlled-stress case, and equation F1b-1.12 for controlled-strain case) and for viscous parts (equation F1b-1.11 for controlled-stress case and equation F1b-1.13 for controlled-strain case).

The damage parameters V and W were calculated for different stress and strain amplitudes, respectively. The values for V were higher than unity and increased with the number of loading cycles. The rate of change of *V* with respect to the number of load cycles increased with the stress amplitude (figure F1b-1.6). Furthermore, the parameter *V* represents two parts: (i) one part associated with the variation from linearity of the elastic compliance (figure F1b-1.6a), and (ii) second part associated with the variation from the linearity of the viscous compliance (figure F1b-1.6b). For a controlled-strain test the analogous parameter *W* is used to quantify the damage in the viscoelastic and elastic components of the material.



(a) Controlled-Stress (b) Controlled-Strain

Figure F1b-1.5. (a) $\Delta g_1 \Delta g_2$ versus Time for Elastic and Viscous Parts, Controlled-Stress Analysis, and (b) $\Delta h_1 \Delta h_2$ versus Time for Elastic and Viscous parts, Controlled-Strain Analysis.



(a) (b)

Figure F1b-1.6. Damage Parameter (*V)* versus Time for Different Stress Amplitudes, Variation from the Linearity of the: (a) Elastic Compliance, and (b) Viscous Compliance.

Work Planned Next Quarter

The third step in the characterization of non linear viscoelastic behavior and fatigue cracking is to model the non linear viscoelastic response of the FAM within each load cycle. This model is already developed and will be evaluated using the DMA data in the next quarter.

The results for different elements of non linear modeling discussed above were not obtained using the same set of materials and mixture design procedure. In the next quarter a comprehensive methodology will be developed and exhaustively evaluated using a common set of materials tested for fatigue under different loading conditions.

References

Golden, H. J., T. W. Strganac, and R. A. Schapery, 1996, A Test and Analysis Protocol to Rapidly Characterize Nonlinear Viscoelastic Properties of Ballon Materials. American Institute of Aeronautics (AIAA) Meeting, Paper 96-0572.

Park, S. W., and Y. R. Kim, 1999, Interconversion Between Relaxation Modulus and Creep Compliance for Viscoelastic Solids. *Journal of Materials in Civil Engineering*, 11(1): 76-82.

Schapery, R. A., 1969, On the Characterization of Nonlinear Viscoelastic Materials. *Polymer Engineering and Science*, 9: 295-310.

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

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Work Element F1c: Aging

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

Progress This Quarter

Recent research has expanded knowledge of binder oxidation kinetics and the impact of oxidation on binder physical properties, especially during the slower constant-rate oxidation period that follows the fast, but declining rate initial reaction period. Review of prior work conducted this quarter has been directed at comparing some of the early work on binder oxidation with the more recent work, for the purpose of understanding better the two reaction periods as a whole. Both reaction periods contribute to binder hardening but which is more significant over the long term depends on climate and oxygen availability to the binder (air voids), in addition to the reaction characteristics of the specific binder, i.e., to the amount of oxidation that occurs during the fast rate period for a given asphalt (termed the initial jump in oxidation and hardening).

Also in this quarter, literature from previous TxDOT Projects 0-4468, "Evaluate the Fatigue Resistance of Rut Resistant Mixes" and 0-4688, "Development of a Long Term Durability Specification for Modified Asphalt" was gathered for review in terms of the different responses of different mixtures to aging measured in terms of fatigue life predicted by the calibrated mechanistic with surface energy (CMSE) approach.

Work Planned Next Quarter

These reviews of prior work are ongoing and will be used to determine appropriate experimental procedures, conditions, and materials as well as to provide background for transport model development (Subtask F1c-3).

Subtask F1c-2: Develop Experimental Design (Year 1 start) (TAMU)

Progress This Quarter

In this quarter, experimental design commenced with consideration of the mixture parameters that may affect mixture response to binder oxidation and subsequent performance. These parameters include binder content, aggregate gradation, presence of additives such as lime, and the resulting air void distribution and binder film thickness. In addition, literature from previous TxDOT projects was gathered for review in terms of the mixtures tested in direct tension and evaluated in terms of fatigue life predicted by the calibrated mechanistic with surface energy (CMSE) approach. The initial discussion of the experiment design was coordinated with TxDOT Project 0-6009, "Evaluation of Binder Aging and its Influence in Aging of Hot Mix Asphalt Concrete" that starts in the next quarter.

Work Planned Next Quarter

The planned activity for the next quarter is to continue the experimental design, estimate quantities of component materials required, and begin material procurement. Interconnected air voids or those with access to oxygen and binder film thickness will be explored further as candidates for a key mixture parameter controlling mixture response to binder oxidation and subsequent performance.

Subtask F1c-3: Develop a Transport Model of Binder Oxidation in Pavements (Year 1 start) (TAMU)

Progress This Quarter

Work has proceeded toward developing a combined heat and mass diffusion transport model for reaction of binders in compacted mixtures and pavements. Issues are the relative importance of diffusion and reaction rates in the binder as well as the accessibility of oxygen to the binder from the porous structures of the mixtures. The model that is being developed is conceived to provide oxygen to the binder radially from pores that pass through the mixture. Complicating the model is the presence of aggregate that forces a tortuous path for the oxygen, thereby producing a reduced effective diffusivity. The extent to which diffusion resistance slows the oxidation process relates directly to the oxidation rate relative to the diffusion rate. The model is essential to guiding the efficient and effective use of both laboratory and field mixture aging data for assessing the rate of binder hardening in pavements and its impact on pavement durability. The model also will be important to Category F3, Modeling.

Work Planned Next Quarter

In the next quarter we expect to complete formulation of the basic transport model and then to use the model as a guide to design field and laboratory experiments for the purpose of evaluating the impact of diffusion resistance on the oxidation rate of binders in pavements as a function of air voids, binder content, and other parameters.

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

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

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

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Work Element F1d: Healing

Subtask F1d-1: Critically Review Previous Work on Healing under FHWA Contracts DTFH61-C-92-00170 and DTFH61-C-99-00022 (Year 1 start) (TAMU)

Progress This Quarter

A detailed literature review was conducted to identify the methodologies adopted to quantify healing and its effect on the fatigue cracking of asphalt mixtures. The review also included literature related to the investigation and modeling of healing mechanisms for viscoelastic materials other than bituminous materials. Key findings from this review are briefly summarized below.

Laboratory Documentation: Some of the most recent, significant documentation of healing in the laboratory was demonstrated by Kim et al. (2001), by Carpenter and Shen (2006), by Malliard et al. (2004), and by Little et al. (2001). The approaches behind some of these methods are discussed in more detail in the section entitled "Quantification of Healing".

Data from these laboratory studies clearly demonstrate that healing is real and significant. Little et al. (2001) showed that rest periods (of 24-hour duration) applied in traditional flexural beam bending experiments increased the fatigue life by more than 100 percent depending on the type of binder used. Kim et al. (2001) used torsional loading of asphalt mastics to demonstrate that healing periods of between 30-seconds and 2-minutes extend fatigue life and decrease the rate of dissipated damage causing energy (measured as pseudo strain energy). Carpenter and Shen (2006) skillfully verified this conclusion by demonstrating that the application of short rest periods between each load cycle not only extends fatigue life but is also responsible for the so called "endurance limit" of some asphalt mixtures. Bhairampally et al. (2000) demonstrated that the inclusion of rest periods between compressive load cycles extended the time to tertiary damage and that this extension depended on the type of asphalt.

Field Documentation: Some of the most convincing field data regarding healing was reported by Williams et al. (2001). They selected four pavement sections at the Turner Fairbank accelerated load facility (ALF) considering a full factorial of two thicknesses and two asphalt layer types over a homogeneous subgrade. Surface wave measurements were made to assess pavement stiffness before, immediately after, and 24-hours after loading passes. Regardless of the pavement type, the trend was that more healing (recovery of stiffness) was recorded closer to the centerline suggesting that more fatigue damage results in a greater potential for and a greater amount of microdamage healing. Williams et al. (2001) reported other convincing support for healing using surface wave analysis of pavements at Mn/ROAD pavement sections and on U.S. Highway 70 in North Carolina using designed experiments. Nishizawa et al. (1997) used data from four thick pavements to demonstrate that fatigue cracking did not occur because healing effects at the low strain and low damage levels compensated for (off set) crack growth.

Hypothesis: Development of a fracture process zone at the crack tip is a precursor to the extension of an existing crack in a viscoelastic material (Schapery 1981). A common example of a fracture process zone is the formation of craze fibrils in thermoplastic polymers. Craze fibrils form following loss of entanglement of the molecular chains. At low temperatures and high strain rates, crazing occurs primarily due to scission of molecular chains, where as, at higher temperatures it occurs primarily due to disentanglement of the molecular chains (Berger and Kramer 1987).

deGennes (1971) proposed a model to explain the movement of a polymer molecule in a worm like fashion inside a cross linked polymeric gel, also known as the reptation model. Berger and Kramer (1987) demonstrated that the disentanglement time for chains in the crazing zone during the crack growth process was in agreement with the reptation model. In a reverse approach, Wool and O'Connor (Wool and O'Connor 1981) used the same reptation model to determine the time required for healing caused by the interdiffusion of molecules between crack faces.

Wool and O'Connor (1981) ingeniously described net macroscopic recovery or healing in a material by combining an intrinsic healing function of the material with a wetting distribution function using a convolution integral as follows:

$$R = \int_{\tau=-\infty}^{\tau=t} R_h(t-\tau)\frac{d\phi(\tau, X)}{d\tau}d\tau \qquad \text{(F1d-1.1)}$$

where, R is the net macroscopic healing, $R_h(t)$ is the intrinsic healing function of the material, $\phi(t, X)$ is the wetting function, and τ is the time variable.

The wetting distribution function, $\phi(t, X)$, defines wetting at the contact of the two crack surfaces on a domain X over time t. The intrinsic healing function, $R_h(t)$, defines the rate at which two crack faces that are in complete contact with each other ("wet") regain strength due to interdiffusion and randomization of the molecules from one face to the other. From a material property point of view, an asphalt binder that has a molecular structure that favors interdiffusion of molecules will promote healing.

Kim et al. (1990) correlated net healing of asphalt mixtures with the molecular structure (intrinsic healing function) of the asphalt binder. In contrast Little et al. (2001) correlated net healing of asphalt mixtures with the surface energy (wetting function) without accounting for the differences in the intrinsic healing function of the asphalt binders. As described in equation (1), the correlation of net healing must be made with the wetting function by taking into account the cumulative effect of intrinsic healing and wetting. An important research task of this work element is to develop a methodology by which to evaluate the net healing of asphalt materials based on their material properties.

Methods to Quantify Healing: Several different approaches have been used by different researchers to quantify the magnitude of healing in different types of asphalt binders, mastics or mixtures. The commonality among most of these approaches is that healing is quantified by measuring the response from a cyclic load test by allowing intermittent periods of recovery. Some of these methods are briefly discussed in this section.

Carpenter and Shen (2006) used the Ratio of Dissipated Energy Change (RDEC) in a cyclic load test to quantify the fatigue cracking resistance of the asphalt mixture. The fatigue resistance of the mixture is quantified as the plateau value or PV which is the magnitude of the RDEC in the steady state response regime of the cyclic load test. A higher magnitude of the PV indicates greater incremental damage energy and shorter fatigue cracking life. To account for healing, they introduced rest periods after each load cycle. In this approach, the effect of healing can be quantified as the reduction in the PV due to the application of rest periods in the cyclic load test. Kim and Roque (2006) used a similar approach to quantify the healing characteristics of asphalt binders used in different asphalt mixtures. They quantified healing in terms of the recovered dissipated creep strain energy per unit time.

Maillard et al. (2004) conducted tensile tests on films of asphalt binder lodged between glass spheres to simulate an asphalt film that is bound by aggregates. They measured the rate of healing in the asphalt film by transmitting ultrasonic waves through the sample. A decrease in the amplitude of the ultrasonic signal corresponds to damage in the film. An increase in the amplitude of the ultrasonic signal for an undisturbed sample after applying a tensile load corresponds to the healing process.

Kim et al. (2003) used the Dynamic Mechanical Analyzer (DMA) to measure the fatigue cracking characteristics of fine aggregate and asphalt binder matrix. They quantified healing as the increase in fatigue life of the mixture due to the application of a specified number of rest periods during the test. Little and Bhasin (2006) used a similar approach to quantify the healing propensity of binders in different FAM. They computed the dissipated pseudo strain energy, W_R, as the area in the stress – pseudo strain hysteresis curve for any given cycle. The parameter, b, which represents the rate of accumulation of damage was obtained from the relationship of the dissipated pseudo strain energy with number of load cycles, N, from experimental data using the following form:

$$W_R = a + b\ln(N) \qquad \text{(F1d-1.2)}$$

In order to quantify healing for different materials, they applied nine rest periods of four minutes each during the cyclic test at high strain amplitude. The rest periods were applied at 2.5, 5, 10, 15, 20, 25, 30, 40, and 50 percent of the fatigue life value of that particular material measured without any rest period. When rest periods were applied, the parameter, *b*, was computed by fitting the dissipated pseudo strain energy measured immediately after the rest period to the corresponding number of load cycles using the aforementioned equation. A relative decrease in the parameter, b, was then used to quantify the healing potential for each material.

<u>Work Planned Next Quarter</u>

Researchers will continue the literature review in the area of healing with emphasis on areas other than bituminous materials.

Subtask F1d-2: Select Materials with Targeted Properties (Year 1 start) (TAMU)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

Materials selected for other areas of work will be tested for their healing related properties such as surface free energy and intrinsic healing function using the newly developed DSR test method (see Subtask F1d-4).

Subtask F1d-3: Develop Experiment Design (Year 1 start) (TAMU)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

The literature review conducted in task F1d-1 and the material properties measured in F1d-3 will be used to develop a detailed experiment design for this work element.

Subtask F1d-4: Investigate Test Methods to Determine Material Properties Relevant to Asphalt Binder Healing (TAMU)

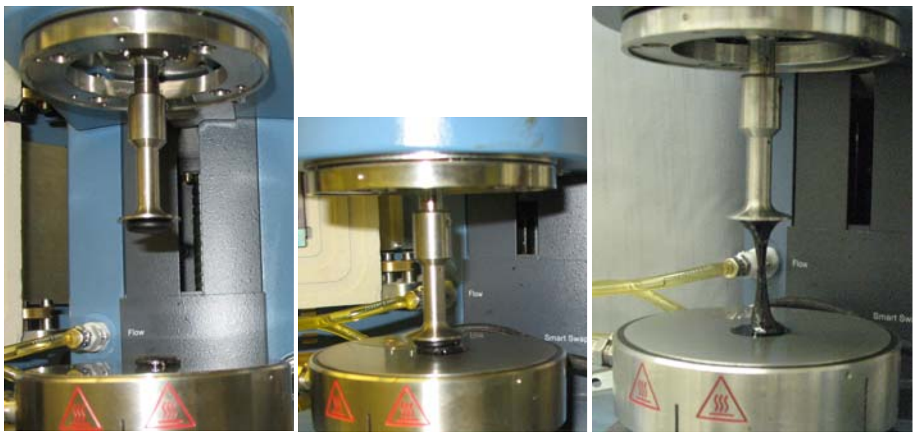
Progress This Quarter

We developed a simple test method to determine the intrinsic healing function of neat asphalt binders. The intrinsic healing function is required to model the healing process. This function was briefly discussed in Subtask F1d-1 above. A more detailed discussion of this function is also provided under Subtask F1d-8. The test procedure requires the use of a Dynamic Shear Rheometer (DSR). The highlights of this procedure and limited results that provide interim evidence to the validity of this approach are presented here.

Two 28 mm diameter and 3.5 mm thick specimens of the asphalt binder are fixed onto the two end plates of the DSR (figure F1d-4.1a). The loading axis is then lowered to reach a target thickness of 6.5 mm. This ensures that the bitumen surfaces of the two specimens are in intimate contact with each other (figure F1d-4.1b). This is referred to as the two-part specimen. Following this, the instrument readjusts the gap to achieve a constant normal force or 40±10 g and maintains it throughout the remainder of the test.

The initial adjustments to bring the bitumen surfaces into intimate contact with each other and readjustment of the normal force by the instrument takes about one minute. Following this initial setup, the DSR is programmed to measure and record the dynamic shear modulus (G*) at 0, 2, 4, 6, 8, 10, 15, 20, 25, 30, 40, 50 and 60 minutes for the two-part bitumen specimen. The contact normal force is maintained throughout the test. At each instance, the dynamic shear modulus is measured at 0.001 % strain by applying 50 cycles at a frequency of 10 Hz.

The same procedure is repeated using a one-part or single 6.5 mm thick test specimen of the bitumen. The percentage healing at any given time is computed as the ratio of the value of G* obtained using the two-part specimen test to the value of G* obtained using the one-part or specimen test at each time interval. This normalization offsets the effect of secondary changes, such as creep due to the small normal force, on the measured value of G*. The evidence of the healing that occurs at the interface of the two bitumen specimens is clearly visible upon the removal of the specimens after the test (figure F1d-4.1c).



a) Two bitumen specimens affixed to the two end plates of the DSR

b) Bitumen specimen after being brought into contact with each other to measure change in

c) Separation of the test specimens after completion of the test

Figure F1d-4.1. Illustration of the test method to obtain parameters for the healing function using a DSR.

By bringing the two bitumen surfaces in intimate contact with each other within a short duration of time, the condition of instantaneous wetting is achieved. In this case, the wetting distribution function reduces to a Dirac-delta function:

$$\frac{d\phi(\tau)}{d\tau} = \delta(\tau) \qquad \text{(F1d-4.1)}$$

As a result, the healing function in equation F1d-1.1 reduces to the following form:

$$R = R_h(t) \qquad \text{(F1d-4.2)}$$

In other words, the macroscopic healing function measured over time can be used to obtain the intrinsic healing function. The procedure assumes that the inter diffusion that occurs during the first minute of the test is minimal and is accommodated in the instantaneous healing parameter of the healing function. This assumption may not be valid if the test is conducted at elevated temperatures that entail significant inter diffusion within short time periods.

The amount of healing measured using this test method is then used with the following equation to obtain the healing function parameters R_0, p, q, and r. The significance of this relationship is described in more detail in section F1d-8.

$$R_h(t) = R_0 + p\left(1 - e^{-qt^r}\right) \quad \text{(F1d-4.3)}$$

Figure F1d-4.2 and table F1d-4.1 present the results from these measurements for three different binders.

The parameter R_0 in equation F1d-4.3 reflects the effect of instantaneous healing that is due to the interfacial cohesion between the crack surfaces. Figure F1d-4.3 compares the values of R_0 and the work of cohesion, W_c for the selected bitumen. As expected, the magnitude of the parameter R_0 for the three bitumen follows the same order as the work of cohesion or surface free energy determined using the Wilhelmy plate method. Although the data are limited, they supports the consistency of the analytical frame work and test methods used to obtain the material properties related to healing.

Table F1d-4.1. Parameters for the healing function.

Bitumen	R_0	***p***	***q***	***r***
AAD	39	60	2.E-03	1.73
AAM	55	66	7.E-05	2.01
ABD	60	1728	1.E-03	0.69

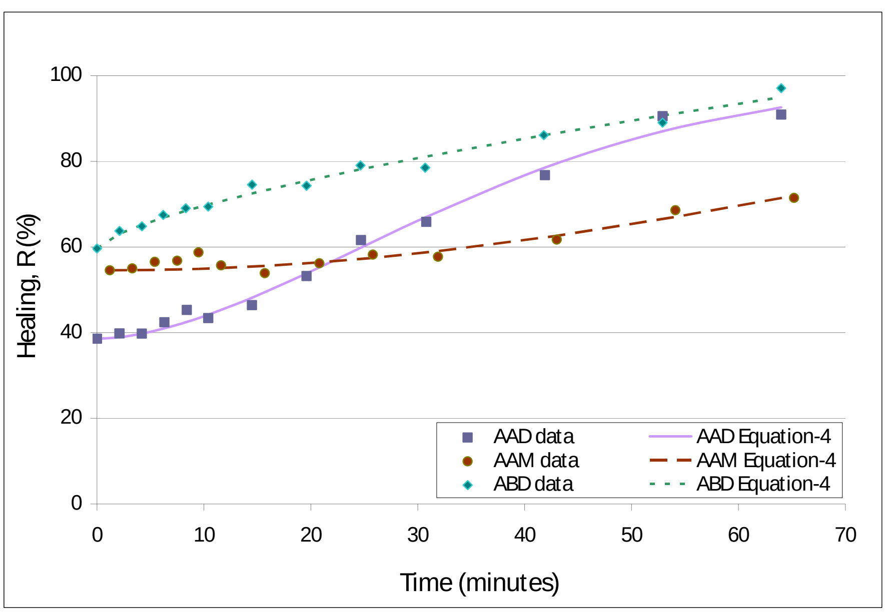


Figure F1d-4.2. Healing function for selected bitumen obtained using the DSR data.

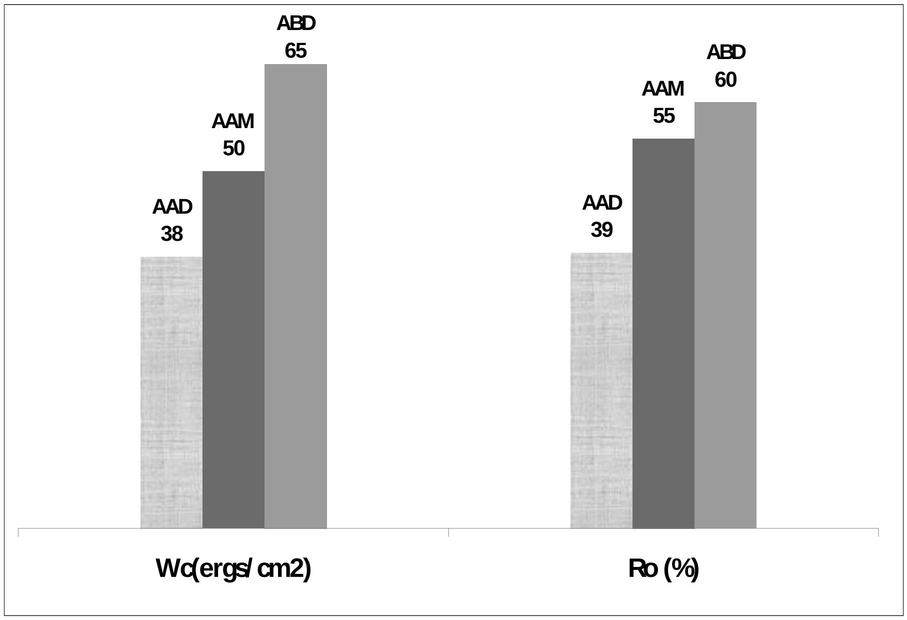


Figure F1d-4.3. Surface free energy vs. parameter for instantaneous healing from DSR tests.

Both the wetting and healing functions are required to accurately predict the magnitude of healing in the asphalt materials. Since this study is only in its initial stages, only the healing function was used to determine the expected level of healing for the selected bitumen for a healing period of 4 minutes. These values were then compared to the relative increase in the fatigue cracking life as measured on FAM specimens using the DMA. Figures F1d-4.4 and F1d-4.5 illustrate these comparisons. It is evident from these figures that for aggregate RL, the rank order of the mixes in terms of the effect of healing on fatigue cracking life was very similar to the order based on or predicted by the healing function. For aggregate RA, the impact of healing on fatigue life was the smallest for bitumen AAD. This is consistent with the prediction based on the healing function. The comparisons of the effect of healing from the healing function for bitumens AAM and ABD with aggregate RA were different than expected. After careful consideration, this is not altogether surprising, since at this stage we are only comparing the healing function to the observed macroscopic healing in the FAM. Other parameters, which affect the healing function, will be considered in the next stage of this research. However, these results provide interim validation of the approach being followed and reinforce the need to develop this procedure.

Work Planned Next Quarter

The use of Pulse Generated Echo – Nuclear Magnetic Resonance (PG-NMR) and high resolution Magnetic Resonance Imaging (MRI) will be evaluated in order to determine material properties such as self diffusivity that dictate the intrinsic healing properties of the asphalt binder. The Department of Chemistry at the Texas A&M University houses an excellent NMR facility with nine different NMR instruments with full time experienced personnel. This facility is accessible for use in this project.

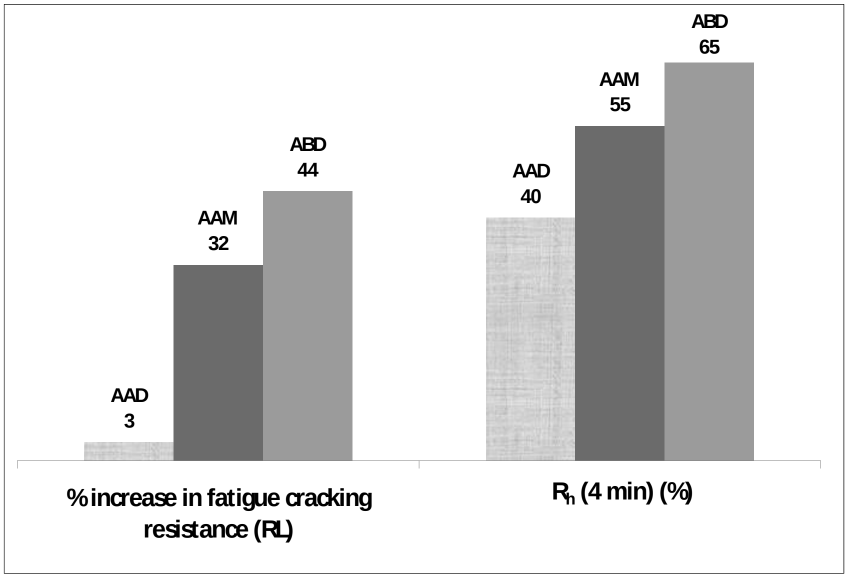


Figure F1d-4.4. Expected healing for wetted surfaces at 4 minutes vs. effect of healing on fatigue cracking life with 4 minute rest period for FAM with RL aggregate.

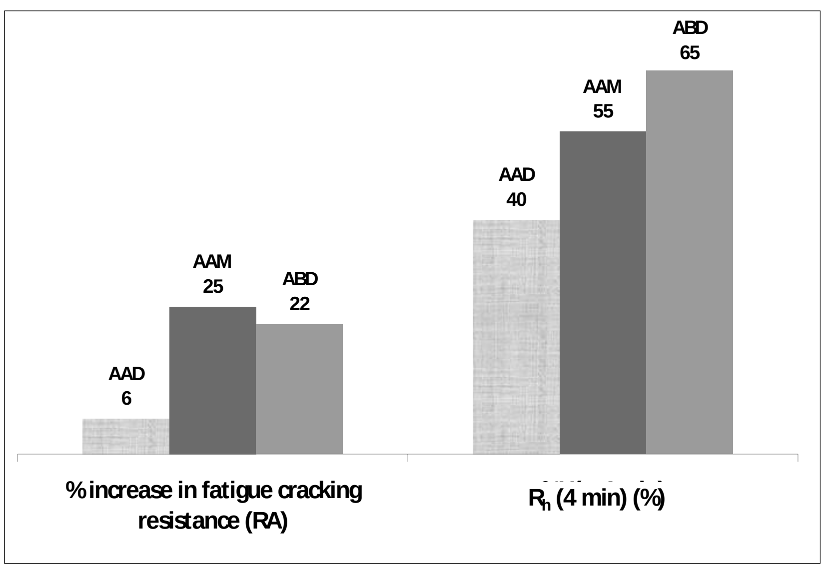


Figure F1d-4.5. Expected healing for wetted surfaces at 4 minutes vs. effect of healing on fatigue cracking life with 4 minute rest period for FAM with RA aggregate.

Subtask F1d-5: Testing of Materials (TAMU)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Subtask F1d-6: Evaluate Relationship between Healing and Endurance Limit of Asphalt Binders (Year 1 start) (UWM)

Subtask Lead: Carl M. Johnson

Progress This Quarter

Preliminary work has begun on finding a test method to characterize the healing characteristics of asphalt binders. Testing so far has included time sweep testing of two RTFO-aged binders using the 8-mm geometry in the Dynamic Shear Rheometer (DSR). The two binders involved with the testing are from a previous study conducted for the Pacific Coast Conference on Asphalt Specification (PCCAS) on the relation between G*sinδ and mixture fatigue performance. One is a PG 64-22 unmodified, and the other is an AR4000. In addition to standard time sweep testing, a modified time sweep procedure that includes rest periods has been used. An example of the data is shown in figure F1d-6.1.

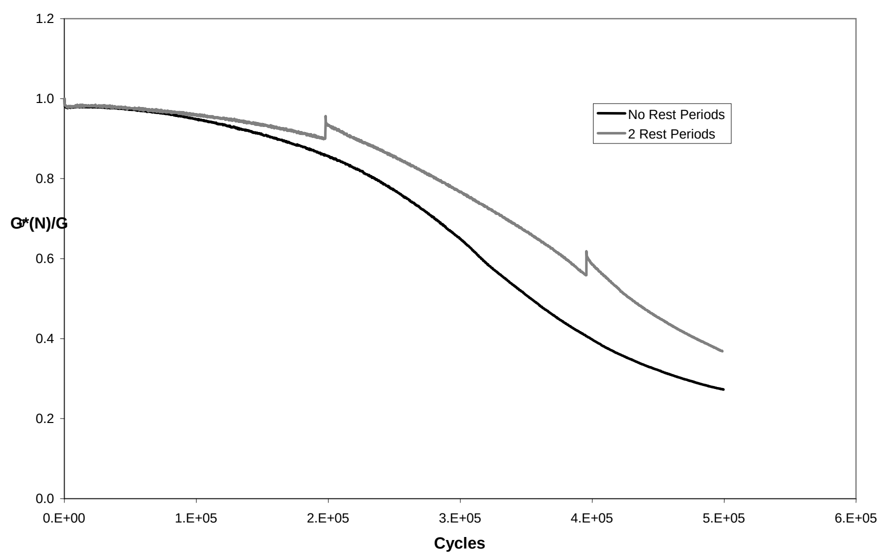


Figure F1d-6.1. Time sweep testing of PG 64-22 binder with and without rest periods.

The graph shows that the rate of stiffness reduction slows with the introduction of rest periods, which has been shown numerous times with asphalt mixes. However, research that involves testing the healing properties of the binder directly is limited, so further work is being done to characterize this behavior. A literature review focused on research conducted by North Carolina State University for asphalt mixtures was started. Discussions with researchers at the University of Genoa-Italy and the Poly-technique University of Catalonia-Spain have been initiated regarding their work on healing and endurance limits. A protocol for data analysis and modeling of fatigue with rest periods is under development.

<u>Problems Encountered and Solutions</u>

None.

<u>Work Planned Next Quarter</u>

Work will continue on refining an appropriate analysis procedure. Currently, the research group intends to use continuum damage theory as an initial method. Implementation of the method will require further review of previous work in continuum damage mechanics.

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

<u>Progress This Quarter</u>

No activity this quarter. AFM work has not commenced.

<u>Work Planned Next Quarter</u>

No work planned.

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

<u>Progress This Quarter</u>

As discussed in the literature review summarized in Subtask F1d-1, the healing process can be modeled by the combining the effects of wetting and intrinsic healing. Mathematically, this can be achieved using a convolution form for these two processes. This section summarizes a framework that was developed to model healing in the form of a parameter that can be used with fatigue cracking models.

Wetting Function: The first step in the healing process, i.e., wetting of the two faces of a nano crack is represented by a wetting distribution function $\phi(t, X)$ as described in the convolution integral (equation F1d-1.1). Schapery (1989) developed a relationship between the work of cohesion and the material properties related to the wetting of crack surfaces. Based on this relationship, the wetting distribution function or rate of wetting of a crack surface can be shown as follows:

$$\frac{d\phi(t,X)}{dt} = \dot{a}_b = \beta\left[\frac{1}{D_1 k_m}\left\{\frac{\pi W_c}{4(1-\nu^2)\sigma_b^2\beta} - D_0\right\}\right]^{-1/m} \quad \text{(F1d-8.1)}$$

In equation F1d-8.1, W_c is the work of cohesion; ν is the Poisson's ratio; D_0, D_1, and m are creep compliance parameters obtained by fitting $D(t) = D_0 + D_1 t^m$; and k_m is a material constant that can be computed from m. The terms, σ_b, β, and $\dot{a}_b$ are illustrated described below (figure F1d-8.1).

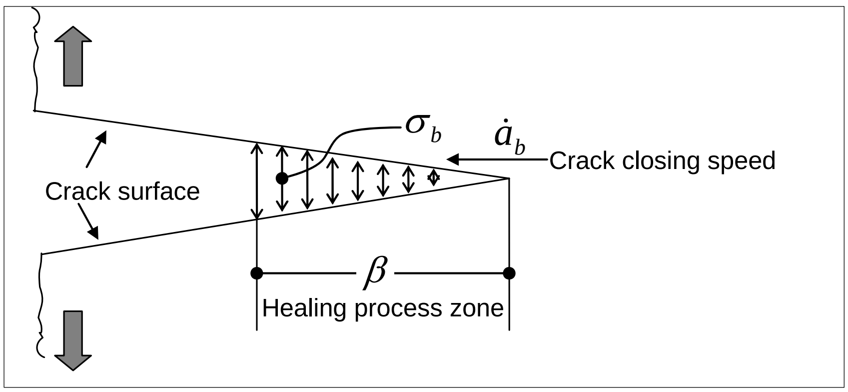


Figure F1d-8.1. Crack propagation and fracture process / healing zone in mode I loading.

The dimensional consistency of equation F1d-8.1 can easily be verified. The right hand side of equation F1d-8.1 contains mechanical and viscoelastic properties of the material, i.e., Poisson's ratio and creep compliance parameters. These properties can be easily determined using laboratory tests. The right hand side of equation F1d-8.1 also contains three material properties, i.e, the work of cohesion (W_c), the length of the healing process zone (β), and the tensile stresses that cause the crack faces to close (σ_b).

In most cases healing is quantified in terms of the percentage of strength gained after the rest period. To represent such a case, the wetting distribution function must be modified in order to represent the fraction of the newly formed crack surface that wets during the healing process. For a one dimensional case, this can be done by eliminating the domain *X* and normalizing the crack growth function in equation F1d-8.1 with the length of the crack that has grown in N cycles, ΔR_N, as follows:

$$\frac{d\phi(t)}{dt} = \frac{\beta'}{\Delta R_N}\left[\frac{1}{D_1 k_m}\left\{\frac{\pi W_c}{4(1-\nu^2)\sigma_b^2\beta} - D_0\right\}\right]^{-1/m} \quad \text{(F1d-8.2)}$$

where,

β' $= \beta$, when $\beta < \Delta R_N$

$= \Delta R_N$, when $\beta \geq \Delta R_N$.

The substitution for β in equation F1d-8.1 to obtain equation F1d-8.2 provides a form that is consistent with the observed healing behavior in asphalt mixtures. Consider a case when rest periods are provided very frequently such that the incremental crack growth is small and the incremental length of the crack does not exceed the length of the healing process zone ($\beta \geq \Delta R_N$). For example, Carpenter and Shen (2006) evaluate the effect of healing on endurance limit by providing a rest period after every load cycle. A similar effect can also be obtained by adding fine, well-dispersed filler in the asphalt mastic. For example, Kim et al. (2003a) demonstrate the effect of introducing hydrated lime filler particles on the healing of asphalt mastics. In such a case the wetted length is maximized simply because the incremental crack progression is kept within a certain critical limit and the entire crack can heal (although it might not gain the same strength as the original binder). This is discussed in the following sub section on the intrinsic healing function, $R_h(t)$. On the other hand, if rest periods are spaced apart so that significant crack growth occurs before a rest period is provided, i.e., $\beta < \Delta R_N$, then the maximum length of the healed crack is limited to the length of the healing process zone.

The tensile stresses that cause the crack faces to close (σ_b) can be considered to be directly proportional to the surface free energy or the work of cohesion of the material (W_c). This is a reasonable assumption since materials with higher surface free energy would also have a higher affinity to cohere and develop greater tensile stresses between the two surfaces. Based on the typical order of magnitudes of the various parameters, the contribution of the creep compliance parameter, D_0, can be neglected. Based on this consideration, it is easy to see from equation F1d-8.2 that materials with significantly higher work of cohesion will have a higher rate of wetting and consequently healing.

Intrinsic Healing Function: The second and third steps of the healing process, i.e., strength gain due to interfacial cohesion and inter diffusion of molecules between the wetted surfaces is represented by the intrinsic healing function $R_h(t)$ as described in the convolution integral (equation F1d-1.1). Based on Einstein's relation for a 'one dimensional random walk in the tube', Wool and O' Conner (1981) demonstrated that the intrinsic healing function is best represented using the following form:

$$R_h(t) = R_0 + K\, t^{0.25} \bullet \varphi(t) \qquad \text{(F1d-8.3)}$$

In equation F1d-8.3, t is the time, and $\varphi(t)$ is used to represent the effect of time surface rearrangement of molecules. The symbol $\bullet$ represents the convolution process. This model was developed for simple polymer molecules and for short time healing. Wool and O' Conner also report that for longer durations the power factor changes from 0.25 to 0.5.

The healing function represents the sum effect of: (i) instantaneous strength gain due to interfacial cohesion at the crack interface, represented by the parameter R_0, and (ii) time dependent strength gain due to inter diffusion of molecules between the crack surfaces, represented by $Kt^{0.25} \bullet \varphi(t)$. In this study, a sigmoidal function was used to represent the latter.

The sigmoidal function for time dependent strength gain or healing is similar to the form that is used to model other processes such as kinetics of phase transformations in solids (Callister 2007). The form of the healing function that was used is shown below (equation F1d-8.4).

$$R_h(t) = R_0 + p\left(1 - e^{-qt^r}\right) \qquad \text{(F1d-8.4)}$$

$R_h(t)$ is a time dependent dimensionless function that represents the increase in a mechanical property of the wetted crack interface, typically as a fraction or percentage of the same property for the intact material. This function can be used to represent any mechanical property of interest, for example, shear modulus.

Since R_0 reflects the effect of instantaneous healing due to cohesion at the crack interface, its magnitude is expected to be proportional to the work of cohesion or surface free energy of the material. The results summarized under Subtask F1d-4 support this hypothesis. Since this parameter depends on the surface free energy of the material, it would also depend on extrinsic properties such as temperature. The parameters p, q, and r, represent the effect of healing that is due to the inter diffusion of molecules between the crack surfaces. Therefore, these parameters will be dictated by intrinsic material properties such as molecular weight, and activation energy for diffusion. In addition, these parameters will also depend on extrinsic properties such as pressure and temperature. By testing different materials under similar conditions the effect of extrinsic properties on the healing function parameters can be eliminated.

Additional Considerations: The effect of healing on strength gain at crack surfaces is apparent when rest periods are applied. However, healing properties of a material can significantly affect the fatigue cracking life of a bituminous material even when there are no rest periods. A stress or strain reversal can occur due to the nature of the cyclic loading in laboratory based fatigue cracking tests. For example, this is most readily visualized in a tension-compression type of cyclic test where the cracks are forced to close for a certain part of each load cycle. In such cases, the rate and extent of crack closure will be dictated by the nature of the applied load cycles, and this must be accounted for in the wetting function.

Work Planned Next Quarter

In the previous quarter we developed a framework to model the healing phenomenon with explicit relationships for the wetting and intrinsic healing function and a test method to determine parameters for the latter. In the next quarter we will focus on development of test and/or analytical methods to determine the two remaining unknowns for this model, the wetting length and bond stresses.

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Subtask F1d-9: Design Experiment on Selected Binders with Synchrotron (TAMU)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

CATEGORY F2: TEST METHOD DEVELOPMENT

Work Element F2a: Binder Tests and Effect of Composition

Subtask F2a-1: Analyze Existing Fatigue Data on Polymer Modified Asphalts (Year 1 start) (UWM)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Subtask F2a-2: Select Virgin Binders and Modifiers and Prepare Modified Binders (Year 1 start) (UWM)

Subtask Lead: Codrin Daranga

Progress This Quarter

For this task, extensive testing is being conducted on modified and unmodified binders. Modifiers included to date include SBS, Elvaloy, and PPA. Binders include four sources commonly used in the Midwest region. The method of preparation of modified asphalts is being varied. Several modified binders have been prepared and are in the process of being tested. Fatigue testing as well as typical SHRP testing is being performed. We are collecting data that will help us understand the effects of temperature, storage time, modifier type, modifier concentration and modifier reactivity with fillers over the binder critical fatigue properties.

Problems Encountered and Solutions

None.

Work Planned Next Quarter

For the next quarter we will continue testing and start data analysis.

Subtask F2a-3: Subject Samples of Virgin and Modified Binder to Several Laboratory Aging Procedures (UWM)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Subtask F2a-4: Collect Fatigue Test Data for All Samples (UWM)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Subtask F2a-5: Analyze Data and Propose Mechanisms by which Aging and Modification Influence Fatigue of Binders (UWM)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Work Element F2b: Mastic Testing Protocol

Subtask F2b-1: Develop Specimen Preparation Procedures (Year 1 start) (TAMU)

Progress This Quarter

We have developed a new method for DMA specimen preparation. In this new method, the asphalt binder content is taken to be equal to that used in preparing the full mixtures. In essence, the fine aggregate matrix represents the portion of the full mixtures without the coarse aggregates. In the previous approach, it was found that the binder content was too high to allow mixing, compaction, or coring of specimens with uniform geometry. We have experimented with two alternatives to overcome this limitation. The first alternative was to reduce the binder content by a given percentage (that it determined experimentally) to allow for adequate compacting of Superpave gyratory compaction (SGC) specimens and coring of DMA specimens from the SGC specimen. However, we have found that this solution introduces a random change in the design of the FAM design as compared to the original mix.

The second alternative, which we adopted, was to reduce the compaction temperature by 30°C degrees. It is important to note that the mixing and short term aging temperatures were not changed in this procedure. This ensured proper wetting of the fine aggregate particles by the asphalt binder in the mix, comparable to the full asphalt mixture. Since, the FAM does not contain coarse aggregate particles; it requires a lower temperature to achieve the same workability as the full asphalt mixture. Hence, reduction in the compaction temperature can be justified in preparation of SGC compacted samples. This second alternative does not introduce change to the mix design and at the same time allows preparation of SGC compacted samples to obtain FAM specimens by coring with uniform geometry.

Work Planned Next Quarter

The newly developed specimen preparation procedure will be evaluated using different material types. Any refinement that may be required to this procedure will be addressed. Once the specimen preparation procedure is finalized, it will be documented using AASHTO format.

Subtask F2b-2: Document Test and Analysis Procedures in AASHTO Format (TAMU)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

See Work Planned for F2b-1.

Work Element F2c: Mixture Testing Protocol (TAMU)

Progress This Quarter

In this quarter, literature from previous TxDOT Projects 0-4468, "Evaluate the Fatigue Resistance of Rut Resistant Mixes" and 0-4688, "Development of a Long Term Durability Specification for Modified Asphalt," was gathered for review in terms of the required laboratory testing and analysis for mixtures tested in direct tension and evaluated in terms of fatigue life predicted by the calibrated mechanistic with surface energy (CMSE) approach. The repeated direct tension test and the monitoring of dissipated pseudo-strain energy was the focus of this review to facilitate extension of the DMA fatigue analysis to mixtures.

Work Planned Next Quarter

In the next quarter, work will commence to extend the DMA fatigue analysis to mixtures to separate the different mechanisms of energy dissipation during fatigue cracking.

Work Element F2d: Tomography and Microstructural Characterization

Subtask F2d-1 (new addition): Micro Scale Physio-Chemical and Morphological Changes in Asphalt Binders under Relaxation, Fatigue Loading, and Healing Conditions (TAMU)

Progress This Quarter

The primary motivation for introducing this subtask is to better understand the physio-chemical and morphological changes associated with the following four processes:

i) relaxation,
ii) plastic deformation and fatigue crack initiation,
iii) fatigue crack propagation, and
iv) healing

This subtask will assist in understanding the nature of viscoelastic creep, crack nucleation and propagation and healing vis-à-vis the physio-chemical properties of asphalt binders that are associated with these phenomena. This information can also be used to ensure that the material property measurement and modeling aspects of this research are in line with the physically observed micro scale damage phenomena. The following is a brief description of the methodology that will be used in order to conduct this investigation.

The experimental set up consists of thin film of asphalt binder on a glass or crystal substrate (figure F2d-1.1). The substrate is clamped onto a mini loading frame that contains a piezoelectric actuator. The piezoelectric actuator is calibrated to apply normal deflection of up to 130 microns on the bottom of the glass or crystal substrate via a hemispherical contact to ensure line loading. Tensile strain on the surface of the asphalt binder film is generated by subjecting the substrate to flexural stresses. The magnitude of tensile strain can easily be computed and controlled by adjusting the amount of normal deflection applied by the piezoelectric actuator. By varying the applied voltage field, the surface of the binder film can be subjected to a static tensile strain in order to monitor relaxation behavior or a cyclic tensile strain in order to monitor crack nucleation, initiation, and healing behavior. It is also possible to extend the test to a direct tension of shear mode, if required, at a later stage.

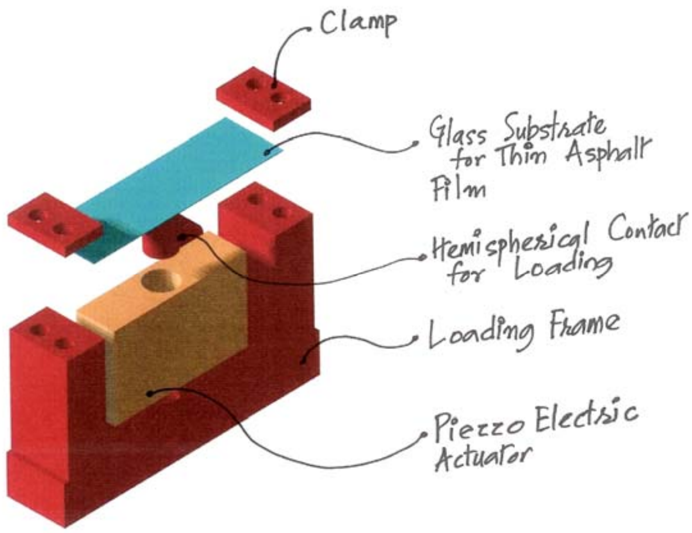

Figure F2d-1.1. Isometric representation of the mini loading frame.

The small size of this loading frame (figure F2d-1.2) makes it possible for it to be used in-situ with a variety of microscopic techniques such as optical microscopy, FTIR and atomic force microscopy. This device is in the design and fabrication stage.

The micro scale chemical changes and morphological changes in the region of the highest tensile stresses can be recorded using FTIR and atomic force microscopy. In an earlier study, Little et al. (1994) presented the proof of this concept by demonstrating the relaxation behavior of different functional groups in thin films of asphalt binders subjected to shear stresses. It is envisaged that this device and methodology will provide invaluable insight into the understanding of relaxation, crack propagation, and healing in asphalt binders and mastics.

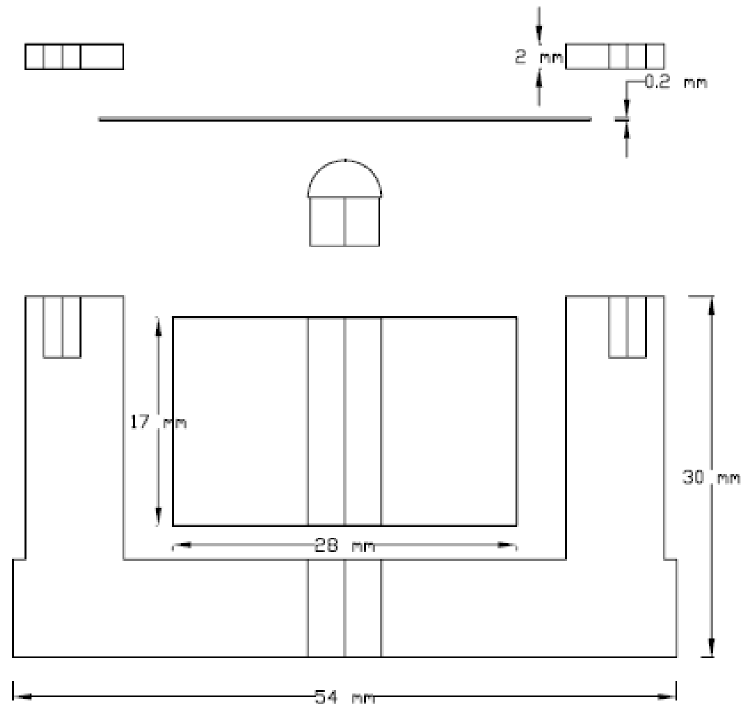

Figure F2d-1.2. Front view of mini loading frame with key dimensions.

Work Planned Next Quarter

The fabrication of this device and some preliminary tests using the FTIR and optical microscopy will be conducted in the next quarter.

References

Little, D. N., et al., 1994, Rheological and Rheo-Optical Characterization of Asphalt Cement and Evaluation of Relaxation Properties. *Transportation Research Record: Journal of the Transportation Research Board*, 1436: 71-82.

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

Subtask F2e-1: Evaluate Binder Fatigue Correlation to Mixture Fatigue Data (Year 1 start) (UWM)

Subtask Lead: Carl M. Johnson

Progress This Quarter

This quarter, a new test is in the process of being developed as a possible surrogate for binder fatigue characterization. Binders used in FHWA ALF testing are being compared against the crack length developed during fatigue testing with promising results. The binder test procedure involves using RTFO-aged material in the 8-mm geometry used by the DSR. A constant shear rate (monotonic test) is applied to the material, and a characteristic stress-strain curve is created (figure F2e-1.1). Currently, analysis drawn from these curves is showing good correlation with pavement fatigue data measured during the ALF testing. However, more testing needs to be completed in order to further investigate the strength of these correlations.

Figure F2e-1.1. Typical stress-strain curve for constant shear rate test.

Problems Encountered and Solutions

None.

Work Planned Next Quarter

Further testing of the ALF binders will continue in order to verify the preliminary findings. Also, testing on binders used in a laboratory mixture fatigue study is planned for comparison to other fatigue data. Literature review is ongoing, and alternate analysis methods are also being evaluated.

Subtask F2e-2: Selection of Testing Protocols (TAMU, UWM)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Subtask F2e-3: Binder and Mixture Fatigue Testing (TAMU, UWM)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Subtask F2e-4: Verification of Surrogate Fatigue Test (TAMU, UWM)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Subtask F2e-5: Interpretation and Modeling of Data (TAMU, UWM)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Subtask F2e-6: Recommendations for Use in Unified Fatigue Damage Model (TAMU, UWM)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

CATEGORY F3: MODELING

Work Element F3a: Asphalt Microstructural Model (TAMU, UWM, WRI)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Work Element F3b: Micromechanics Model

Subtask F3b-1: Model Development (TAMU)

Progress This Quarter

A primary task conducted at the University of Nebraska during this quarter was to start an extensive review of the micromechanics-based computational models to characterize damage-dependent behavior of asphalt materials and mixtures. The review efforts mainly focused on (i) investigation of the state of the art of modeling techniques typically based on the micromechanics and computational methods such as the finite element method, (ii) strategy for development of the model that can appropriately account for geometric heterogeneity and nonlinear-inelastic constitutive behavior of the asphalt materials/mixtures, and (iii) strategy for appropriate integration of material properties (as model inputs) obtained from other tasks into the micromechanics-based computational model being developed by the researchers at the University of Nebraska.

Work Planned Next Quarter

The planned activity for the next quarter is to continue the review of various micromechanics-based computational modeling techniques as well as the current model that has been developed by the researchers at the University of Nebraska, so that theoretical issues of the current model can be better refined to predict the complex nonlinear-inelastic fatigue damage behavior of asphalt materials and mixtures. In addition, a joint meeting between the researchers from the Texas A&M University, University of Nebraska, and the University of Wisconsin-Madison, will be held in order to integrate microstructural characterization of materials/mixtures (Work Element F2d: Tomography and Microstructural Characterization) and evaluation of fundamental materials/mixture properties (Project Category F1: Material and Mixture Properties). The micromechanics model will be elaborated by incorporating the material property inputs generated by various consortium partners.

Subtask F3b-2: Account for Material Microstructure and Fundamental Material Properties (TAMU)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Work Element F3c: Development of Unified Continuum Model

Subtask F3c-1: Analytical Fatigue Model for Mixture Design(TAMU)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

Existing analytical fatigue models, such as the crack growth index, will be reviewed. Any shortcomings of the existing model will be identified and a strategy to resolve these will be recommended. This activity will be closely related to the development of a model to determine non linear viscoelastic properties in subtask F1b.

Subtask F3c-2: Unified Continuum Model (TAMU)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Subtask F3c-3: Multi-Scale Modeling (TAMU)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Work Element F3d: Calibration and Validation (TAMU, UNR, UWM)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

PROGRAM AREA: ENGINEERED MATERIALS

CATEGORY E1: MODELING

Work element E1a: Analytical and Micro-mechanics Models for Mechanical Behavior of Mixtures (Year 1 start)

Subtask E1a-1: Analytical Micro-mechanical Models of Binder Properties (TAMU)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Subtask E1a-2: Analytical Micro-mechanical Models of Modified Mastic Systems (TAMU)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Subtask E1a-3: Analytical Models of Mechanical Properties of Asphalt Mixtures (Year 2 start) (TAMU)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Subtask E1a-4: Analytical Model of Asphalt Mixture Response and Damage (Year 3 start) (TAMU)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Work element E1b: Binder Damage Resistance Characterization (DRC)

Subtask E1b-1: Rutting of Asphalt Binders (UWM)

Subtask Lead: Haifang Wen

Progress This Quarter

The team attended the FHWA ETG meeting from July 23–27, 2007 in Denver, CO. The team learned about progress on the rutting parameter of asphalt binder, especially the work done by FHWA on modified asphalt. Non-recoverable compliance is being proposed by FHWA as the performance test for rutting of asphalt binder. Current Superpave specification for neat binder remains the same. The team will coordinate with the work of others in this area, especially for future modeling of asphalt binder at high temperatures. A detailed literature search and review on the subject of stress sensitivity of binder behavior has been started.

In the modeling of rutting behavior area, the data collected by the research team from previous studies are being analyzed. A detailed review of the literature related to the stress sensitivity of creep behavior of viscoelastic materials resulted in identifying a few mechanistic models available. These are being reviewed, and preliminary investigation of the applicability and effectiveness of these models has been conducted.

In the rutting of mastics at high temperature area, the team studied the effect of filler type (mineralogy) on the rutting. Limestone and granite fillers were used in the experiments. Multiple stress creep tests were conducted at the high PG grade temperature. The test results were analyzed in terms of terminal strain, non-recoverable compliance, and percent recovery. Although mastics with limestone filler outperformed mastics with granite filler in terms of fatigue at intermediate temperature, the effect of type of filler on rutting is insignificant at high temperature. The speculation is that the physical stiffening effect of filler is much higher than the effects at the interface because binders are very soft and the rigidity of the fillers controls the stiffening.

Problems Encountered and Solutions

None.

Work Planned Next Quarter

Complete the literature review and analysis of existing data. Start experiments to study the effect of time and stress level on rutting of asphalt binder. Analyze the test data for better characterization and modeling of rutting behavior of asphalt binder.

Subtask E1b-2: Feasibility of Determining Rheological and Fracture Properties of Thin Films of Asphalt Binders and Mastics using Nano-indentation (Year 2 start) (UWM)

Progress This Quarter

Year 2 start.

Work Planned Next Quarter

No work planned.

Work element E1c: Warm and Cold Mixes

Subtask Lead: Andrew Hanz

Subtask E1c-1: Warm Mixtures (UWM)

Progress This Quarter

Presented the Warm Mix Work Plan at the FHWA Models Expert Task Group in Denver, CO on July 23. Received comments from the panel and have incorporated them into efforts related to the year one work plan. Have been placed on the mailing list as a friend of the FHWA Warm Mix Asphalt Technical Working Group and have made reservations to attend their next meeting on December 12–13 in Baltimore. Also discussed the warm mix work plan and coordination with the efforts of NCHRP 9-43 to coordinate efforts and avoid duplication. Completed a summary of effect of wax-based additives on binder properties using the BBR. The data collected and analyzed included effect of physical hardening on S (60) and m (60). Held a meeting with one of the potential suppliers of water-based warm mix additives to discuss mechanisms of effect on binders and possible methods of mixing additives with binders in the field. Assigned a graduate student to focus on the subtask. The current focus is on performing a comprehensive literature review focused on identifying the variety of warm mix additives available, test methods to quantify the effects of warm mix additives on binder and mixture performance properties, methods for quantifying effects of additives on mixture workability and compaction, relationship of laboratory workability measurements to compaction in the field, and measurement of plant emissions. Obtained asphalt binder, mix design, and aggregates to be used for development of binder and mixture testing protocols specified in the work plan. The initial testing materials include a PG 64-22 binder and E10 mix designs from a granite aggregate source with 9.5 mm, 12.5 mm, and 19.5 mm NMAS. Data produced using these materials will supplement the future test data collected using the common materials chosen by the ARC. Trial blends using unmodified mixes have been prepared to determine optimum asphalt contents and set benchmarks for future mixture testing. Mr. Peter Bellin, a retired pavement engineer from Germany was invited to visit UW-Madison to discuss the history of warm mix use in Germany. Mr. Bellin has prepared a lecture of the use of warm mix in Germany and other European countries. He will be staying for three weeks to discuss with team development of work plan. His trip is funded by a grant from UW-Madison.

Problems Encountered and Solutions

Difficulties were encountered in measuring the change in viscosity and its time dependence for mineral based hydrated warm mix additives. The solution is to investigate different mixing and testing methods to ensure that effect of mineral additive is being captured in tests.

Binder testing procedures need to be developed in order to quantify the effects of warm mix additives. The solution is to evaluate binder testing procedures using available materials. Procedures will be refined for testing of the common ARC materials.

The ETG comments on the Warm Mix work plan need to be addressed as well as coordinating this work with NCHRP Projects. The solution is discussion of these work plans with the NCHRP Project 9-43 Principal Investigator and to coordinate activities with selected contractor for the NCHRP 9-47. Also, UWM will participate in the Warm Mix Asphalt Technical Working Group.

Work Planned Next Quarter

Complete literature review. Procure materials. Literature review will guide selection of warm mix additives to investigate. Inventory of available materials at UW will also be performed to ensure sufficient aggregates and binders are available to last through the break in construction season. Attend FHWA Warm Mix Asphalt Technical Working Group Meeting in Baltimore, MD on December 12 and 13. Prepare draft of year 2 work plan.

Subtask E1c-2: Development and Evaluation of a Volumetric Mix Design Process for Cold Mix Asphalt (UWM, UNR)

Subtask Lead: Andrew Hanz

Progress This Quarter

A student was assigned to expand on the literature review work performed in the last quarter. The research assistant and subtask leader have been focused on the literature review for this subtask. The comments received from the ETG members were reviewed and a strategy was developed to address them. The comments from the ETG members will be fully addressed pending completion of the literature review. A meeting was scheduled in Madison with UNR personnel on October 23 to discuss the year 2 work plan and collaboration efforts. A meeting was scheduled with SemMaterials in Tulsa, OK to discuss the cold mix work plan and the current state of the practice. This meeting is a follow-up to a visit to the SemMaterials production facility in Salt Lake City, and discussion with their experts that took place on August 7, 2007. Hussain Bahia visited South Africa to observe the use of cold mix technologies in paving applications and also to discuss the most recent practices in use of emulsions. Hussain Bahia and Kim Jenkins developed a white paper on performance grading of emulsions. Also Hussain Bahia prepared a lecture on use of emulsions for surface treatments and the world wide practice of using emulsions. The lecture was delivered as part of the Mirapav Conference in Utah.

Problems Encountered and Solutions

A problem was perceived in getting the research team up to speed in regards to current state of practice for application of cold mix technologies to paving. The solution is getting the research team up-to-date through a comprehensive literature review, the meeting scheduled at SemMaterials, and attendance at the AEMA workshops in Las Vegas and California.

There is also a need to address the ETG comments submitted for Phase II work plan. The solution is to discuss the comments and address them in collaboration with personnel from UNR as the year 2 work plan is formulated.

Work Planned Next Quarter

It is planned to complete the literature review on cold mix technologies. Materials (aggregates, emulsifiers, and asphalts) will be obtained for use in development of test procedures and protocols for the project. Data collected using these materials will be used as a supplement to the data collected using the common materials selected by the ARC. It is also planned to attend the following meetings:

- October 8, 2007: SemMaterials
- October 23, 2007: UW/UNR ARC Project Meeting
- November 7–8, 2007: AEMA Workshop
- December 2007: AEMA Workshop

CATEGORY E2: DESIGN GUIDANCE

Work element E2a: Comparison of Modification Techniques (Later start) (UWM)

Progress This Quarter

Later start.

Work Planned Next Quarter

No work planned.

Work element E2b: Design System for HMA Containing a High Percentage of RAP Material (Year 1 Start)

Progress This Quarter

The following Experimental Plan for this work element was developed based on a meeting of the researchers on August 31, 2007, in Reno, NV.

Attendees: Jon Epps, Adam Hand, Hussain Bahia, Randy West, Fred Turner, Peter Sebaaly, and Elie Hajj

Subtask E2b-1: Develop a System to Evaluate the Properties of RAP Materials (AAT, UNR, UWM, WRI)

The objective of this subtask is to develop systems to evaluate the properties of the aggregates and binders in the RAP materials. Two experiments will be conducted: one experiment to recommend a system to evaluate the properties of the RAP aggregates and one experiment to recommend a system to evaluate the properties of the RAP binder.

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

Objective: The objective of this experiment is to recommend a system to evaluate the properties of the RAP aggregates. In order to recommend the most effective system, it is critical to evaluate the impact of the current extraction techniques on the properties of the extracted RAP aggregates. This objective will be achieved by producing RAP mixtures in the laboratory and extracting the aggregates using different extraction techniques. The physical properties of the aggregates before mixing with the asphalt binder and after the extraction process will be evaluated and compared.

Experimental plan: Three existing extraction methods will be evaluated under this experiment: centrifuge, reflux, and ignition oven. It is believed that the reflux method had the least impact on the properties of the aggregates after extraction however this was never verified. The proposed experimental plan consists of the following:

- Identify four aggregate sources with different mineralogy (i.e., soft limestone, hard limestone, granite, basalt). Select two sources from the east and two sources from the west of the U.S.
- UNR will identify and evaluate the aggregate sources from the west and NCAT will identify and evaluate the aggregate sources form the east.
- UNR will identify one binder to be used with the two aggregate sources from the west and NCAT will identify one binder to be used with the two aggregate sources from the east. Both binders will be graded following the PG system.
- For each combination of aggregate source and binder, conduct the experiment listed below. UNR will evaluate the two west sources and NCAT will evaluate the two east sources.
    - Develop an intermediate Superpave gradation for each of the aggregate sources.
    - Measure the physical properties of the blend aggregates: gradation, LA abrasion, soundness, absorption, specific gravity, fine aggregate angularity (FAA), coarse aggregate angularity (CAA), fractured faces, sand equivalent, durability index, and cleanness value.
    - Conduct a Superpave mix design for each combination of aggregate source and binder based on 6 millions ESALs for a top lift.

- For each mixture, compact three Gyratory specimens and subject them to the short-term and long-term oven aging processes recommended by Superpave.
- Extract the aggregates from the aged compacted specimens using the centrifuge, reflux, and ignition oven following the most current standard procedures. Use an 85%TCE+15% Ethanol solution for the reflux and centrifuge methods.
- Measure the same physical properties of the extracted aggregates that were measured on the virgin aggregates.
- Evaluate the impact of the extraction method on the physical properties of the aggregates by comparing the measured properties of the aggregates before and after extraction.
- Conduct the following experiment to evaluate the impact of reflux and centrifuge on the properties of the recovered binder.
    - Prepare two replicate samples from each mix without any aging.
    - Recover the asphalt binder from the centrifuge and the reflux methods using the Rota-vap method.
    - Grade the recovered asphalt binders according to the Superpave grading system and the guidelines provided by the NCHRP Research Results Digest No. 253.
    - Compare the properties of the recovered binders from the two extraction methods to their original properties.

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

Objective: The researchers strongly believe that the process of extracting and recovering the RAP binder followed by determining its PG grade and using it in the blending chart to identify the required grade of the virgin binder is not a very reliable/practical method for the design of HMA mixtures containing RAP materials.

The objective of this subtask is to identify an innovative system that can evaluate the impact of the RAP binder on the required properties of the virgin binder without resorting to the extraction-recovery process. The proposed research approach is based on the assumption that evaluating the mastic portion of the RAP material can lead to valuable information on the properties of the RAP binder and on the interaction between the RAP binder and the virgin binder in the final blended mix.

Experimental plan: The following experimental plan will be followed:

Materials

- Identify four different RAP sources:
    - Modified-Stiff: AAT from the DC area
    - Modified-Very Stiff: UNR from Nevada

- Unmodified-Stiff: NCAT from the Southeast
- Unmodified-Very Stiff: UNR from Palm Springs California

- Select three virgin binders grades:
  - PG64-22: UNR from Paramount
  - PG64-28: NCAT unmodified from CITGO
  - PG58-34: UWM from Wisconsin
- Verify the grade of all three selected binders.
- Sieve the RAP mixtures on the #8 sieve. The material passing #8 sieve will be referred to as RAP(-#8) mastic and will be used for further testing.

Evaluation 1: Evaluate the Mastic with 100% Virgin Binders

- For each source, extract the RAP aggregates from the RAP(-#8) mastic according to the procedure identified in E2b-1.a with the least impact on the aggregate properties.
- Determine the RAP(-#8) mastic binder content for each RAP source material.
- Mix the extracted RAP aggregates with each of the three selected virgin binders to produce a virgin mastic material at a10% twm binder content.
- Measure the high temperature and low temperature properties of the virgin mastic mixtures in the BBR and/or DSR. (actual tests to be recommended by UNR and UWM).

Evaluation 2: Evaluate the Mastic with Blended Binders

- Mix the RAP(-#8) mastic with each of the three selected virgin binders at a 10% twm binder content.
- Measure the high temperature and low temperature properties of the virgin mastic mixtures in the BBR and/or DSR. (actual tests to be recommended by UNR and UWM).
- Extract and recover the RAP + virgin binders from the mastic materials.
- Grade the recovered asphalt binder according to the Superpave grading system.

Evaluation 3: Evaluate the Binder Grade of the RAP Mixtures

- Design mixtures containing 20 and 40% RAP from the four RAP sources using the binder grades recommended through Evaluations 1 and 2 using a single source of virgin aggregate (i.e., Lockwood, NV).
- Measure the E* Master curves for all mixtures and use the Hirsch model to estimate the properties of the RAP binder.
- Extract and recover the binders from the prepared mixtures.
- Grade the recovered RAP binders according to the Superpave grading system and the guidelines provided by the NCHRP Research Results Digest No. 253.

Work Planned Next Quarter

Conduct a meeting with the researchers at UW-M on October 22-23, 2007 to finalize the mechanical testing program of RAP materials. Obtain RAP and virgin materials to conduct the experimental plan. Start working on the evaluation of RAP materials.

Subtask E2b-2: Compatibility of RAP and Virgin Binders (AAT, UNR, UWM, WRI)

Objective: The objective of this experiment is to develop a test that is capable of evaluating the degree of compatibility between the RAP binder and the virgin binder.

Experimental plan:

- Three level of compatibility might be present in HMA mixtures with RAP material:
    - Chemical and physical compatibility between RAP binder and virgin binder: use always.
    - Chemical and physical incompatibility between RAP binder and virgin binder: do not use at anytime.
    - Chemical incompatibility but physical compatibility between RAP binder and virgin binder: use with caution on long-term durability.
- WRI researchers will work with a team of industry experts to identify materials that fit the three classes of compatibility identified above.
- WRI researchers will obtain samples from the identified sources.

WRI researchers will develop a chemical test that is capable of identifying the three types of compatibility/incompatibility of HMA mixtures containing RAP.

Subtask E2b-3: Develop a Mix Design Procedure (AAT, UNR, UWM)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Subtask E2b-4: Impact of RAP Materials on Performance of Mixtures (AAT, UNR, UWM, WRI)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Subtask E2b-5: Field Trials (AAT, UNR, UWM)

Progress This Quarter

In cooperation with researchers at NCAT, a field trial project was identified in South Carolina. The work plan for this subtask was also developed and is as follows.

Objective: Early evaluation of field performance of HMA mixtures with 40% RAP material designed without changing the binder grade and with the appropriately changed binder grade.

Experimental plan: Construct field test sections at five different locations in the U.S.

- Palm Springs, CA: Granite Construction
- West Texas, TX: Granite Construction
- Alabama or Florida: NCAT
- Wisconsin or Minnesota: UWM

- It is desired to have field projects at the above locations that include 40% RAP materials in two test sections:
    - One test section with 40% RAP using the same binder grade for the project
    - One test section with 40% RAP using the appropriately changed binder grade
- Each test section will consist of 500 tons of mix (i.e. one transport of 20 tons binder).
- UNR may provide some financial support to offset the cost of changing the binder grade.
- UNR and NCAT will provide support for the design and evaluation of the mixtures.

Work Planned Next Quarter

RAP Materials will be sampled from the SC project by the NCAT researchers. Identify additional field trial projects.

Work element E2c: Critically Designed HMA Mixtures (Year 1 start) (UNR)

Progress This Quarter

The following Experimental Plan was developed based on a meeting of the researchers on August 17, 2007 in Reno, NV.

Attendees: Jon Epps, Adam Hand, Peter Sebaaly, and Elie Hajj

Subtask E2c-1: Identify the Critical Conditions (UNR)

Objective: The objective of this task is to define the critical loading conditions under a moving truck load. This objective will be met through a mechanistic analysis of the HMA pavement as it is subjected to moving loads at various speeds and under braking and non-braking conditions.

Experimental plan:

- Use the 3D-Move software to evaluate the stress conditions under dynamic loads within the HMA layer.
- Analyze the following pavement structures:
    - 4” HMA over 6” base
    - 6” HMA over 8” base
    - 8” HMA over 10” base
- Analyze the following geometries:
    - Level road
    - 4% grade road
- Analyze the following speeds:
    - 60 mph without braking
    - 40 mph without braking
    - 20 mph with and without braking
    - 2 mph with braking
- Tire-Pavement Pressure Distribution
    - Uniform
    - Non-uniform
- Analyze the following HMA mixtures:
    - One aggregate source: Lockwood
    - Intermediate Superpave gradation with ½” nominal max size
    - Three binders: PG52-22, PG58-22, PG64-22
- Analyze the following HMA layer temperature
    - 40^{o}C
    - 50^{o}C
    - 60^{o}C
    - 70^{o}C
- Conduct Superpave mix designs for the three mixtures for 6 millions ESALs and for a top lift.
- Subject the mixture to Superpave short-term aging.
- Measure the E* Master Curves for all three mixtures.
- Use the measured properties of the HMA mixtures in the 3D-Move analyses.

- Use a modulus of 35,000 psi and 15,000 psi for the base and subgrade, respectively.
- Use the 18-wheeler truck configuration at 125 psi inflation pressure.
- Evaluate the distributions of vertical displacements, vertical and lateral stresses within the HMA at the surface and 1/2" depth increments for the top 2" of the HMA layer and at 1" increment thereafter within the influence zone of the loaded tires.
- Analyze the data to identify the following:
    - Time of loading throughout the HMA
    - Magnitude of the confining and deviator pressures throughout the HMA layer

Work Planned Next Quarter

Conduct mechanistic analyses of HMA pavements to identify the critical loading times for the various loading conditions.

Subtask E2c-2: Conduct Mixture Evaluations (UNR)

Objective: The objective of this task is to evaluate the critical conditions of HMA mixtures defined as the critical combination of testing temperature and loading rate under the repeated load triaxial (RLT) testing conditions.

Experimental Plan:

- Use the same three mixtures that were designed under Subtask c-1.
- Test the mixtures in the RLT at various temperatures of 40, 50, 60, and 70^{o}C and at the state of stresses and loading times that were determined in subtask c-1.
- Analyze the RLT of the various mixtures in terms of the relationship between the permanent axial strain as a function of number of load cycles.

Work Planned Next Quarter

Obtain materials for the laboratory evaluation program.

Subtask E2c-3: Develop a Simple Test (UNR)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Subtask E2c-4: Develop a Standard Test Procedure (UNR)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Subtask E2c-5: Evaluate the Impact of Mix Characteristics (UNR)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Work element E2d: Thermal Cracking Resistant Mixes for Intermountain States (Year 1 start)

Subtask E2d-1: Determine Parameters for an Aging Model for Asphalt Binders in HMA Mixtures placed in the Intermountain Region (UNR, UWM)

Progress This Quarter

Conducted a research meeting on September 6, 2007 and developed the experimental plan.

Work Planned Next Quarter

Finalize the experimental plan based on input from the research team. Meet with the LTPP regional contractor to identify field sections. Obtain materials from the Westrack Project.

Subtask E2d-2: Identify the Causes of the Thermal Cracking (UNR, UWM)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Subtask E2d-3: Identify an Evaluation and Testing System (UNR, UWM)

Subtask Lead: Codrin Daranga

Progress This Quarter

The research group completed the design of a new TG testing chamber (figure E2d-3.1) to evaluate the thermo-mechanical properties of both binder and mixtures over a wide temperature range (approx. -80 to 40ºC). Issues related to thermal diffusion, hysteresis in binders and mixtures, boundary conditions, initial conditions, thermal uniformity, and testing measurements (including stability of sensors under very low temperature) are being studied and addressed in the new design.

Data have been collected for two samples with three cycles of cooling and heating. Figure E2d-3.2 shows a typical cyclic behavior of one mixture. The data collected so far clearly indicates that the cooling and heating rate needs to be carefully monitored to minimize the hysteresis effects. It is also clear that contraction coefficients could be significantly different than expansion coefficients of asphalt mixtures. A detailed analysis of data collected previously for a Pooled Fund Study led by the University of Minnesota is underway to understand the cyclic effects.

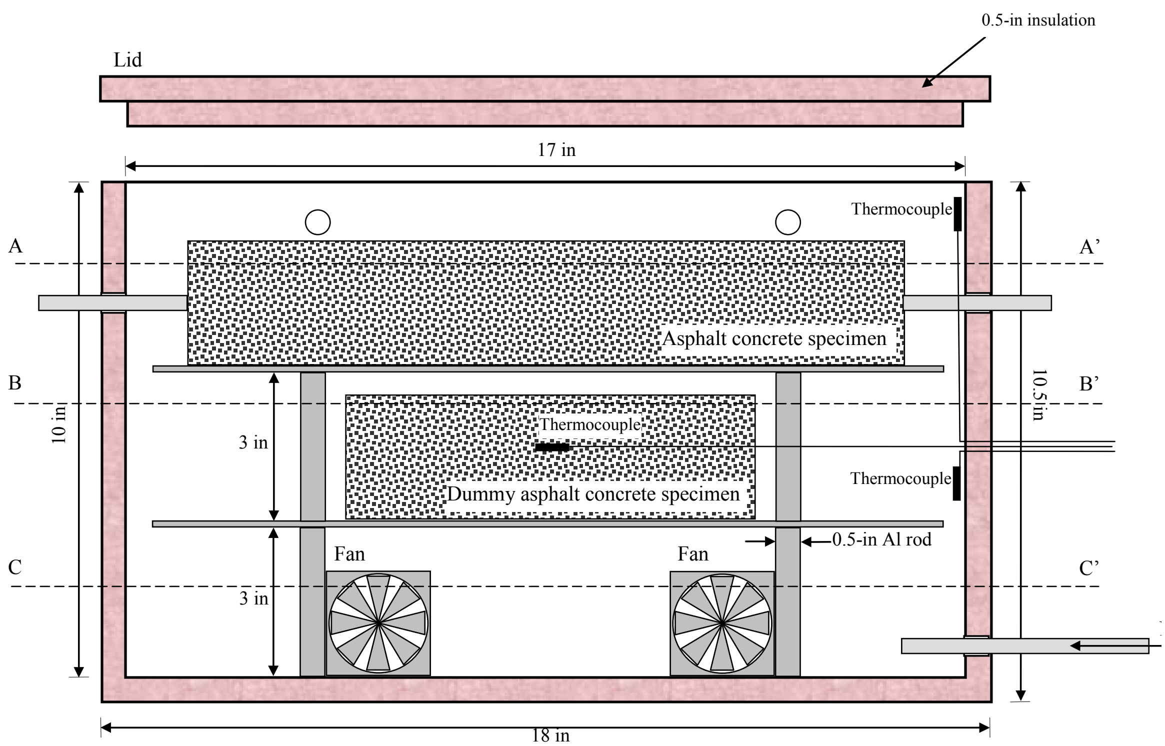

Figure E2d-3.1. View of the proposed TG chamber.

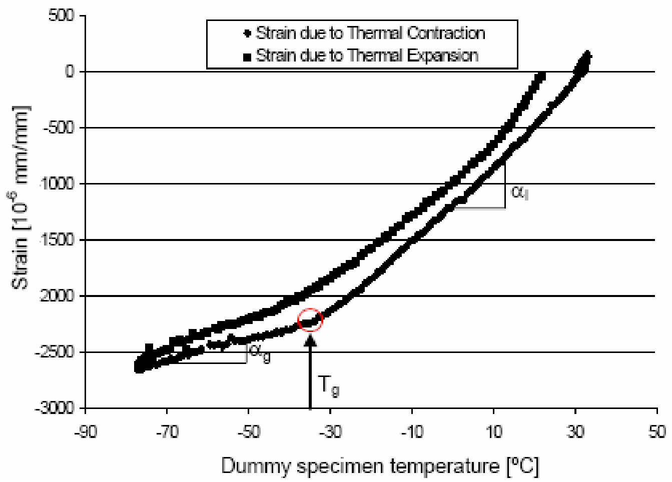

Figure E2d-3.2. Typical heating and cooling cycle behavior of one mixture.

Problems Encountered and Solutions

None

Planned Work Next Quarter

Build and test the new TG testing chamber. This chamber will allow for free thermal deformation and no-thermal deformation conditions to allow the evaluation of thermal cracking of asphalt pavements.

Subtask E2d-4: Modeling and Validation of the Developed System (UNR, UWM)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Subtask E2d-5: Develop a Standard (UNR, UWM)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Work element E2e: Design Guidance for Fatigue and Rut Resistance Mixtures (Year 1 Start)

Subtask E2e-1: Identify Model Improvements (AAT)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Subtask E2e-3. Perform Engineering and Statistical Analysis to Refine Models (AAT)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Subtask E2e-4. Validate Refined Models (AAT)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Subtask E2e-5. Prepare Design Guidance (AAT)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

PROGRAM AREA: VEHICLE-PAVEMENT INTERACTION

CATEGORY VP1: WORKSHOP

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

Progress This Quarter

The logistics and planning were finalized for the Workshop to be held on October 25-26, 2007 at TFHRC.

Work Planned Next Quarter

Conduct the Workshop on October 25-26, 2007 at TFHRC.

CATEGORY VP2: DESIGN GUIDANCE

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

Work Element Lead: Dante Fratta

Subtask VP2a-1: Evaluate Common Physical and Mechanical Properties of Asphalt Mixtures with Enhanced Frictional Skid Characteristics (UWM)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Subtask VP2a-2: Evaluate Pavement Macro and Micro-textures and Their Relation to Tire and Pavement Noise-generation Mechanisms (UWM)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Subtask VP2a-3: Develop a Laboratory Testing Protocol for the Rapid Evaluation of the Macro and Micro Texture of Pavements (UWM)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Subtask VP2a-4: Run Parametric Studies on Tire-pavement Noise and Skid Response (UWM)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Subtask VP2a-5: Establish Collaboration with Established National Laboratories Specialized in Transportation Noise Measurements. Gather Expertise on Measurements and Analysis (UWM)

Progress This Quarter

Work focused on performing a literature review: collecting bibliography and identifying possible partners and resources. Low-cost laboratory profilers for characterization of pavement surfaces were evaluated, as were instrument specifications.

Problems Encountered and Solutions

Additional student support was needed. In response, a research assistant has been assigned to the work element.

Work Planned Next Quarter

Profiling instruments will be tested and the literature review will be completed for this work element during the next quarter. A collection of mixtures will be characterized at the UW-Madison pavement laboratory.

Subtask VP2a-6: Model and Correlate Acoustic Response of Tested Tire-pavement Systems (UWM)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Subtask VP2a-7: Proposed Optimal Guideline for Design to Include Noise Reduction, Durability, Safety and Costs (UWM)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

CATEGORY VP3: MODELING

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

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

PROGRAM AREA: VALIDATION

CATEGORY V1: FIELD VALIDATION

Work element V1a: Use and Monitoring of Warm Mix Asphalt Sections (Year 1 start) (WRI)

Progress This Quarter

The FHWA Western Federal Lands Highway Division and the Office of Pavement Technology collaborated to construct two sections of different Warm-Mix asphalt materials and one Hot-Mix asphalt section on a project in Yellowstone National Park (YNP). The project was between the East YNP Entrance (about 52 miles west of Cody, WY) and Sylvan Pass, a total length of 11,154 meters or approximately seven miles. WRI and the Asphalt Research Consortium proposed to use this project as a validation site and thus to sample construction materials and to monitor the performance of the three different pavement materials.

The project plan was to place two, two-inch lifts of material in each of 4.6 m eastbound and westbound lanes (includes 1.2 m shoulder) of the road (side-by-side) for approximately 3718 meters or about 2.3 miles. In simple terms, each of the three materials would be placed in approximately one-third of the total paving project. The asphalt used in the project was a PG 58-34 asphalt from Idaho Asphalt. For the Warm-Mix sections, 0.3% of Advera (zeolite), based on mix weight, was used as the first additive and 1.5% of Sasobit (wax), based on asphalt weight, was used as the second additive.

Mainline paving construction began on August 21, 2007 with placement of the Hot-mix asphalt and continued through September 8. Several construction problems such as equipment break-downs and weather caused the planned layout of the materials to be altered from the original plan. In addition, the project engineer decided that some of the originally placed materials needed to be removed by rotomill and replaced. All of the rotomilled areas were replaced with Hot-mix asphalt. The resultant layout of the two-lift pavement of the Hot-mix areas, the Advera areas, and the Sasobit areas therefore became quite complicated as shown in figure V1a.1. Although figure V1a.1 appears complicated, there was still sufficient pavement area to establish monitoring sections for each individual material without interference from another material. The monitoring sections are also shown in figure V1a.1. Because the road continuously climbs from the East Gate to Sylvan Pass, it was decided to establish three monitoring sections in each material, two monitoring sections in the westbound (uphill) direction and one monitoring section in the eastbound (downhill) direction.

WRI personnel sampled all construction materials during construction and these will be included in the Asphalt Research Consortium Materials Library.

Work Planned Next Quarter

In the next quarter, it is planned to begin evaluation of the construction materials from the YNP project.

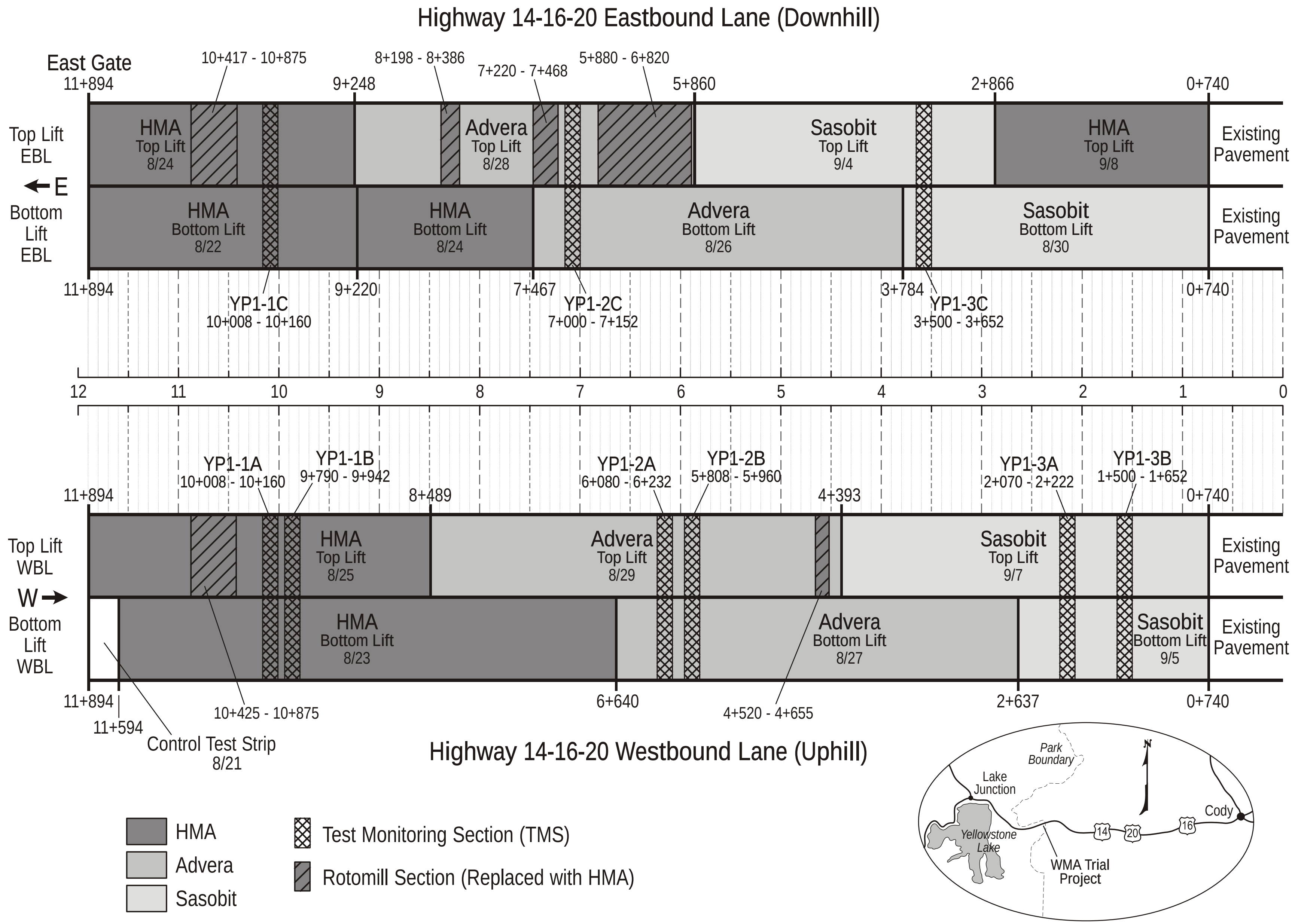

Figure V1a.1. Layout of the Pavement Materials at the Yellowstone National Park site.

Work element V1b: Construction and Monitoring of additional Comparative Pavement Validation sites (Year 1 start) (WRI)

Progress This Quarter

In October 2007 four cells of the Low Volume Road at the MnROAD Test Facility in Albertville, MN were paved with asphalt concrete. These cells will be used as a validation site for both the Asphalt Research Consortium and the Fundamental Properties contracts between FHWA and WRI.

The PG grade of the base asphalt used for each cell was 52-34 modified to 58-34. The base asphalt in Cell 33 was modified with 0.75% polyphosphoric acid (PPA) and 0.5% phosphate ester antistrip. In cell 34 the base asphalt was modified with 1.0% SBS, 0.3% PPA and 0.5% phosphate ester antistrip. Cell 35 contained 2% SBS as the only modifier. In cell 79, the base asphalt was modified with 1.1% Elvaloy, 0.3% PPA and 0.5% phosphate ester antistrip (see table V1b.1). The plant mix paved into each cell contained 5.6% of the modified asphalt binder and 1% hydrated lime mixed with granite aggregate.

Table V1b.1. Materials placed in Four MnROAD cells.

	Polymer	Acid	Antistrip
Cell 33	----	0.75% PPA (115%)	0.5% Innovalt W (phosphate ester)
Cell 34	1% SBS	0.3% PPA (115%)	0.5% Innovalt W (phosphate ester)
Cell 35	2% SBS	----	----
Cell 79	1.1% Elvaloy	0.3% PPA(115%)	0.5% Innovalt W (phosphate ester)

During the paving, 720 lbs of loose mix samples were collected from each of the four cells at MnROAD. Additionally, 1000 lbs of aggregate and thirty two gallons of liquid asphalt (eight gallons of each modification) were collected at the Commercial Asphalt mix plant in Maple Grove, MN. All of these materials were shipped to WRI and will be stored at WRI for use at a later date.

Work Planned Next Quarter

The effectiveness of the use of PPA in asphalt concrete will be evaluated using samples collected from the MnROAD validation site. This work will be conducted under the Fundamental Properties contract between WRI and FHWA

CATEGORY V2: ACCELERATED PAVEMENT TESTING

Work element V2a: Scale Model Load Simulation on Small Test Track (Later start) (TAMU)

Progress This Quarter

No activity this quarter

Work Planned Next Quarter

No work planned.

Work element V2b: Construction of Validation Sections at the Pecos Research & Testing Center (Later start) (TAMU)

Progress This Quarter

No activity the quarter

Work Planned Next Quarter

No work planned.

CATEGORY V3: R&D VALIDATION

Work element V3a: Continual Assessment of Specifications (Year 1 start) (AAT, UWM)

Work Element Lead: Hussain Bahia

Progress This Quarter

The activities focused on review of the recent data generated from the MSCR test and binder fatigue. For the MSCR test, a detailed analysis of the trends in effect of varying stress on the creep and recovery response was carried out. Modeling of the stress sensitivity using phenomenological models has started. The objective is to derive a simple indictor of stress sensitivity that can be included in the binder specifications. The analysis has shown that stress levels of 100 and 3200 Pa, which are currently recommended by the ETG, are not sufficient to show differences between binders. Stress levels in the range of 30,000 Pa (30 KPa) are required. It was also shown that the total time of loading makes a significant difference. Some of the modified binders analyzed show a tertiary creep behavior after a certain number of cycles.

For development of a binder fatigue parameter, the concept of Dissipated Creep Strain Energy was applied to data collected using the DTT. A draft paper was completed regarding the analysis of the DTT data and it shows some promise that a relationship could be derived between DCSE form DTT and binder fatigue as measured with tome sweeps. In addition, a new type of monotonic test protocol was developed using the DSR. The initial data shows that calculating the fracture energy (area under stress-strain curve to maximum stress) correlates well with the fatigue data from the ALF fatigue experiment. The repeatability and details of the analysis for the Monotonic Shear Binder Test (MSBT) is underway. In another development of the binder fatigue protocol, it was discovered that rest periods included in time sweep routines of some rheometers can cause significant changes in the fatigue damage accumulation. A summary of the analysis was completed and will be sent as a white paper in the near future. This discovery could explain the differences seen between fatigue results of rheometers.

As part of this task a review of the elastic recovery test results as compared to the MSCR test has continued. An initial database for modified binders that has been created for another research project at UW-Madison is showing some trends that could lead to specific recommendations to replace the elastic recovery with MSCR test at a selected stress level.

Problems Encountered and Solutions

None.

Work Planned Next Quarter

Work on the MSCR test analysis and the MBST will continue next quarter. Two white papers on each subject will be completed. More elastic recovery data will be collected.

Work element V3b: Validation of the MEPDG Asphalt Materials Models Using New MEPDG Sites and Selected LTPP Sites (UNR)

Subtask V3b-1: Design and Build Sections (Start Year 1, Year 2, and Year 3) (UNR)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

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

Progress This Quarter

Year 2 start.

Work Planned Next Quarter

No work planned.

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

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Subtask V3b-4: Testing of Extracted Binders from LTPP Sections (Start Year 1) (UNR)

Progress This Quarter

No activity this quarter.

Work Planned Next Quarter

No work planned.

Subtask V3b-5: Review and Revisions of Materials Models (Start Year 2, Year 3, Year 4, and Year 5) (UNR)

Progress This Quarter

Year 2 start.

Work Planned Next Quarter

No work planned.

Subtask V3b-6: Evaluate the Impact of Moisture and Aging (Start Year 3, Year 4, and Year 5) (UNR)

Progress This Quarter

Year 3 start.

Work Planned Next Quarter

No work planned.

PROGRAM AREA: TECHNOLOGY DEVELOPMENT

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

Progress This Quarter

The Asphalt Research Consortium plan and schedule for development of existing technologies was presented to the Fundamental Properties and Advanced Models ETG on July 23, 2007 in Denver, CO. Discussion of the proposed plan produced some adjustments to the plan regarding the method of review of selected technologies by ETG members and also to the proposed schedule. The modified plan requires the Consortium to prepare a rating system and executive summaries for technologies that are ready for further development. The Chairpersons and Co-Chairpersons of the three ETG's and FHWA representatives review the technology summaries and forward them to the ETG members for review and rating for further development. After review, the ratings are summarized and those technologies receiving favorable ratings will be moved to further development. A report on the technology review activities and a request for ETG members to serve as product reviewers will be conducted at the next ETG meetings in early 2008. The agreed upon schedule is shown in table TD1.1.

Work Planned Next Quarter

The work planned for next quarter is to receive and summarize product ratings from the ETG members. Discuss the summarized ratings with FHWA personnel and select the appropriate products for further development.

Table TD1.1. Schedule for development of early research products.

Item	Date	Responsible Party
Develop Executive Summaries and Rating System	8/31/07	Consortium
FHWA/ETG Chair Review	9/30/07	FHWA/ETG Chair
ETG Members Rate Products	10/31/07	ETG Members
Summarize Ratings	11/30/07	Consortium
Select Products for Development	12/31/07	Consortium/FHWA
Report to ETG's and Solicit Members for Product Review Committees	Next ETG	Consortium
Prepare Product Development Plans	Next ETG +	Consortium
Review Product Development Plans	Next ETG +	Product Review Committees
Execute Product Development Plans	Next ETG +	Consortium with review from Product Review Committees

Work element TD2: Develop Early Products (Year 2) (AAT)

Progress This Quarter

Year 2 start.

Work Planned Next Quarter

No work planned.

Work element TD3: Identify Products for Mid-Term and Long-Term Development (Year 2, 3, and 4) (AAT)

Progress This Quarter

Later start.

Work Planned Next Quarter

No work planned.

Work Element TD4: Develop Mid-Term and Long-Term Products (Years 3, 4, and 5) (AAT)

Progress This Quarter

Later start.

Work Planned Next Quarter

No work planned.

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)

Progress This Quarter

The ARC website was maintained and updated.

In other website activity, the University of Wisconsin-Madison drafted an initial concept for the design and content of the University of Wisconsin's website dedicated to ARC activities. It is expected that the site will go online and be linked to the main ARC site at the University of Nevada Reno (UNR) during the next quarter.

Work Planned Next Quarter

Continue maintaining and updating the ARC website.

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

Progress This Quarter

Information was collected for the First ARC Newsletter. All Consortium members prepared introductions of their research team leaders for inclusion the premier issue of UNR's consortium newsletter.

Work Planned Next Quarter

It is planned to publish the first ARC Newsletter.

Work element TT1c: Prepare Presentations and Publications (AAT, TAMU, UNR, UWM, WRI)

Progress This Quarter

Several Consortium members made presentations at the Fundamental Properties and Advanced Models ETG, the Mix and Construction ETG, and the Binder ETG meeting in Denver, Colorado during the week of July 23 – 27, 2007.

The following papers were submitted for possible publication and/or presentation.

Bhasin, A., V. C. Branco, E. Masad, and D. N. Little. "A Critical Review of Energy Methods to Characterize Fatigue Cracking of Asphalt Materials." Submitted for consideration in the *Journal of the Association of Asphalt Paving Technologists*.

Bhasin, A., D. N. Little, R. Bommavaram, and K. L. Vasconcelos. "A Framework to Quantify the Effect of Healing in Bituminous Materials Using Material Properties." Submitted for consideration in the *International Journal of Road Materials and Pavement Design.*

Branco, V. C., E. Masad, A. Bhasin, and D. N. Little. "Fatigue Analysis of Asphalt Mixtures Independent of Mode of Loading." Submitted for consideration in the *Transportation Research Record,* TRB, National Research Council, Washington, D.C.

Caro, S., E. Masad, G. Airey, A. Bhasin, and D. N. Little. "Probabilistic Analysis of Fracture in Asphalt Mixtures Caused by Moisture Damage." Submitted for consideration in the *Transportation Research Record,* TRB, National Research Council, Washington, D.C.

Ojo, J. O., D. Fratta, H. U. Bahia, C. Daranga, and M. Marasteanu. "Thermo-Volumetric Properties of Asphalt Binders and Mixtures." Submitted for the 6th RILEM International Conference on Cracking in Pavements.

Work Planned Next Quarter

At this time, no specific presentations or publications are anticipated. However, it is expected that publications and presentations will be a frequent occurrence for all Consortium members.

Work element TT1d: Development of Materials Database (Duration: Year 2 through Year 5) (AAT, TAMU, UNR, UWM, WRI)

Subtask TT1d-1: Identify the Overall Features of the Web Application

Progress This Quarter

Year 2 start.

Work Planned Next Quarter

No work planned.

Subtask TT1d-2: Identify Materials Properties to Include in the Materials Database System

Progress This Quarter

Year 2 start.

Work Planned Next Quarter

No work planned.

Subtask TT1d-3: Define the Structure of the Database

Progress This Quarter

Year 2 start.

Work Planned Next Quarter

No work planned.

Subtask TT1d-4: Create the Database

Progress This Quarter

Year 2 start.

Work Planned Next Quarter

No work planned.

Work element TT1e: Development of Research Database (Duration: Year 2 through Year 5) (AAT, TAMU, UNR, UWM, WRI)

Subtask TT1e-1: Identify the Information to Include in the Research Database System

Progress This Quarter

Year 2 start.

Work Planned Next Quarter

No work planned.

Subtask TT1e-2: Define the Structure of the Database

Progress This Quarter

Year 2 start.

Work Planned Next Quarter

No work planned.

Subtask TT1e-3: Create the Database

Progress This Quarter

Year 2 start.

Work Planned Next Quarter

No work planned.