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FIRST YEAR WORK PLANS

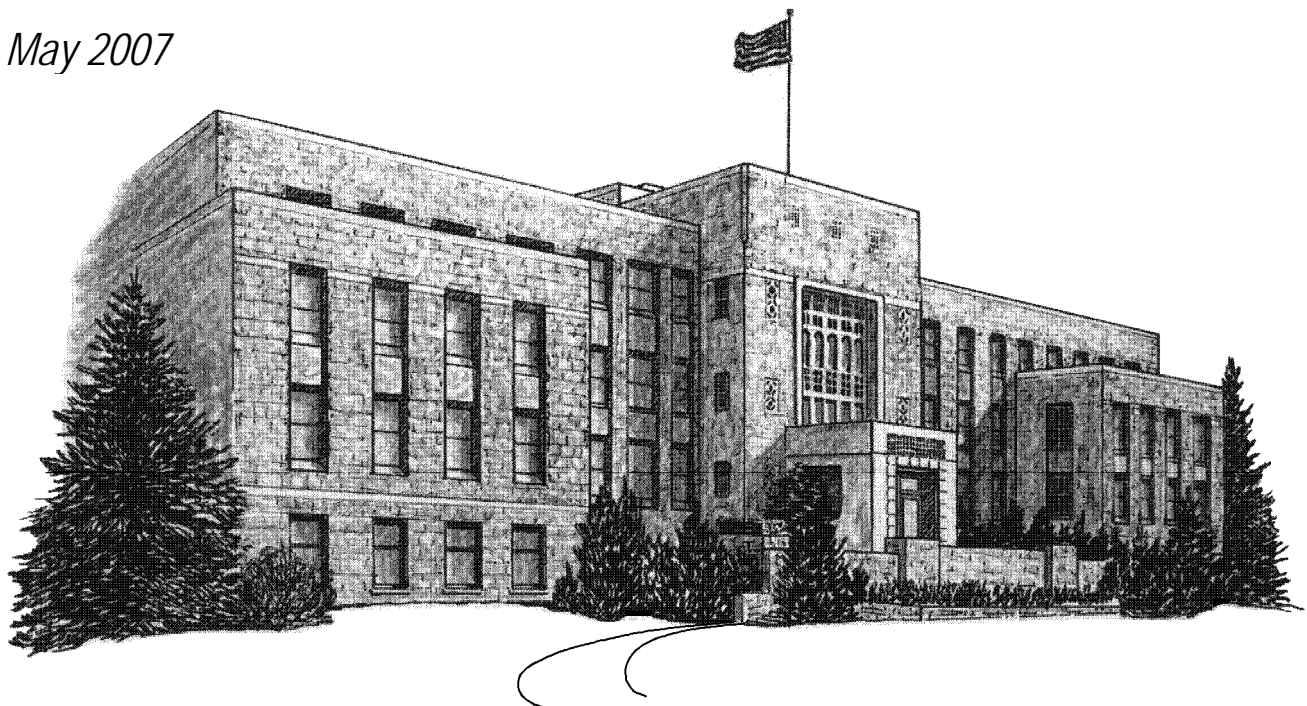
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ASPHALT RESEARCH CONSORTIUM

*PROGRAM AREA:
MOISTURE DAMAGE
FATIGUE*

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

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**RESEARCH PLAN FOR YEAR 1 OF FEDERAL HIGHWAY
ADMINISTRATION CONTRACT DTFH61-07-H-00009
“ASPHALT RESEARCH CONSORTIUM”**

FOREWORD

This document is the proposed Research Plan for Year 1 of 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 Year 1 research plans are grouped into seven areas, Moisture Damage, Fatigue, Engineered Paving Materials, Vehicle-Pavement Interaction, Validation, Technology Development, and Technology Transfer. The format of the presentation of the work plans varies somewhat because of the different interactions of the work elements. The Moisture Damage and Fatigue areas contain work elements that are interrelated and thus will work together to advance the knowledge of mechanisms and models in these areas. In addition, there are some work elements that compliment one another by investigating a common principle using different methods. For example, in the Moisture Damage area, the principle of measuring surface energy of asphalts and aggregates is being pursued using the “macro” (or bulk) approach using the Wilhelmy plate and Universal Sorption Device for asphalts and aggregates, respectively. The surface energy of asphalts and aggregates is also being pursued using Atomic Force Microscopy at the nano scale. Using the two different methods provides a check on one another so that the true significance and importance of surface energy can be evaluated and related to performance properties. There are also examples of Modeling activities that compliment each other in a similar fashion. The Consortium members firmly believe that this approach make the research more robust.

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

Finally, the areas of Technology Development and Technology Transfer are the areas where the research deliverables will get transmitted to the user community. The Technology Development area will 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 will also transfer Consortium research findings to the asphalt community using the Consortium website, presentations, publications, and workshops.

The Asphalt Research Consortium members strongly believe that the proposed 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.

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PROGRAM AREA: MOISTURE DAMAGE

INTRODUCTION

The Moisture Damage Process

It is generally agreed among highway engineers that moisture damage in asphalt pavement is one of the most wide-spread and most severe forms of pavement distress that leads to early pavement failure. Moisture damage occurs in all types of climates including hot, dry, desert climates. Moisture damage may result in stripping, raveling, fatigue damage and/or permanent deformation, i.e., moisture invasion into pavement reduces its structural strength thereby promoting one or more of the above described (visible) forms of distress.

There are, no doubt, multiple mechanisms by which moisture changes (reduces) the structural strength of pavement. It has been shown that water can etch certain types of aggregate surfaces to disrupt the asphalt-aggregate bond, and it has been shown that asphalt can and will transport water thereby making it available at an aggregate surface. It has been shown that asphalts generally oxidize more rapidly when they are wet than when dry, and further, that oxidation produces small amounts of highly surface-active materials which are capable of emulsifying and/or softening asphalt. There is strong evidence that microorganisms cause damage to pavement, especially in hot, wet climates, but the severity of this mechanism of damage is not yet clear.

Research Needed to Better Understand and Evaluate Moisture Damage

Numerous test methods have been developed over the past 50 or so years that are designed in order to predict the moisture sensitivity of any asphalt-aggregate mixture. These are empirical tests which, for the most part, do not correlate well with observed moisture sensitivity of pavement in the field. One test (the Hamburg wheel-tracking test) is so severe that many moisture-insensitive pavement mixtures fail the test. Another, the Lottman test, is considered by many to be a relatively reliable predictor of moisture sensitivity, but it requires so much time (multiple weeks) to perform that it cannot be used in the pavement design process. Other tests give mixed results. A major problem with all empirical tests, except the Lottman test, is that they are conducted over a very short period of time (hours to a few days) whereas moisture in pavement may require a few months to a few years to cause (early) failure. So, there is a definite need to develop test methods that simulate the effect of water over time.

The mission of this program is to elucidate all of the major mechanisms of failure that result from the presence of water in pavement. The most promising concept today to evaluate the propensity of pavement to suffer moisture damage is to measure the surface energies of asphalt and aggregate. This method gives fundamentally sound measures of the thermodynamic stability of asphalt-wet aggregate versus water-wet aggregate. Fundamental thermodynamic measurements show that a water-wet aggregate is preferred over an asphalt-wet aggregate. However, there is a need to understand and model the kinetics (rate) of displacement of asphalt by water.

Previous research has shown that aggregate surface energy is the major variable that influences the binder-aggregate adhesive bond. However, this finding is primarily based on measurements of newly prepared mixes, i.e., using new (unaged) asphalts. Clearly, asphalts age in pavement and consequently the properties of asphalts change and vary substantially with age. So, in the future the concept of using fundamental thermodynamic measurements to predict moisture sensitivity must include different aged asphalts. Further, the correlation of thermodynamic stability to the kinetics of displacement must also be established. This type of relationship has been established for other chemical systems, so, in principle, it can be done for asphalt-aggregate systems also.

Moisture damage that leads to early pavement failure consumes a disproportionate amount of highway maintenance funds, so, development of a rapid, reliable method to predict moisture sensitivity of pavement mixtures is imperative. In summary, one of the primary goals of this program will be to develop a system to match asphalts (new and aged), aggregates, and additives that are highly resistant to moisture damage. This must also be a system that is rapid enough to be employed as part of the pavement design process. Since surface energy is defined by composition, some portion of a comprehensive system to match asphalts, aggregates, and additives very likely will involve chemical analyses which are very rapid compared to physical tests.

In addition to the selection of materials, this program will target the development of tests and model for evaluating and quantifying the resistance of asphalt mixtures to moisture damage. It is envisioned that the test methods will be similar to those discussed in the fatigue work plan. These tests will focus on the dynamic mechanical analysis of asphalt mastics and fine portion of the mixtures and the repeated dynamic loading of full mixtures. The models will also be similar to the micromechanical and unified continuum models discussed in the fatigue work plan. The main difference is that the influence of moisture will be included in the models' parameters.

HYPOTHESES

The development of tests and models that reliably predict the moisture susceptibility of mixes depends on the identification of the mechanisms that contribute to moisture susceptibility. The working hypotheses for the development of a methodology to rapidly and reliably predict moisture susceptibility of mixes is:

The moisture susceptibility of a mixture is determined based on the combined effect of material properties such as aging of asphalt, pH of the water, aggregate structure, surface energy of the asphalt and the aggregate as well as mixture properties such as void distribution within the mixture.

OBJECTIVES

1. Identify the mechanisms that contribute to moisture susceptibility of mixes.

2. Understand the contribution of material properties such as aging of the asphalt, pH of the water, aggregate structure, diffusion properties of the binder or mastic, and surface energy of the asphalt and aggregate to the moisture susceptibility of mixes.
3. Understand the contribution of mixture properties such as internal void structure and diffusivity of the mixture.
4. Develop and validate the utility of tests and models to evaluate the moisture susceptibility of mixes.

EXPERIMENTAL DESIGN

Although it is premature at this point to propose an exact experimental design, the development of an experimental design will be among the initial subtasks of each work element. The experiment design will be communicated to the AOTR before the work is begun, and each experimental design or plan will be approved and/or developed by the project statistician, who is in our case Dr. E. S. Park of the Department of Statistics at Texas A&M. Dr. Park has a research appointment with TTI and is very familiar with the design of experiments in asphalt related research. She has served as team statistician on several asphalt related research projects including NCHRP Project 9-37, "Using Surface Energy Measurements to Select Materials for Asphalt Mixtures".

The TTI team will use the Buckingham PI theorem of experiment design to identify dimensional ratios of material properties to minimize the size of the experiment and maximize the information to be obtained from them. This approach was used successfully in many fields of mechanics such as fluid flow and aerodynamics.

WORK ELEMENTS

Category M1: Adhesion

Work Element M1a: Affinity of Asphalt to Aggregate

It is well recognized that adhesion and cohesion both between the coarse aggregate and the binder and within the mastic itself are important parameters that contribute to the mechanical properties of bonded materials. The performance of asphalt pavement is deeply related to the presence of moisture and the loss of chemical and physical affinity between asphalt binders and aggregates. In order to evaluate the susceptibility of asphalt pavement to moisture damage, the chemical and physical affinity is measured using loose asphalt mixtures or compacted asphalt mixtures in field-simulated environments. Although some of the tests show results comparable with real field responses, these tests fail to address the structural complexities of asphalt mixtures. Furthermore, these tests provide little insight for the development of analytical analysis.

Exploratory studies at the University of Wisconsin-Madison have shown a good correlation between binder adhesion and cohesion testing results and moisture effects on asphalt mixtures as

measured by various tests such as the Hamburg wheel test and the tensile strength ratio (TSR). Recent work at the Texas A&M University has also indicated that surface energy measurements and the estimated adhesion and cohesion derived from these measurements can explain some of the moisture damage behavior observed in the laboratory.

This work plan will study the possible relationship between adhesion and cohesion measured directly using a Dynamic Shear Rheometer (DSR) device modified to include the mineral surface and the surface energy measurements collected with the Universal Sorption Device. The intent is to compare the effectiveness of each system and propose a simple and practical surrogate binder- specific test to evaluate affinity of binder (or mastic) to mineral aggregate surface. This study will be based on the use of simplified specimen geometries based on the DSR device and processed rock disks. Preliminary results using this newly developed moisture damage test have shown the applicability of the methodology to evaluate various testing conditions. Furthermore, the results will be correlated to data from the pull-off (PATTI) test which is the focus of another work plan conducted by the consortium. This work plan will also allow building on the progress achieved so far and extend the work to mastics and effects of fillers in general on moisture damage.

The main purpose of this work element is to find and evaluate physical/engineering correlations between mixture moisture damage test results with binder test results collected with the modified DSR procedure for different asphalt mixtures and mastics. In addition, new testing protocols for the evaluation the potential of moisture damage using the DSR will be proposed based on the results from the planned experimental tasks. This objective will be achieved by carrying out the sub-tasks discussed herein.

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

The data collected in this task will be shared with other consortium members to decide on a set of binders, fillers, and aggregates that will be used in this and other consortium work elements focused on moisture damage. It is expected that the materials will include at a minimum the following material parameters:

- 1) Asphalt binders:
 - a. Several PG grades: 58, 64, 70, and 76.
 - b. Base binders should be from two different sources
 - c. Modification methods; styrene-butadiene-styrene (SBS), terpolymer (Elvaloy), ethylene vinyl acetate (EVA), and chemical modification
- 2) Three different fillers: acidic (quartzite), basic (calcite), and neutral (such as Ottawa sand)
- 3) Aggregates:
 - a. Mineralogy: limestone (with two different moisture-susceptibility histories) and granite (with two different moisture-susceptibility histories)

- b. Angularity and gradation: one coarse aggregate and one fine aggregate with significant differences in their surface areas.
- 4) Conditioning water: distilled water, sodium chloride solution, and calcium chloride solution.

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)

In this task, the modified DSR device will be used. The testing system consists of composite sample of two cored rock disks (25 mm diameter and 5 mm thickness) sandwiched with asphalt binder (1 mm film thickness). The two disks are glued on the DSR metal spindle and the base metal plate respectively. A water cup circumscribing the composite sample is used to allow the sample to be submerged. Shear stress sweeps are then used to measure the change of rheological properties according to increased stress before and after conditioning with water. Results for selected combinations will be also compared to PATTI test results.

This test setup will be used to collect data for shear stress sweep at different times of conditioning, temperatures, and rates of loading. A wide range of combinations of materials based on the results of Task 1 will be included. The results will be analyzed in coordination with Texas A&M University research activities to verify that what is being measured is in fact explainable by fundamental surface energy measurements and that the conditions selected for measurements are effective in determining adhesive bond strength as well as cohesive strength.

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

Based on the results of Task 2, a reduced number of aggregates, binders, water conditioning parameters (time, temperature, media), and testing temperatures will be selected. A detailed work plan will be developed to test moisture damage resistance of mixtures, using the most recent protocol for TSR, or any newly developed moisture susceptibility test. A detailed literature review and phone interviews with researchers involved in developing mixture moisture damage tests will be conducted and tests will be selected accordingly.

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.

In this task, the relationships between the modified DSR test results and the mixture test results will be analyzed using statistical analysis as well as using the surface energy measurements. If meaningful correlations are found, modeling of the relationships will be pursued to give physical/engineering explanations to the correlations and to sort the important variables that should be considered in using asphalt–aggregate tests. In addition, the probability of success of a binder-specific test will be determined and compared to the probability of success of the selected mixture moisture damage test.

Subtask M1a-5: Propose a Novel Testing Protocol

Based on the results of Task 4, a final testing protocol will be developed. The cost of modification of DSR devices and the practicality of the test will be analyzed. Manufacturers of DSR devices in the US will be contacted to discuss possible commercialization of the test protocol. Also, selected State DOTs will be contacted to get feedback on the use of these tests. Based on collected feedback, a protocol will be developed in the AASHTO format.

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)

The work of adhesion between asphalt binder and aggregate computed using surface energy components is due to the physio-chemical interactions between these two materials. The presence of active functional groups or chemically active fillers in asphalt binders may also contribute to adhesion by the formation of chemical covalent bonds (Bhasin and Little 2006). The contribution of these reactions to the work of adhesion will be assessed in this sub task using a micro-calorimeter. The objective of this subtask will be achieved as follows:

- i) Determine surface energy components of modified and unmodified asphalt binders and model compounds that represent functional groups within the asphalt binder using the Wilhelmy plate device and/or sessile drop method (materials may overlap with subtask F1a-3).
- ii) Determine surface energy components of aggregates and representative pure minerals using the Universal Sorption Device (materials may overlap with subtask F1a-3).
- iii) Determine the total energy of adhesion between asphalt binders and aggregates using the micro-calorimeter.
- iv) Evaluate methods to determine work of adhesion from total energy of adhesion measured using the micro-calorimeter to eliminate the contribution of entropy.
- v) Compare total energy of adhesion versus work of adhesion due to surface free energy and quantify contribution of chemical bond formation to interfacial adhesion.

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

Thermodynamics and mechanical properties of asphalt binder adhering to aggregate surfaces compounded by the presence of water are directly related to the physico-chemical properties of each of these materials (asphalt, water, aggregate). To date still much is unknown regarding the processes of soft condensed matter wetting in terms of molecular orientation and phase ordering, that fall within the realm of surface entropic events, in even much simpler systems than the system considered here. Nano-technological methodologies, which include the wide range of scanning probe microscopy techniques, presently make it possible to investigate, at and near molecular scale, entropic events that may be crucial to adhesion in asphalt pavements compounded by moisture attack.

- i) Work elements for the present subtask will include investigation via AFM imaging and nano-mechanical techniques of thin-film materials of wet and dry oxidized asphalt binder, mastic samples damaged by freeze-thaw cycle experiments, and core samples, to de-convolute the entropic nature of adhesion mechanisms between asphalt and aggregate, polymer, filler, etc.
- ii) Coordinate with research focusing on the fundamental physical-chemical properties of both asphalt and aggregate, by such methods as flocculation titrimetry with an emphasis on hydrogen-bonding mechanisms, NMR imaging techniques to directly quantify asphalt-water interfacial surface free energy as a function of time and temperature, and characterization of the changes in functional composition of the asphalt binder of both wet and dry aged and unaged binder materials. This may include FTIR microscopy and advanced chromatographic techniques.

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

Thermodynamic descriptions of the work of adhesion between asphalt binders and aggregates are based on macroscopic properties of these materials. Work at TTI-WRI under funding administered by the FHWA has demonstrated that electrostatic interactions are small but important interactions that affect 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, hydrophobic interactions, organic hydrolysis reactions, and secondary precipitation reactions between inorganic salts and organic molecules.

Asphalt binders as well as aggregates are highly heterogeneous in terms of their chemical or mineralogical composition. Identification of the molecular mechanisms of interaction between specific organic functional groups and mineral surfaces will allow prediction of adhesion in heterogeneous materials through an additive mixing model. This sub task will investigate molecular mechanisms responsible for adhesion and debonding using pure representative minerals and model organic compounds (representing functional groups in asphalt binder). This research will couple spectroscopic characterization of water and organic bonding at the mineral and aggregate surface using sum frequency generation spectroscopy, infra-red and raman spectroscopy, and other microscopic and macroscopic tests. This information is extremely important in order to: i) provide tools 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 Element 1c: Quantifying Moisture Damage Using DMA

The Dynamic Mechanical Analyzer (DMA) provides a unique tool to quantify the impact of moisture damage in fine aggregate matrix (FAM) of asphalt mixtures. The fine aggregate matrix is comprised of binder, filler, and aggregate particles finer than #16 sieve. Several field studies and observations have shown that the fine portion of the mixture carries most of the resistance to moisture damage. This phase holds coarse aggregate particles together in an asphalt mixture. The DMA allows for the exclusive characterization of the FAM by eliminating the complex

interaction effects due to the heterogenous air void structure with coarse aggregate particles present in an asphalt mixture. However, since the FAM utilizes fine aggregates that represent mineralogy of coarse aggregates used in the whole asphalt mixture, the test procedure does consider the influence of mineral aggregate–binder interaction or stripping. The DMA will be used to quantitatively assess the relative impact of:

- i) work of adhesion,
- ii) work of cohesion, and
- iii) provide the rate of energy dissipation, which is an important parameter for the analytical model discussed in section F3c.1 of the fatigue work plan and section 2a of the moisture work plan.

Category M2: Cohesion

Work Element M2a: Work of Cohesion Based on Surface Energy

Work of cohesion based of asphalt binder or mastic is a fundamental material property that dictates the magnitude of work required for crack growth within the material. Previous research at the Texas A&M University has led to the development of test methods to determine the surface energy components of asphalt binders.

Moisture damage can occur due to disintegration of the adhesive bond between the asphalt binder and the aggregate as well as due to inherent deterioration in the mechanical properties of the asphalt binder or mastic due to the presence of water. It is important to determine the work of cohesion of asphalt binders or mastics, after the mastic or binder has been saturated with water. This work element will be addressed in the form of the following two subtasks:

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

Work of cohesion of asphalt binders is an important material property input for various analytical and micromechanics models. A pertinent question is; how the magnitude of this material property changes for an asphalt binder that is saturated with moisture and how its can be measured. The objective of this subtask will be to address this question. This will be achieved as follows:

- i) Conduct literature review to explore possible techniques to determine the work of cohesion for asphalt binders or mastics that have been saturated with water. The literature review will include methodologies used under similar conditions with polymers. Direct and indirect methods will be included in the review. The literature review will provide recommendation on the feasibility to make such measurements and interpretation of data from these methods.
- ii) Explore the possibility of using existing static (sessile drop) and dynamic test methods (Wilhelmy plate) to determine the surface free energy and work of cohesion for saturated asphalt binders or mastics. Investigate the limitations or considerations in using such a technique to derive the parameters of interest.

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

The thermodynamics and mechanical properties of asphalt binder and cohesive properties compounded by the presence of water are directly related to the physico-chemical properties. Just as with adhesion, cohesive processes of molecular orientation and phase ordering in the native binder fall within the realm of entropic events.

- i) Work elements for the present subtask will include investigation of thin-film materials of wet and dry oxidized asphalt binder, via AFM imaging and nano-mechanical techniques. The emphasis will be on AFM force-distance analysis employing chemically functionalized cantilever tips to investigate components of surface free energy, spin coating techniques to investigate dynamic wetting based on lubrication theory, and micro/nano-contact mechanics approaches based on scanning probe technologies.
- ii) Again, coordination with research of investigation of the fundamental physical-chemical properties, with the emphasis on the asphalt binder, by such methods as flocculation titrimetry with an emphasis on hydrogen-bonding mechanisms, NMR imaging techniques to directly quantify asphalt-water interfacial surface free energy as a function of time and temperature, and characterization of changes in functional composition of the asphalt binder of both wet and dry aged and unaged materials based on spectroscopic techniques including FTIR microscopy.

Work Element M2b: Impact of Moisture Diffusion in Asphalt Mixtures

Principles of thermodynamics determine the equilibrium state and the potential difference between the current and equilibrium state that drives moisture damage in asphalt mixtures. However, in order to combine environmental conditions and external loads into a model used to predict realistic pavement responses, it is imperative to include kinetics of moisture damage in addition to these thermodynamic quantities. The following three components dictate the time required for moisture to cause debonding under given environmental (boundary) conditions: i) flow and retention of moisture in the pavement structure, which is governed by the void structure of the mixture; ii) diffusion of moisture from voids to aggregate-binder interfaces, which is governed by the diffusivity rates of the binder or mastic films; and iii) debonding of aggregate-binder interface, which is governed by the thermodynamic potential and kinetic rate constants at the interface. The various subtasks within this work element will be designed to formulate the three components listed above into a form that can be implemented in a numerical scheme to simulate moisture damage in asphalt mixtures under any given environmental boundary conditions and loads.

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

Diffusion of moisture through air voids, asphalt binder or mastics is an important rate controlling phenomenon in the moisture damage process. There is a lack of repeatable and reliable methods for measuring this important property. This subtask will develop experimental methods to measure moisture diffusion in asphalt mixtures and their constituents. The following steps will be carried out in this subtask:

- i) Identify and develop test methods to measure diffusion of moisture through asphalt binder / mastic films and asphalt mixtures. Based on the previous experience, the use of psychrometers to measure relative humidity (or suction) appears to be a very good candidate.
- ii) Determine diffusivity of different types of asphalt binders and mastics. Analytical techniques such as Fourier Transform Infra-Red (FTIR) have been used in the past to determine the rate which water displaces the asphalt binder from its interface with the standardized surfaces (Nguyen et al. 1996). The attenuated total reflectance (ATR) is a technique for using the FTIR that allows the interface to be subjected to a variety of boundary conditions. Using different controlled thickness of asphalt binder films or mastics, one can determine the rate of diffusion of moisture through the binder or mastic films.
- iii) Determine the absorption-desorption-absorption rates for different asphalt binders. In other words, determine the diffusivity of the asphalt binder after subjecting it to one or more cycles of absorption and desorption. The hypothesis here is that, diffusivity rates of dry asphalt film are significantly smaller than diffusivity rates of an asphalt film that has been subjected to one full cycle of moisture absorption and desorption. The ATR-FTIR technique, as described in (ii) above will be used to make these measurements.
- iv) Determine the effect of pore pressure on the diffusivity rates for asphalt binders / mastics. Action of external loads can induce pore pressure in entrapped water, especially if the mixture is in the pessimum void structure range. This pore pressure due to external loads can accelerate diffusion of the moisture through the binder or mastic film. For the binder and mastic films, the ATR-FTIR technique as described in (ii) above will be used to make these measurements. Due to equipment limitation, the magnitude of water pressure that can be allowed on the binder or mastic film might not be equivalent to that of the pressure exerted due to wheel loads on the pavement. However, within certain limits, the impact of pore pressure on the diffusivity constants of the binder or mastic can be easily estimated using this test technique.

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

This subtask will evaluate factors that influence kinetics or rate of debonding after moisture is at the aggregate-binder interface. This subtask is to verify the hypothesis that once water is at the binder-aggregate interface, the rate of debonding is mostly influenced by the thermodynamic potential for water to cause debonding (determined using surface energy components) and micro texture of the aggregate surface. This will be accomplished as follows:

- i) Determine and compare rate of debonding for different binder-aggregate interfaces as a function of the thermodynamic potential for moisture damage determined using surface energy components. The aggregate surfaces will be prepared to have uniform roughness.
- ii) Determine influence of aggregate surface texture or specific surface area (sub micron scale) on the rate of debonding for different binder-aggregate interfaces.

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

In order to evaluate the susceptibility of moisture damage within asphalt pavements, the chemical and/or physical affinity is commonly measured with loose asphalt mixtures or compacted asphalt mixtures in a field-simulated environment. Although some of these tests show results comparable with real field data, the actual mechanism of moisture damage and the role of components in the failure response cannot be sorted from these tests. Therefore, there is significant room for improvement, mainly because of the structural complexity of asphalt mixtures and the confounding effects that result from it. The difficulty of accurately measuring the role of the various variables (e.g., binder cohesion, adhesive bond, airvoids, aggregate surface characteristics and shape, etc.) makes an analytical approach for selecting materials that will resist moisture damage very complex. The use of simplified testing systems that can separate the contribution of different components under the effect of water could provide a more effective method for moisture damage analysis and prediction of damage risk. Among the many ideas proposed in the last 10 years two systems show the greatest potential for satisfying the simple analytical approach criteria. One is the Pneumatic Adhesion Tensile Testing Instrument (PATTI) and the other is the testing procedure developed using a Dynamic Shear Rheometer (DSR) to measure cohesive strength (Cho and Bahia 2007).

The PATTI device was initially developed by the National Institute of Standards and Technology (NIST) and was utilized by Youtcheff and Aurilio (1997) at FHWA to evaluate the adhesive loss of asphalt-aggregate systems exposed to water. The PATTI device is advantageous for several reasons: it allows the use of aggregate surface, the sample specimen is conditioned in water after applying asphalt between the pull stub and aggregate surface, and it allows one to observe the failure surface to define adhesive versus cohesive failure. In addition, the device is low-cost, simple, and well described by an ASTM standard. The PATTI device and methodology are therefore considered as a good testing procedure for measuring moisture damage properties of binders.

The DSR thin film cohesion test was developed more recently based on concepts widely used in paint and adhesive fields (reference). The main advantage of using the DSR test is the very precise control of factors such as temperature, film thickness, and rate of loading. The DSR test allows precise measurements of time-based responses such as load, deflection, and rheological properties. The DSR test also permits the application of different loading paths (e.g., shearing and uniaxial loading). The initial testing data show the potential of the methodology for measuring factors affecting moisture damage for a wide variety of testing conditions. For example by combining different aggregate-made discs and varying the binder film thickness, we will be able to gain more insight on the binder's cohesive properties and aggregate-binder adhesive responses.

Moisture damage is also affected by polymer modification. Using these new measurement systems, modified asphalt cements have shown to have better cohesion and adhesion properties than their non-modified counterparts. Better understanding of the influence of different types of polymer modifiers on the binder's cohesion properties, as well as the interaction with mineral surfaces of the different chemical modifiers is desired. This better understanding will help

develop enhanced testing methods and the selection of procedures for improving the resistance to moisture damage of pavements.

Moisture damage is also known to be affected by mineral fillers. The effect of fillers on moisture damage has not been explored carefully. Mineral filler constitute a major portion of the surface area of the binder- mineral aggregate interface. These two systems are suitable for testing cohesion and adhesion of mastics and thus could give some specific insight of effects of fillers.

This work element includes objectives focused on the PATTI and DSR thin film rheology test. It is expected that both of these systems will be evaluated to define factors that have significant effect on responses:

- Modification of the pull-off test (PATTI) to allow one to measure load and deflection and control film thickness. The cost and practicality of the modification as well as the precisions will be evaluated.
- Further development of the DSR thin film test by evaluating the following factors:
 1. The effect of different pulling rates on the PATTI and DSR responses.
 2. The testing temperature plays an important role in adhesion and cohesion. The effects of testing temperature on the results will be quantified and used to define role of climate on moisture damage. The testing temperature will also help in establishing relationships between different mixture testing temperatures.
 3. Changing loading frequencies in the shear mode will have an important effect on the cohesion and adhesion test results and it will better simulate different traffic speed.
 4. The temperature during the water conditioning plays an important role in effect of water on cohesion and adhesion of binder or mastic.

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

The pull-off test is a simple and efficient way to investigate the combined effect of cohesion and adhesion properties of binders and changes due to moisture effects. However the test in its current format is not able to produce stress-strain curves. It measures maximum pressure which can only be used as an index. This task will focus on evaluating the possibility of modifying the pull-off test so that it would produce load vs. deflection responses. This modification will enable the calculation of the total energy to failure and the study of how the failure process by identifying trends in the behavior of the binder during loading. The differentiation between cohesive and adhesive failure will also be studied. A consideration of a metal or glass surface that allows full adhesion could be used to measure cohesion. The dry and wet testing on aggregate surfaces could be used to study effects of aggregate interactions with or without water conditioning.

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

Modified binders will be prepared using different “base” virgin and modifiers. Each “base” binder will be modified using the selected chemical additives. Preliminary testing at the selected conditions will be conducted in this task. The results will validate the applicability of the test methods to modified asphalts and their effectiveness in measuring the contribution of modifiers in the cohesive behavior of binders. The results will lead to the selection of a reduced number of combinations to be tested in Sub-Task 2c-3.

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

Selected samples of the modified and unmodified binders tested in sub-task 2c-2 will be tested using the DSR instrument. This testing will be used to validate the results from the modified PATTI test and to indicate which modification is necessary and which is not to measure important in the evaluation of binder cohesion and aggregate- binder adhesion behavior. The tests will be structured to investigate the influence of the temperature of testing, the conditioning temperature, and the pulling rate. Also the comparison between the axial pull-off testing and shear stress sweep will be included in the testing.

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

The same testing protocol used for testing binders will also be used for the testing of selected mastics. The results will identify suitability of the test systems to binder-filler mastics.

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

The increase in cost of the PATI device and the information gained by the modification will be analyzed to make a recommendation regarding the use of the test for studying thin film cohesion and affinity of binders and mastics to aggregates. In this task, manufacturers of the PATTI device will be contacted to explore the cost and commercialization possibilities the modified PATTI test. State DOTs and consulting labs will be contacted to collect feedback about the practicality of the test system and the merits of standardizing the modified PATTI test for the evaluation of binder cohesion and aggregate-binder adhesion. Presentations at the binder and mixture ETGs will be prepared and delivered to collect feedback from experts. The feedback will be summarized and used to make modifications in the developed system.

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

The objective of this task is to analyze experimental data and evaluate the responses collected during the various tasks to make recommendations regarding the modified PATTI test and its applicability to moisture damage of asphalt mixtures. The results of binder and mastic will be shared with other work elements to evaluate the relationship to surface energy and the results of the Sorption Device.

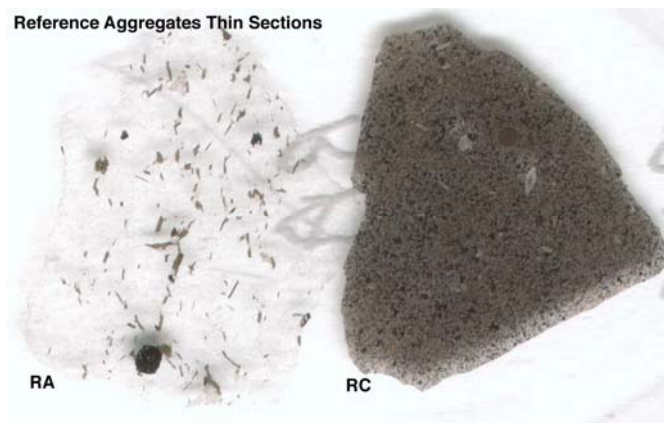
Category M3: Aggregate Surface

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

Physical and chemical properties of aggregates at the macro and micro 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 (Table 1). The image to the right shows thin sections of two common aggregates. The images clearly show the mineralogical heterogeneity of the 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	$Ca_{(0.5-0.7)}Na_{(0.3-0.5)}(Al,Si)AlSi_2O_8$	
Andesine	Plagioclase Feldspar ¹	$Na_{(0.5-0.7)}Ca_{(0.3-0.5)}(Al,Si)AlSi_2O_8$	Dominant feldspar in andesite, an igneous rocks. Minor component in granite and metamorphic rocks.

Olivine ²	Nesosilicates	(Mg,Fe) ₂ SiO 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) ₂ O 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) ₈ O 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 ₃ O 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 NaAlSi₃O₈, Albite to pure CaAl₂Si₂O₈, 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.

Our task will be to characterize the chemical properties of representative minerals given in Table 1 using elemental mapping by electron microprobe, backscatter electron spectroscopy and X-ray dispersive spectroscopy

Steps involved in the detailed characterization of the aggregates:

- i) 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.

- ii) 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:

- specific surface area for different size fractions,
- major mineralogical composition,
- chemical composition (major oxide) of minerals, and
- concentration of water and acid solubles.

Results from this task will also be extremely useful to explain mechanisms from other tasks such as effect of binder aging on the properties of the binder-aggregate interface.

Category M4: Modeling

The modeling efforts and approaches will be similar to those discussed in the fatigue work plan. These approaches are summarized here for completeness.

Work Element M4a: Micromechanics Model

Similar to the fatigue work plan, it is envisioned that the lattice and cohesive zone models will be the primary methods to develop the micromechanical analysis framework. The asphalt mix microstructure will be captured using X-ray CT imaging at multiple resolutions. The measured material properties with the influence of moisture (adhesive and cohesive bonds, viscoelastic properties) will be assigned to the various constituents of the microstructure. However, upscaling methods need to be applied in order to transfer the experimental measurements conducted at various scales to the model scale and resolution.

Work Element M4b: Analytical Fatigue Model for Mixture Design

The same fracture model developed for fatigue will be used here. The main difference is that the model will include parameters that are obtained from testing specimens subjected to moisture conditioning. The model accounts for the energy dissipated in fracture, energy dissipated in permanent deformation, physio-chemical properties of mixture (adhesive and cohesive bonds), and viscoelastic properties (Masad et al. 2006). This model can also be used to analyze experimental measurements conducted on the mastic and fine portions of the mix using the

dynamic mechanical analysis and on full mixtures using repeated loading. As discussed in the fatigue work plan, the testing protocols will be developed under work element F2b and F2c. In the Moisture work plan, we will develop the methods for moisture conditioning of mastic, FAM and mixture specimens.

Work Element M4c: Unified Continuum Model

The unified continuum model described in the fatigue plan will be further developed in order to account for the effects of moisture. This will be achieved by solving the coupling between the fluid flow equations and the constitutive equations that govern the mixture mechanical behavior. The fluid flow equations are solved to determine the moisture distribution within the mixture. The constitutive equations will be solved to determine the mechanical behavior given the moisture present in the mixture.

Moisture will be treated as an external variable that influences the evolution of the model's parameters and functions. The model yield surface will evolve as a function that combines stresses (hydrostatic and deviatoric) and moisture content. All the model parameters will be determined by testing specimens after moisture conditioning. This approach is similar to developments in geo-environmental studies that account for the coupling between the concentration of chemicals and the constitutive behavior of geomaterials. The presence of moisture in asphalt mixtures will be modeled analogous to the presence of chemicals in geomaterials.

The basics for developing the continuum model with the effect of moisture are documented in the literature. In the past few years, considerable developments have been achieved in coupling the chemical reactions with the performance of geomaterials (Hueckel 2002). In the asphalt pavement area, researchers have developed numerical models for the simulation of fluid flow in the asphalt mixture microstructure (Al-Omari and Masad 2004 and Kutay et al. 2007). The researchers at Delft have made significant advances in developing a model that couples the fluid flow equations with the constitutive equations governing the mechanical behavior (Kringos and Scarpas 2005 and 2006). The processes that are considered in the Delft model are summarized in Table 2. This work element will build on recent advances by focusing on making the improvements listed in Table 3.

Table 2. Processes simulated in the model of moisture damage of Kringos and Scarpas (2005 and 2006).

Damage process	Description	Comments
Desorption of the mastic (process 1)	Loss of mastic that is washed away by a non-stationary flow (advective flow). The process occurs in a short timescale and affects the outer layers of the binder that surround the aggregates.	Macroscopic phenomenon. Advective transport will not occur without flow.
Dispersion of the mastic (advective dispersion) (process 2)	Deterioration in the material's cohesive bond (loss of concentration or dispersion) caused by moisture diffusion into mastic. The process occurs on a long timescale.	Microscopic phenomenon. Requires the presence of a water flow field although the process is dominated by the diffusion coefficients of the material.
Deterioration of the aggregate-binder interface (process 3)	Long term process due to a combined effect of moisture diffusion and mechanical loading.	Microscopic phenomenon. An energy-based model was developed to include moisture content as a control parameter.

Table 3. Accomplishments of the current model and future work.

Accomplishments	Future work
Mathematical formulation of fluid flow in asphalt mixtures using two different methodologies	Calibrate current models.
Mathematical formulation of three important processes related to moisture damage	Include more complex and realistic geometry.
Successful numerical implementation of aforementioned processes	Include pore pressure and any other relevant effects.
Simulation of damage with a mechanical and thermodynamic coupled model	Analyze moisture damage processes in different types of mixtures.
Better understanding of moisture damage mechanisms in open graded friction courses	Analyze the validity of the current damage evolution law and consider new formulations for coupling micro- or mesodamage with macrodamage. Determine the relevance of material properties in terms of the time required for the manifestation of damage.

Category M5: Moisture Damage Prediction System

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

This task will develop a moisture damage prediction system that will consist of the following components:

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

YEAR 1 PROJECT DIRECTION

The focus of year 1 will be to:

- Evaluate mechanical tests (PATTI test and DSR) to determine the affinity of asphalt binders for aggregates.
- Evaluate thermodynamic tests (surface free energy and micro calorimeter) to determine material properties and affinity of asphalt binders for aggregates.
- Develop test methods to determine the rates of diffusion of moisture through asphalt binder and mastic films as well as through asphalt concrete mixtures.
- Evaluate the use of PATTI test to assess thin film rheology of unmodified and modified asphalt binders.
- Conduct thorough mineralogical and chemical characterization of aggregates that will be used in the consortium research.

SCHEDULE

		Year 1	Year 2	Year 3	Year 4	Year 5
M1a	Affinity of Asphalt to Aggregate - Mechanical Tests	X	X	X	X	
	1a-1 Use of modified DSR and PATTI tests	x	x			
	1a-2 Evaluate moisture damage of asphalt mixtures	x	x	x	x	
	1a-3 Compare moisture damage from 1a-1 and 1a-2		x	x	x	
	1a-4 Propose a novel test protocol			x	x	
M1b	Work of Adhesion	X	X	X	X	X
	1b-1 Adhesion using Micro calorimeter and SFE	x	x	x	x	x
	1b-2 Evaluating adhesion at nano scale using AFM		x	x	x	x
	1b-3 Mechanisms of water-organic molecule competition	x	x	x	x	x
M1c	Quantifying Moisture Damage Using DMA		X	X	X	X
M2a	Work of Cohesion Based on Surface Energy	X	X	X	X	X
	2a-1 Methods to determine SFE of saturated binders	x	x	x		
	2a-2 Evaluating cohesion at nano scale using AFM		x	x	x	x
M2b	Impact of Moisture Diffusion in Asphalt	X	X	X	X	
	2b-1 Diffusion of moisture through asphalt/mastic films	x	x	x		
	2b-2 Kinetics of debonding at binder-aggregate interface		x	x	x	
M2c	Thin Film Rheology and Cohesion	X	X	X	X	
	2c-1 Evaluate measurements from PATTI test	x	x			
	2c-2 Evaluate PATTI test to detect effect of modifications	x	x	x		
	2c-3 Validating PATTI test based on results from DSR		x	x		
	2c-4 Mastic testing using PATTI and DSR tests			x	x	
	2c-5 Practicality evaluation of modified PATTI test			x	x	
	2c-6 Recommendations for modified PATTI test				x	
M3a	Impact of Surface Structure of Aggregate	X	X	X		
	3a-1 Aggregate surface characterization	x	x	x		
M4a	Development of Model		X	X	X	X
	4a-1 Micromechanics model development		x	x	x	x
	4a-2 Analytical fatigue model for use during mixture design		x	x	x	x
	4a-3 Unified continuum model			x	x	x
M5a	Moisture Damage Prediction System				X	X

RELATIONSHIP TO FHWA FOCUS AREAS

The moisture damage work elements support the FHWA Focus Area of Optimizing Pavement Performance by providing a relationship between material property and pavement performance.

BUDGET

		Year 1	Year 2	Year 3	Year 4	Year 5
M1a	Affinity of Asphalt to Aggregate - Mechanical Tests (UWM)	75,000	75,000	75,000	75,000	
M1b	Work of Adhesion (TAMU)	75,000	75,000	50,000	50,000	25,000
	Work of Adhesion (WRI)		134,500	146,000	152,500	126,500
M1c	Quantifying Moisture Damage Using DMA (TAMU)		75,000	75,000	100,000	75,000
M2a	Work of Cohesion Based on Surface Energy (TAMU)	75,000	75,000	75,000		
	Work of Cohesion Based on Surface Energy (WRI)		134,500	146,000	152,500	126,500
M2b	Impact of Moisture Diffusion in Asphalt (TAMU)	75,000	150,000	150,000	175,000	
M2c	Thin Film Rheology and Cohesion (UWM)	75,000	100,000	75,000	75,000	
M3a	Impact of Surface Structure of Aggregate (TAMU)	75,000	100,000	125,000		
M4a	Development of Model (TAMU)		125,000	125,000	125,000	150,000
M5a	Moisture Damage Prediction System*				150,000	150,000
TOTAL		450,000	1,044,000	1,042,000	1,055,000	653,000
		4,244,500				

Note* Tentatively only budget from TAMU is reflected here but this element will involve coordination from all agencies.

REFERENCES

Al-Omari, A., and E. Masad (2004). "Three Dimensional Simulation of Fluid Flow in X-ray CT Images of Porous Media," *International Journal for Numerical and Analytical Methods in Geomechanics*, Vol. 28, pp. 1327-1360.

Bhasin, A., and D. N. Little (2006). "Application of Micro-Calorimeter to Characterize Adhesion Between Asphalt Binders and Aggregates." *Journal of Materials in Civil Engineering*, In Review.

Hueckel, T. (2002). "Reactive Plasticity for Clays during Dehydration and Rehydration. Part I: Concepts and Options", *International Journal of Plasticity*, Vol. 18, No. 3, pp. 281-312.

Kringos, N., and N. Scarpas (2005a). Raveling of Asphaltic Mixes Due to Water Damage: Computational Identification of Controlling Parameters. *Transportation Research Record*, 1929, 79-87.

Kringos, N., and A. Scarpas (2006). Numerical Simulation of the Physical Processes Inducing Moisture Damage in Asphaltic Mixtures. *in 10th International Conference on Asphalt Pavements (ICAP)*, Quebec, Canada, 732-741.

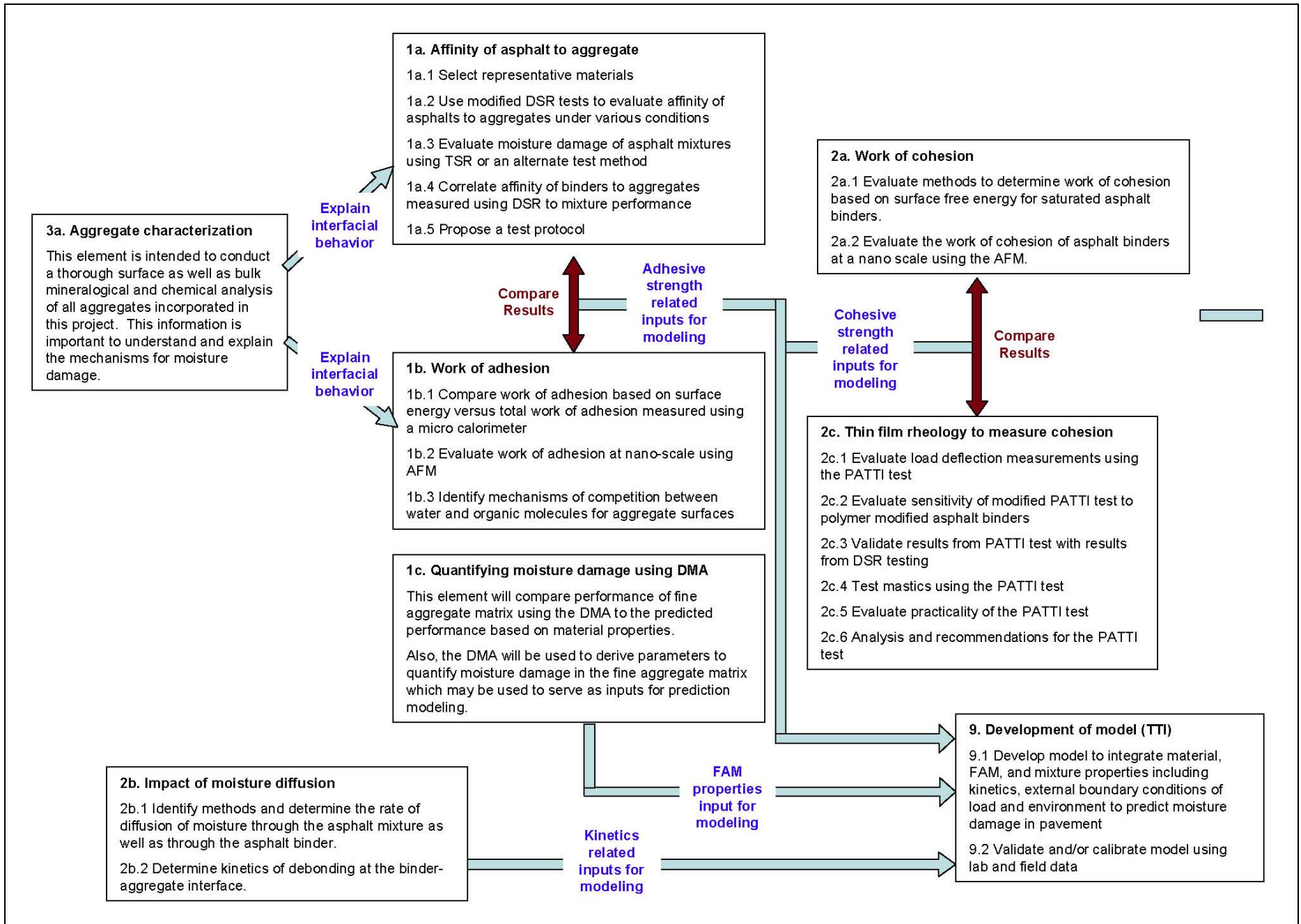
Kutay, E. M., M. Aydilek, E. Masad, and T. Harman (2007). "Evaluation of Hydraulic Conductivity Anisotropy in Asphalt Specimens." *International Journal of Pavement Engineering*. Vol. 8, No. 1, pp. 29-43.

Masad, E., C. Zollinger, R. Bulut, D. Little, and R. Lytton (2006). "Characterization of HMA Moisture Damage Using Surface Energy and Fracture Properties." *Journal of the Association of Asphalt Paving Technologists*, Vol. 75, pp. 713-748.

Nguyen, T., E. Byrd, D. Bentz, and J. Seiler (1996). "Development of a Method for Measuring Water-Stripping Resistance of Asphalt/Siliceous Aggregate Mixtures." NISTIR 5865, National Institute of Standards and Technology, Gaithersburg, MD.

Appendix M1

Flow Chart Illustrating Integration of Elements for Moisture Damage Work Area



PROGRAM AREA: FATIGUE

INTRODUCTION

The Fatigue Process

Fatigue damage is normally defined as incremental damage that occurs gradually in the pavement due to stresses induced by traffic loading. The fatigue cracking mechanism can be divided into two stages: initiation of cracks of sufficient length to grow under repeated loading and propagation of these cracks due to repeated loading. When a sufficient number of cracks develop within a wheel path, severe distress results and pavements quickly lose serviceability. However, fatigue may also manifest as permanent deformation or rutting in the wheel path. Such permanent deformation is traditionally considered to be due to plastic flow, but it can also be the result of weakening of the mixture due to a concentration of small cracks caused by a fatigue process. Researchers in the asphalt research consortium consider both of these mechanisms to be part of the fatigue process. We also consider recovery during rest periods to be part of the fatigue process, or that the fatigue process is actually a balance between crack propagation on the one hand and healing on the other. Healing is quantified by the recovery of the mechanical ability of a material to store and release fracture energy and the result of healing is extended fatigue life. The reality and significance of the impact of healing during rest periods has been proven in previous WRI-directed research and is now well established in the literature by some of the most respected research entities in the world.

Complicating the fatigue process is the changing nature of the binder over time due to oxidative hardening in pavements. Evidence is mounting that binders oxidize in pavements, even well below the surface. This oxidation reduces healing, reduces stress relaxation of the binder, and increases binder stiffness. These combined material property changes result in a binder that is more susceptible to fatigue, a hypothesis that has been confirmed by laboratory mixture tests.

Research Needed to Better Understand and Evaluate Fatigue Damage

Historically fatigue damage has been quantified in the laboratory as the number of load cycles applied to a specimen that causes the specimen to fail due to crack growth. Such fatigue tests normally either apply the same level of stress at each load cycle (controlled-stress) or apply the same level of strain at each load cycle (controlled-strain). The consensus among materials and pavement engineers has been that thick, stiff pavements should be tested in a controlled-stress mode, while thin pavements should be tested in a controlled-strain mode. The results of these tests are hard to compare simply based on the number of cycles to failure. A pressing need has been to develop a unified method, based on sound mechanics, to evaluate both modes of fatigue testing. In addition to the mode of introducing load in a fatigue experiment, several other factors impact the fatigue damage characteristics of asphalt mixtures. These include adhesive and cohesive bond strengths within the mixture, anisotropy of the aggregate matrix, composition of the mastic portion (including interaction between mineral filler and asphalt), aging, and the ability of the mixture to recover during rest periods (healing). The WRI and Texas A&M research teams have demonstrated the importance of adhesive and cohesive bond strengths in the

fatigue process. Further, they have developed protocols to measure surface energies of the mixture components (binder and aggregate) from which bond strengths can be reliably calculated.

Recent work at Texas A&M has demonstrated that a unified model based on dissipated pseudo strain energy and fracture mechanics and including bond strength can indeed unify the stress-controlled and strain-controlled modes of loading. A first generation version of this approach has been developed and reported as a deliverable of research at Texas A&M under the recently completed WRI-led contract with FHWA (DTFH61-99C-00022). This approach is based on separating the dissipated pseudo strain energy measured during cyclic, torsional fatigue testing into the components associated with permanent deformation, change in the phase angle, and changes in stiffness among load cycles. It is critically important to finalize this analysis methodology and to validate the efficacy of this approach.

Work at Texas A&M has demonstrated that well-dispersed fillers (aggregate smaller than about 75 μm) substantially affect the growth of microcracks and that the effect of the fillers is determined by their mineralogy and physical properties. Healing during rest periods has a profound impact on fatigue life and also impacts the potential for mixtures to exhibit an endurance limit. Research at Texas A&M has shown that the healing process is related to the filler properties of the mastic and the adhesive and cohesive bond strengths of the mixture. This work needs to be completed and expanded.

Of course, when studying the fatigue damage process, it is absolutely necessary to consider the impact of moisture. Moisture affects the cohesive strength of the mastic as well as the bond strength between the asphalt binder and/or mastic and the aggregate particles. The ability to measure surface energy and to calculate cohesive and adhesive bond strengths (dry and in the presence of moisture) has provided a tool by which to scientifically investigate the effects of moisture on fatigue. We will focus on the asphalt -aggregate interaction as it affects the fatigue process, dry and in the presence of moisture. We will also focus on the impact of moisture on the cohesive bond strength of the mastic.

This research must remain focused on the deliverables that the Consortium is committed to provide. In the area of fatigue, the Consortium is committed to provide tools capable of assessing the fatigue damage process and of identifying specific factors that influence fatigue damage, i.e., aggregate properties, binder properties, mixture volumetrics, presence of moisture, filler type, etc. We are committed to developing and delivering predictive models that rely on the fundamentals of integrated fracture mechanics, micromechanics, and elasto-visco-plastic continuum damage mechanics. We are also committed to developing the most promising characterization tools into ASTM and AASHTO type specifications. One such tool that continues to surface as an excellent method by which to assess fatigue damage potential, the impact of rest periods, the impact of moisture, and the impact of fillers is dynamic mechanical analysis (DMA). Our goal is to develop this into a guideline type specification test in the second year of the grant.

Other tests that have been proven to be useful in characterizing the bond strength in asphalt mixtures are the Wilhelmy plate, universal sorption device, sessile drop apparatus and the micro-

calorimeter. We will continue to develop these test methods in order to deliver practical and easy-to-use test methods that can be integrated into the routine analysis of asphalts and aggregates. We will work closely with FHWA in order to determine the relationship between bond energy and compliance calculations and more direct measurements of bond strength such as the pull-off test being developed at FHWA.

In this research, we will utilize the most recent technologies in imaging and nondestructive evaluation to understand the mechanisms of crack initiation and propagation in asphalt mastics and mixtures. In recent years, the research at Texas A&M has made significant strides in nondestructively measuring crack distribution and evolution in asphalt mixes using X-ray Computed Tomography and image analysis techniques. These measurements will be used in our efforts to validate the models that will be developed by the Consortium.

HYPOTHESES

Fatigue damage is the result of the growth of small cracks and voids to form larger cracks that result in damage. The initiation of cracks to a critical size and the propagation of these larger cracks can be successfully explained and evaluated based on the principles of viscoelasticity and viscoplasticity, dissipated pseudo strain energy, micromechanics, and fracture mechanics. A unified model of fatigue damage must be based on sound principles of mechanics and pertinent materials characteristics and must also consider adhesive and cohesive bond strengths of the mixture, the ability of the mixture to heal or recover damage between load cycles, the impact of the mixture's internal structure on stress distribution within the mixture, and the impact of moisture on mixture properties and the rate of damage and healing in the composite mixture, including the changes in all of these properties with oxidative aging. The damage model should be able to predict fatigue damage from the material properties discussed above and from the dissipated pseudo strain energy measurements derived from fatigue experiments whether they are performed in the controlled-stress or controlled-strain mode of loading.

OBJECTIVES

1. Develop a fundamental understanding of the material properties and mechanics associated with fatigue.
2. Develop a unified fatigue damage model that incorporates and integrates the important mixture properties and responses that affect fatigue life. These properties and responses include cohesive and adhesive bond strengths, viscoelastic properties, fracture properties, energy dissipation, cohesive and adhesive bond strengths, healing and/or recovery during rest periods, effect of binder aging, and the internal structure of the mixture composite. The unified model will be capable of evaluating fatigue when loading is applied in either the controlled-stress or controlled-strain mode.
3. Assess the impact of modification and aging on the binder and mastic and the impact of filler type and quantity on the mastic and/or fine aggregate matrix using the unified model.

4. Develop testing protocols for mixture, mastic, and binder characterization that provide the information required in the unified model for binder, fillers, mastic, and the total composite mixture.
5. Implement the unified fatigue damage model by integrating it into a numerical scheme to assess the fatigue behavior of mixtures under different laboratory and field boundary conditions.
6. Develop micromechanical models that are based on fundamental material properties and can be used to study the interaction among the mixture constituents and their influence on mixture performance. These micromechanical models will be used to relate the parameters of the unified fatigue model to material properties.
7. Verify the unified model using microstructural measurements of fatigue damage by monitoring crack evolution through such non-destructive techniques as computer-assisted x-ray tomography.
8. Validate the unified model and testing methods through comparisons of predictions made based on the model and full scale field testing and evaluation of pavement test sites.
9. Develop component selection guidelines for perpetual pavements based on the unified approach.

These objectives will be achieved in coordination with other research activities on similar topics. Specifically, our research will be coordinated among all members of the Consortium, with other ongoing activities at the Federal Highway Administration (FHWA), LCPC in France, University of Nottingham in Britain, and Delft University in the Netherlands.

Our proposed research plan will complement and be coordinated with the current work at FHWA. The results from the accelerated loading facility (ALF) of the FHWA will be extremely useful to our validation efforts. This is a well controlled experiment with different modified and unmodified binders and different pavement structures. Furthermore, the advances made by the FHWA on binder characterization will be very useful for our research. The FHWA has shown that the binder behavior is highly nonlinear and the differentiation among asphalt binders can only be accomplished through considering the influence of stress level on response. Our fatigue modeling framework considers the nonlinear response of asphalt binders and mixtures among other important factors such as aging and healing effects. Our modeling approach is applicable to asphalt binders, asphalt mastics, and mixtures. Therefore, we plan to develop testing protocols for these materials. Specifically, we will focus on the development of a simple method for the characterization of binder fatigue resistance. This method needs to be simple, efficient, and capable of being implemented into binder specifications. This is necessary given the shortcomings of the current Superpave system in properly characterizing asphalt binders. We strongly believe that the concepts that have already been developed for characterizing fatigue in asphalt mixtures can be adopted, with proper modifications, to characterize binder fatigue resistance.

EXPERIMENTAL DESIGN

Although it is premature at this point to propose an exact experimental design, the development of an experimental design will be among the initial subtasks of each work element. The experiment design will be communicated to the AOTR before the work is begun, and each experimental design or plan will be approved and/or developed by the project statistician, who is in our case Dr. E. S. Park of the Department of Statistics at Texas A&M. Dr. Park has a research appointment with TTI and is very familiar with the design of experiments in asphalt related research. She has served as team statistician on several asphalt related research projects including NCHRP Project 9-37, “Using Surface Energy Measurements to Select Materials for Asphalt Mixtures”.

The TTI team will use the Buckingham PI theorem of experiment design to identify dimensional ratios of material properties to minimize the size of the experiment and maximize the information to be obtained from them. This approach was used successfully in many fields of mechanics such as fluid flow and aerodynamics.

WORK ELEMENTS

Category F1: Material and Mixture Properties

The work on this category will focus on determining material properties that are needed for the development of the unified model and micromechanics models.

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)

Adhesive and cohesive bond strengths are fundamental material properties that can be used to model crack growth in asphalt materials both in wet as well as dry conditions. Work of adhesion between the asphalt binder and the aggregate and the work of cohesion of the asphalt binders can be determined using their individual surface energy components. Initial studies conducted under the FHWA contract DTFH61-99-C-00022 (Fundamental Properties of Asphalts and Modified Asphalts) demonstrated the feasibility of using this approach to model fatigue crack growth in asphalt mixtures. In a recently completed NCHRP project 9-37 (Little and Bhasin 2006) test protocols to determine surface free energy components of asphalt binders and aggregates were developed. The project results also included parameters based on surface energy measurements that may be used to select combinations of materials that are more resistant to moisture damage. The impact of modification due to aging, addition of fillers, addition of polymers, and/or chemical additives on the work of cohesion or adhesion was addressed in limited detail in these and other previous studies. There is a need to critically review the existing methods with respect to determining viscoelastic properties and work of adhesion or cohesion for use with modified asphalt binders.

There is a difference between the magnitudes of work of adhesion or cohesion computed using the thermodynamics approach (surface energy) versus these quantities determined using mechanical tests. Existing literature provides detailed information on the various sources of this difference for elastic as well as viscoelastic materials. Examples of sources for this difference are energy dissipation due to plastic deformation and branching and coalescence of microcracks (Sharon et al. 1996). It is important to review and reconcile the source of these differences in order to improve the fatigue crack growth model for asphalt mixtures.

In summary, the literature review conducted in this task will cover the following areas relevant to the cohesive and adhesive bond strengths of materials:

- i) Need for revision and/or improvement of existing methods to determine work of adhesion and cohesion for modified asphalt binders and recommendations for changes or improvements that may be required.
- ii) Experimental and analytical methods to determine the work of cohesion or adhesion using mechanical tests, including approaches based on contact mechanics.
- iii) Sources of differences between thermodynamic work of adhesion or cohesion and mechanical work of adhesion or cohesion, and methods to account for these differences.
- iv) Acid-base scale to determine the surface free energy components of asphalt binders and aggregates and use of an alternate scale that may improve the sensitivity of the measured surface energy components and is consistent with the use of dissipated energy partitions applied to fracture mechanics and viscoplasticity.
- v) Effect of oxidative aging on the surface free energy components of the asphalt binder.

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

A detailed experiment design will be developed to accomplish the objectives identified in the work element F1a. The experiment design will include details pertaining to the statistical analysis that will be used for each element, including number of samples, and replicate measurements required. The materials selected for the detailed experiment design will be from the common material library for the consortium project. A preliminary list of materials for this library is identified in element 3d of this work plan. Additional materials may be used if the materials library does not contain materials that exhibit the desired range of properties of interest.

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

The work of adhesion and cohesion can be computed using surface energy components of the asphalt binder and the aggregate. This subtask will evaluate existing protocols to determine surface energy of modified asphalt binders as well as asphalt mastics. The work of adhesion and cohesion for several different types of binders and binder-aggregate combinations will also be determined in this subtask. This information will be used in the subsequent subtasks to provide the mechanical work of adhesion and cohesion as inputs for the micro-mechanics and continuum fatigue model.

In summary, the following analytical and experimental elements are envisioned in this subtask:

- i) Assess existing protocols to determine surface energy components for modified asphalt binders and mastics. Previous research at the Texas A&M University has led to the development of detailed test protocols to measure the surface free energy components of asphalt binders (Bhasin and Little 2006; Hefer et al. 2006). However, these protocols were developed based on neat asphalt binders. In this subtask, these existing protocols will be evaluated for their applicability to mastics, aged, and polymer modified asphalt binders. Factors such as specimen preparation and uniformity will be addressed. Results will be cross evaluated using analytical methods and alternate experimental techniques such as the static sessile drop method.
- ii) Develop recommendations and revised test protocol for measuring surface free energy on asphalt binders and guidelines to use and interpret surface energy measurements for asphalt mastics.
- iii) Measure surface free energy of selected unmodified and modified binders (including aged binders) and mastics using the Wilhelmy plate device. The recommended protocols from the aforementioned subtask will be used for these measurements. The common materials library for the consortium project will be used to select binders for these measurements.
- iv) Measure surface energy of selected unmodified and surface treated aggregates using the Universal Sorption Device (USD). A common example of surface treatment of aggregates that effects the aggregate-binder work of adhesion is application of hydrated lime slurry to the aggregate surface. The common materials library for the consortium project will be used to select aggregates for these measurements.
- v) Determine the thermodynamic work of adhesion and cohesion for different combinations of asphalt binders, mastics, and aggregates using their individual surface energy components.

Subtask F1a-4: Mechanical Work of Adhesion and Cohesion

Sources of energy dissipation on a larger scale, such as plastic energy and micro branching, also contribute to the work required for cohesive fracture in asphalt binders or mastics, albeit the energy dissipated from these additional sources is related to the work of cohesion due to surface free energy of the binder. The contribution of these secondary sources to the total work of adhesion and cohesion will be investigated in this subtask using a combination of analytical and experimental methods. The experimental methods will be developed in coordination with tasks under element F2a.

In summary, the following analytical and experimental elements are envisioned in this subtask:

- i) Identify and develop protocols for one or two test methods based on the literature review from 1a-1 to determine the material viscoelastic properties and mechanical work of adhesion and cohesion. Possible test methods for consideration in this element are the direct transverse tension test on asphalt films of varying thicknesses using standardized and aggregate substrates.

- ii) Determine the viscoelastic properties and work of cohesion and adhesion for different asphalt binders and binder-aggregate combinations using the selected test method(s).
- iii) Develop a model to enable back calculation of the work of adhesion or cohesion from the mechanical tests, incorporating the influence of film thickness and viscoelastic effects.
- iv) Reconcile the effect of scale and other energy dissipation mechanisms and develop the relationship between the thermodynamic parameters from subtask 1a-3 and the equivalent back calculated parameters from mechanical tests conducted in this subtask.
- v) Develop framework(s) for the work of cohesion or adhesion with appropriate modifications so that it can be incorporated into the micromechanics or continuum damage models in subsequent tasks. This framework will be based on both thermodynamic measurements and mechanical tests.

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

The surface free energy components of aggregates and binders are computed using adsorption isotherms and contact angles with different probe liquids. Thus far, these computations were made using surface energy values for probe liquids recommended as per the Good-van Oss-Chaudhary (GVOC) scale. The GVOC scale is based on the assumption that the acid and base components of surface energy of water are equal. Several researchers in the field of physical-chemistry have pointed out that this scale introduces a bias which results in an apparently high magnitude for the base component and apparently low magnitude for the acid component of surface energy (Della Volpe and Siboni 2000). Alternate scales for the surface energy components of various probe liquids are also recommended in the literature.

In this subtask the work of adhesion and cohesion will be determined using surface energy components that are derived using different scales. This analysis will determine whether or not the use of a different scale can improve sensitivity of the computed surface energy components of asphalt binders and aggregates. This is especially important for the acid component of asphalt binders which are typically very small in magnitude but are significant contributors to the work of adhesion. This sub task will utilize the data from the Universal Sorption Device (USD), Wilhelmy plate and sessile drop devices obtained from other elements of this subtask as well as other subtasks.

Work Element F1b: Viscoelastic Properties (Year 1 start)

The focus of this work element will be on developing experimental protocols and analysis methods to determine linear and nonlinear viscoelastic properties of the binder, mastic, and mixture.

As discussed later in work element F3c-1, one of the important inputs to the fatigue damage model is the rate of growth of dissipated fracture pseudo strain energy. The determination of this parameter necessitates separating the energy dissipated in nonlinear viscoelastic deformation from the energy dissipated in fracture damage. The difficulty in doing so stems from the fact that nonlinear viscoelastic deformation, plastic deformation and fracture damage are dependent on the stress level.

Subtask F1b-1 Separation of nonlinear viscoelastic deformation from fracture energy under cyclic loading

Cyclic loading is used in the testing of asphalt binders (dynamic shear rheometer), mastics (dynamic mechanical analyzer) and asphalt mixtures (cyclic axial or shear). It has been a challenge to use these tests to separate nonlinear viscoelastic from plastic deformation and fracture due to the following reasons: (a) the stress value could change within a load cycle from the linear response to the nonlinear response, (2) the stress varies radially within the specimen under shear loading, (3) the loading and unloading within each cycle causes energy to dissipate due to plastic deformation but permanent deformation is fully reversible within each cycle.

The nonlinear response will cause the viscoelastic properties (phase angle and modulus) to change within the cycle. In this subtask, we will derive the Schapery's nonlinear viscoelastic model under the boundary conditions of cyclic loading in order to obtain functions for viscoelastic material properties within a loading cycle. This will allow separating the nonlinear response from the linear response predicted using properties measured at small stresses. The permanent strain is quantified by monitoring the material response every quarter of a cycle. This might require some changes to standard software used in test methods in order to obtain the response at points within loading cycles and not only the properties measured at peak stress values.

The fracture parameters will be identified by monitoring the material response by applying fatigue loading until changes in material properties are measured at a given stress level. As cyclic loading proceeds, the nonlinear viscoelastic response should be the same so long as the stress level remains the same. As such, any change in the material response at a given stress level with an increase in loading cycles will be used to quantify fracture damage.

Subtask F1b-2 Separation of nonlinear viscoelastic deformation from fracture energy under repeated and monotonic loading

The continuum modeling of asphalt mixtures has relied on separating the strain into its viscoelastic and viscoplastic components. All available methods assume linear viscoelastic response, which makes the separation of the strain components straight forward (Huang et al. 2007). However, this assumption leads to erroneous decomposition of the strain components. In this subtask, we will develop a repeated loading-unloading testing protocol and analysis methods to separate the nonlinear viscoelastic and viscoplastic components. The mathematical basis for this subtask has been derived recently at Texas A&M University and presented to the expert task group in its meeting in Phoenix Arizona in February 2007. It relies on using statistical fitting for the unloading portion of the repeated test to determine the total permanent strain and one of the nonlinear viscoelastic parameters. These parameters are used in the mathematical form for the loading portion and fitted to the experimental measurements to obtain the remaining nonlinear viscoelastic parameters and the viscoplastic strain as a function of loading time.

Work Element F1c: Aging

Oxidative aging changes binder composition. These changes have dramatic effects on binder (viscoelastic, cohesive, and adhesive) and mixture (viscoelastic, fracture, and permanent deformation) properties. Therefore, it is necessary to understand the material and microstructure factors that influence aging and the factors that govern the response of binders and mixtures to aging. The experiments and analyses will focus on characterizing the influence of aging on fundamental material properties that are included in the parameters of the models discussed in Category F3. Ultimately, the results must be able to provide insight to the asphalt microstructural model, the micromechanics model, and the unified continuum fatigue model. Activities of this work element in Category F1 will coordinate with those of Category F3.

The planning and results of the above subtasks will be coordinated with other elements of the consortium effort. As mentioned above, results that relate to fundamental binder and mixture properties will be communicated to the Micromechanics Model and Unified Continuum Fatigue Model elements. Results of the transport model of binder oxidation in pavements and on mixture parameters that maximize fatigue resistance will provide guidance on engineering mixtures to have enhanced pavement durability.

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

This subtask will develop detailed objectives of this work element within the context of previous work and the objectives of the consortium deliverables in the fatigue area (and other areas as appropriate). Pertinent prior work includes binder oxidation kinetics, binder hardening that results from oxidation, binder oxidation and hardening in pavements, and the effects of binder hardening on mixture properties. Additionally, effects of oxidation on binder cohesion and binder/aggregate adhesion will be reviewed and coordinated with activities in other work elements.

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

A detailed experimental design will be developed to accomplish the objectives identified in subtask F1c-1 and to be carried out in subsequent subtasks, below. This subtask will include selecting binder and aggregate materials, mixture types and aggregate gradation, binder and mixture aging protocols, and test procedures for assessing the impact of binder oxidation on binder and mixture properties. Also, climate regions of interest for transport modeling, and the selection of relevant field sites for validating the transport modeling of binder oxidation will be selected.

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

As an essential element in the process of modeling fatigue damage in mixtures and pavements, the oxidative aging of binders in pavements must be considered. A significant body of data is accumulating that oxidation of binders in pavements is an ongoing process and that it occurs to a significant depth below the surface. The rate at which this oxidation occurs in different climates

and pavement types is a factor to understanding pavement performance. The oxidation rate of binders is accelerated exponentially with temperature, but also depends on the transport of oxygen to the binder. Data strongly suggest that if the accessible air voids in a pavement are sufficiently high, then the access of oxygen is not a limiting factor and that a model that relies solely on the pavement temperature might do very well at estimating binder oxidation rates in pavements. However, for pavements that have sufficiently restricted air voids, the transport of oxygen appears to be a significant factor, more in line with our expectations.

This subtask will address the development of a thermal and oxygen transport model for estimating binder oxidation in pavements. Such a model will require binder oxidation kinetics parameters (activation energies and oxygen reaction order values, plus early rate information), a model for calculating temperature as a function of time and depth in pavements, and a model for describing oxygen transport and diffusion to the binder.

The transport model will require fundamental material properties, including binder oxidation kinetics, diffusivities of oxygen in binders and mastics, and thermal diffusivities of pavements. It is likely that thermal diffusivities can be estimated quite well from existing measurements of pavement temperature as a function of time and depth, as can the impact of nationwide climate differences on pavement temperature. Oxygen diffusivities, however, will be measured as part of this subtask, as will some binder reaction kinetics parameters for which data are not yet available.

Such a model will provide calculations of binder properties in the pavement as a function of both time and depth, properties that can then be passed to the micromechanics and unified continuum fatigue models.

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

Another critical element to understanding the impact of binder oxidation is the extent to which binder oxidative hardening impacts mixture, and thus pavement, properties. Recent data have shown that the hardening and embrittlement of binder that occurs as the result of oxidation causes dramatic decreases in mixture fatigue resistance under controlled-strain conditions. Furthermore, the data have shown that different mixtures can exhibit very significant differences in the extent to which binder hardening impacts this decline of fatigue resistance. Understanding these differences between mixtures is critically important to fatigue prediction. Furthermore, understanding the impact of binder oxidation on fatigue resistance and pavement durability in a controlled-stress environment must be better understood.

The objective of this subtask is to determine the fundamental mixture parameters that establish the extent to which fatigue resistance declines with binder oxidative hardening and thus the reasons that some mixtures are inherently more durable than others. Mixture parameters that likely affect fatigue resistance are binder composition, binder content, air voids content, aggregate gradation, and perhaps aggregate type. To the extent such parameters impact mixture fatigue, the fatigue problem is really a mixture/binder problem rather than simply a binder

problem. Of course, the binder oxidation rate in pavements (Subtask F1c-3) will also impact pavement durability.

This subtask will conduct carefully designed experiments to determine the impact of binder oxidative hardening on fundamental mixture properties that govern mixture fatigue resistance, and for a variety of mixture parameters. The property measurement and the results will be coordinated with the efforts on the micromechanics and unified continuum fatigue models.

Subtask F1c-5: Polymer Modified Asphalt Materials

Polymer modification of asphalt binders offers unique opportunities for improving binder behavior, but also unique questions that must be better understood. Modifiers typically improve the elongational properties of binders and may improve their cohesive and adhesive strengths. However, oxidative aging of modified binders typically reduces the elongational flow improvement to the point that with enough aging, the modified binder behaves like the aged unmodified binder.

The interaction of the polymer modifier and the base asphalt binder appear to be critical in establishing the beneficial effects of the modifier and these interactions need to be better understood. Fluorescence microscopy imaging provides useful qualitative information on polymer-asphalt morphology and its changes with oxidative aging which, combined with measurements of binder rheology, mixture rheology, and mixture fatigue, can provide an improved understanding of polymer modification and its impact on pavement durability.

The work of this subtask will address polymer asphalt interactions and their impact on binder and mixture properties for a variety of modifiers and base binders and particularly as a function of oxidative aging. The work will provide important fundamental data for the asphalt microstructural model, the micromechanics model, and the unified continuum fatigue model.

Work Element F1d: Healing

This work element will begin in year one, and the work plan is described in the following paragraphs.

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

During previous FHWA contracts on Fundamental Properties of Asphalts and Modified Asphalts, DTFH61-92-C-00170 and DTFH61-99-C-00022, Texas A&M University hypothesized that healing of microcracks is related to the surface energy of the crack face. Intuitively, most healing is cohesive or within the mastic, instead of adhesive or between asphalt or mastic and aggregates faces. As a result the surface energies that affect healing are those of the binder and/or mastic. The existing data strongly demonstrate that higher total surface energies of the binder are related to improved healing. The data also convincingly indicates that healing is best in binders with high acid-base components of surface energy but that healing is impeded by a high Lifshitz Van der Waals surface energy component.

Previous work at Texas A&M has also shown that molecular morphology affects healing and that longer, less branched molecules promote healing as opposed to shorter, highly branched molecules. Texas A&M researchers have developed a model for healing rate that can be incorporated in the fatigue model. This model uses a Ramberg-Osgood function to represent the time rate of healing and its cumulative effect with time. This Ramberg-Osgood approach unites short-term (non polar) healing rate and long-term (polar) healing rate together with overall cumulative bond recapture capacity (ratio of polar to non-polar bond energies).

The healing mechanism will also be studied using the recently proposed approach that represents healing with the convolution integral form proposed by Wool and O'Connor (1981) for polymers. This form combines the effect of wetting (due to surface energy) when crack surfaces are pressed back together followed by diffusion and randomization. The diffusion and randomization processes are affected by molecular morphology.

The product of Subtask F1d-1 will be a white paper synthesizing the pertinent literature on healing with a major emphasis on the work done under FHWA contracts DTFH61-C-92-00170 and DTFH61-C-99-00022.

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

A significant part of the research in the area of fatigue will utilize materials that are selected from the common material library for the consortium project. However, in order to verify the elements of the healing mechanism, binders or mastics with a targeted range of properties will be required. This subtask is aimed at determining these properties for different asphalt binders and mastics as well as modifying the binders using model compounds or additives to achieve the targeted range of properties, as required. This will be achieved as follows:

- i) Select binders and mastics to evaluate effect of surface energy on the wetting and healing of micro cracks. This will involve measurement of surface free energy components of different binders using the Wilhelmy plate device. Binders will be modified by addition of chemical additives and/or addition of model compounds to achieve variable surface characteristics of the asphalt binder. This process will ensure that the morphology of the asphalt molecules is not significantly altered.
- ii) Select binders and mastics to evaluate effect of molecular morphology on diffusion and healing. This will involve measurement of surface free energy of different binders using the Wilhelmy plate device. Unlike sub task 1d-2, the objective of this subtask will be to identify or formulate asphalt binders that have significantly different molecular morphology, compliance, and diffusivity, but similar surface energy characteristics. Important characteristics pertaining to the molecular morphology of the asphalt binders (e.g., average chain length, molecular weight distribution) will be determined in other tasks of this research project. This information will be used to blend different binders to achieve the desired differences. Previous research at the Texas A&M University has identified parameters such as methyl to methylene ratio, determined using the FTIR, as a parameter that reflects on the molecular properties related to healing. The selected or blended asphalt binders will be evaluated using this parameter.

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

Once the appropriate set of binders and additives are selected, an experiment design that will provide a statistically reliable assessment of the impact of surface energy (and its components), compliance, diffusivity, and molecular morphology will be developed in coordination with the project statistician, as described in the Experiment Design section. The materials incorporated in the experiment design will be based on the selections made in subtask F1d-2.

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

The propensity of an asphalt binder to heal over time can be considered as a time dependent function of material properties. The measurement of surface energy and its components will most likely be determined by the Wilhelmy Plate method, based on extensive earlier work. Pulse guided – nuclear magnetic resonance, PG-NMR, may be used to measure self diffusivity constants for the binder. However, other methods of assessing the morphology and diffusion and migration potential of molecular species will be investigated. The surface energy (wetting), compliance, diffusivity, and molecular morphology properties of the binders will be compared with the mechanical DMA quantification of healing. A comprehensive evaluation of healing that integrates properties such compliance and bond energy will be conducted. The correspondence between the measured diffusion properties and the measured compliance will be determined.

The most appropriate testing methodologies will be identified and recommendations for further development made in tasks F2a and F2b.

Subtask F1d-5: Testing of Materials

The binders and additives selected in F1d-2 and F1d-3 will be tested using the methods identified in F1d-5 to determine their surface energy properties (total surface energy and non-polar and polar components of surface energy) and molecular morphology. These values will be compared with measurements of healing probably by using Dynamic Mechanical Analysis (DMA). In the DMA experiment the binder (neat or modified) will be mixed with a standard filler and fine aggregate. The sample will be subjected to cyclic, torsional loading in the DMA experiment. Multiple rest periods will be introduced and recovery of energy dissipated due to various mechanisms during these rest periods will be monitored as an indicator of healing. The objective will be to identify the effect of surface energy on the healing through the wetting mechanics and the effect of compliance and diffusivity as determined by molecular morphology through the diffusion and randomization mechanism.

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

During the last 10-15 years the understanding of healing and endurance limits of asphalt mixtures has advanced significantly. Research on binder fatigue and development of binder fatigue tests are relatively new and have not included two important aspects of fatigue, healing and endurance limits. It is expected that advancements in characterizing and modeling of

healing and endurance limits of mixtures can be applied to fatigue measurements of binders in the DSR. This task will focus on two main areas, apply methods developed for healing of mixtures to results of binder fatigue testing in the DSR, and develop methods for estimating the endurance limits of binders using the DSR.

A comprehensive plan for measuring healing potential of binders with and without modification using the DSR will be developed after a critical review of the advancements in mixtures and mastics. The data published on binder fatigue during the last few years will be gathered to introduce a binder fatigue model that allows one to estimate the effect of stress/strain on fatigue life and also to predict endurance limits. An attempt will be made to include healing in the endurance limit prediction model. The task will also include limited validation of the endurance limits and effect of modifiers on altering the limits. The work will be coordinated carefully with the other tasks of this area.

The following tasks will be completed in order to achieve the objectives of this research effort:

- i) Develop a protocol to measure healing of fatigue damage for asphalt binders. This task will include a comprehensive literature review of the world wide literature on methods for measuring healing of asphalt mixtures and other visco-elastic materials. Based on the review, a set of testing protocols with potential to quantify healing of binders will be selected. Preliminary testing of a set of 4 binders will be conducted to evaluate the practicability and feasibility of the tests. The tests will be restricted to using the DSR and the BBR devices.
- ii) Evaluate testing protocols. Further testing of 6 binders (2 unmodified and 4 modified) will be conducted to evaluate the practicability and feasibility of the tests identified in Task 1. The tests will also be restricted to using the DSR and the BBR devices. The best protocol will be defined by its ability to differentiate among binders, cost in terms of time and effort, repeatability, and simplicity of analysis. The outcome of this evaluation will be selected in coordination with other work elements on the unified fatigue damage model. In other words, the outcome should include parameters that can be used as input in the unified fatigue model.
- iii) Evaluate factors affecting healing of binders. In this task, the factors known to affect healing, as identified in Task 1, will be used to develop a comprehensive experimental plan for testing and quantifying the change in healing due to variation of these factors. The factors will include at a minimum, temperature, chemical composition, modification types, aging, loading rate, rest periods, and stress or strain used in testing. Statistical experimental design will be used to minimize the number of combinations.
- iv) Evaluate possible surrogate measures. This task will compare the results from testing conducted in Task 3 with simple chemical, physical, or rheological properties already measured in binder surrogate fatigue testing (stress sweep), slope of the master curve, the $m(60)$ value, and other measures that are already in the PG specification, or can be an extension of the PG testing. This will be done to investigate whether healing can be estimated from other simple measures, eliminating the need for a healing-specific test.
- v) Evaluate role of mineral surface in healing. Selected binders will be mixed with 3 types of mineral fillers (acidic, basic and neutral) to study role of mineral surface on healing

results. Based on the results, limited testing of actual mixtures will be conducted to validate the effect of the mineral surface and define the importance of aggregate presence on healing.

- vi) Make final recommendations for a binder healing test and specification parameter. Based on the results of Tasks 2-5, a final recommendation will be made regarding the practicality of including a healing test and specification parameter in practice. Guidelines will be developed for a test protocol and analysis method, and specification limits will be proposed. Suggestions for future research will be also listed.

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

As described previously healing characteristics of an asphalt binder depend on its surface properties as well as the molecular morphology. AFM imaging and interaction measurements on the asphalt binders selected in this task will provide valuable insight at a nano scale into understanding the mechanism and modeling of the healing phenomenon.

In this effort nanotechnology (AFM imaging; friction and morphology, contact-force AFM, nanoindentation AFM, chemical-force AFM, etc.), interpreted based on contact mechanics and statistical mechanics theories of irreversible energy dissipation at diffuse interfaces may be adopted to describe/model material integrity (equilibrium compositional and phase transformation stability, inter and intra molecular compatibility) fracture, slow crack growth and crazing phenomena. Nanoindentation techniques may for example be adopted for measuring stiffness and creep relaxation properties of asphalt binder material thin-films. Sample thin films may be analyzed by AFM imaging techniques, force-distance work of adhesion measurements (nano-contact mechanics) and nanoindentation, each conducted as a function of time and temperature. The results that obtained from these experiments will be compared between AFM methods and with other methods of analysis, including bulk thermal and rheological properties (DSC, DMA, and DSR). Furthermore, model development will be closely tied to nano-experimental techniques, where free energy expressions pertinent to the various molecular ordering events, (e.g., wax crystallization, Spinodal phase separation, and crazing and crack growth models, etc.) will be investigated. This approach is anticipated to lead to mathematical relations between the various molecular ordering events and the mechanical properties of the material based on fundamental physical and chemical theories of soft condensed matter.

- i) Develop experimental techniques that require the minimum amounts of time and materials to quantify asphalt binder and aggregate surface physico-chemical and nano-mechanical properties based on nanotechnology. (e.g., nano-Thin-Film Chromatography/Composition Analysis, nano-Mechanics nano-indentation nano-surface Tensiometer, AFM solidification analysis, programmable dynamics wetting/Spin-Coating via Lubrication Theory, and programmable combinatorial-automated flocculation titrimetry (PC-AFT).
- ii) Develop approaches (Experimental) based on nanotechnology which lead to data-input computational software (e.g., Virtual Asphaltic Concrete Testing Laboratory (VACTL)) to model physico-chemical and chemo-mechanical systems.

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

This subtask will be conducted in coordination with tasks 3b and 3c. The objective of this subtask will be to frame the healing property of asphalt binders and mastics, and if required the fine aggregate matrix, in a form that can be easily incorporated in the micromechanics model as well as the continuum fatigue model. This sub task will be critical to ensure that healing is appropriately incorporated along with other material properties as a part of these models.

Subtask F1d-9: Design Experiment on Selected Binders with Synchrotron.

Texas A&M has secured the opportunity to use the synchrotron at the University of Saskatchewan. This synchrotron is one of the most modern and powerful in the world. It is possible that the changing image of the molecular structure at a crack face may be able to be captured with this device as it is capable of micro and nano-scale analysis. A cooperative relationship with the University of Saskatchewan provides an opportunity for this testing during the fall of 2007. We will investigate whether or not this opportunity is meaningful. If so a small exploratory initial experiment will be proposed.

Category F2: Test Method Development

Work Element F2a: Binder Tests and Effect of Composition

A successful modification of an asphalt binder with a polymer is intended to improve one or more of the basic asphalt properties such as rigidity, elasticity, brittleness, durability, and compatibility, especially in-blend compatibility. An asphalt-polymer blend is considered compatible if the polymer is soluble in the asphalt cement or if it can be swollen by the asphalt oils without causing flocculation of the asphaltenes. Most polymer modifiers are used to enhance the rutting resistance of asphalt binders. When it comes to the influence of modifiers on fatigue resistance, some have a positive influence, while others can have a negative influence. It is to be expected that by adding more flexibility (increase in toughness) to the binder, fatigue resistance will increase. If on the other hand the modifiers will stiffen the material at medium and low temperatures, than a decrease in fatigue resistance is expected. The morphology of the polymers used as modifiers, as well as their chemical structure and affinities play an important role on how the binder will perform in field applications. The flexibility of rubbers will bring toughness to the asphalt binder, possibly increasing its fatigue resistance. The hardness of waxes will improve rutting resistance properties. On the other hand, crystallinity promoted by rigid wax chains can diminish the fatigue life of asphalt binders and decrease their low temperature cracking resistance. Therefore a fine balance needs to be maintained between flexibility and stiffness, between elastic and plastic domains within the asphalt binder, between the affinity towards polar compounds (e.g. mineral aggregate) and moisture damage resistance, etc. In addition to modifiers, aging can have a significant impact on fatigue. It is however not clear if aging have a negative effect on fatigue under all conditions of loading. For example, aging is expected to increase stiffness and strength but decrease ductility (flexibility). While increasing stiffness could have a positive effect on stress-controlled fatigue, reduced flexibility and toughness could have a negative effect. This work element will focus on developing methods to

estimate effect of modification and aging on fatigue resistance and provide a framework for selecting binders to reduce potential for inferior fatigue resistance. The framework will include polymer and asphalt chemistry as well as mechanical properties. The following tasks will be completed in order to achieve the objectives of this research effort.

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

Fatigue studies of unmodified, SBS and acid modified binders have been performed by UW-Madison in collaboration with FHWA for the last 3 years. Testing was performed using the dynamic shear rheometer (DSR), with three types of procedures of particular focus: stress sweep, stress-controlled frequency sweep, and stress-controlled fatigue. In addition, limited strain controlled testing was conducted. The DSR data was analyzed along side direct tension data using principles of dissipated energy. This data set will be analyzed to identify most dominant trends in effects of polymers and aging on fatigue of binders. Some limited additional testing will be conducted to define the trends and provide a framework for the new testing plan.

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

Based on the results of subtask F2a-1, a complimentary work plan will be developed. Modified binders will be prepared using two different “base” virgin binders and four modifiers (SBS rubber, Elvaloy®, Sasobit® wax, and a polyphosphoric acid modifier). In order to better examine the influence of the butadiene moiety along with the variation in ratio between the lengths of the butadiene and styrene blocks, more than one type of SBS will be tested. Every “base” binder will be modified using each of the chemical additives selected. Sample size to be produced will be determined taking into consideration the testing procedures that the materials will be subjected to.

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

Samples from both the modified and unmodified types of binders will be subjected to lab aging techniques. This is done to enable the study of aging as a determining factor in the fatigue life of binders. Modified and unmodified binder samples will undergo RTFO and one or more PAV treatments.

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

This task will concentrate on testing the previously prepared samples according to the work plan in Task 2.

Subtask F2a-5: Analyze data and propose mechanisms by which aging and modification influence fatigue of binders.

The objective of this task is to analyze all the collected data from the previous task. The focus will be on defining mechanisms by which modifiers and aging control fatigue at various conditions. The outlined mechanisms by which we believe that aging and modification affect

fatigue life of binders will be used to develop guidelines for selecting modifiers and the tests required to qualify modifiers for improvement of fatigue life.

Work Element F2b: Mastic Testing Protocol

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

The test protocol to determine mechanical properties of asphalt mastics and fine aggregate matrix (FAM) is an important component of the unified fatigue damage model. The test method will serve dual purposes of: i) validating the expected response of asphalt mastic or fine aggregate matrix based on fundamental material properties, and ii) generating input that will be required for micromechanical or continuum fatigue model. Significant work has been done in the past at the Texas A&M University to develop the use of a Dynamic Mechanical Analyzer (DMA) to accomplish this. The objective of this subtask will be to detailed test protocol to generate parameters that will serve as inputs for the unified fatigue damage model. This objective will be achieved by accomplishing the following sub tasks.

Subtask F2b-1: Develop specimen preparation procedures (Year 1 start)

The DMA has been used to measure the mechanical properties of asphalt mastic and Fine aggregate matrix (FAM). Different methods have been used for preparing DMA specimens for testing mastics and FAM. The mastic testing relies on preparing specimens with Ottawa sand, filler particles passing sieve # 200, and asphalt binder. An FAM specimen is comprised of asphalt binder and fine aggregates passing the #16 sieve including filler material (passing the #200 sieve). The Fine aggregate portion of the FAM typically follows the same gradation as in the complete asphalt mixture. The binder content for the FAM is determined based on a fixed filler to binder ratio by volume, based on a constant film thickness on aggregate particles, or based on an average film thickness computed using the complete asphalt mixture.

The procedures and relevant assumptions required to design the composition of the mastic and FAM specimens will be evaluated in this sub task. Standard design procedures will be recommended based on considerations that include percent of filler particles in the mixture, representation of the FAM phase in the complete asphalt mixture, validity of the assumptions used in the procedure, and practicality of compacting and preparing test specimens in the laboratory. The method for preparing and storing test specimens cored out of Superpave Gyrotory Compacted (SGC) samples will also be evaluated and standardized.

In summary, this subtask will accomplish the following:

- i) Compare and standardize the procedure to design the mastic and FAM specimens and ensure that they are representatives of the complete asphalt mixture.
- ii) Evaluate and standardize the procedure to mix, compact, core, and store test specimens. The procedure will also provide for acceptable limits and tolerances in geometry and air voids in the test specimen.

- iii) Assess ruggedness of the test method with reference to variability in specimen preparation and handling procedures.

Subtask F2b-2: Document test and analysis procedures in AASHTO format

This subtask will develop a single unified document that describes various test protocols developed in other subtasks. Analytical methods to interpret test data and derive parameters of interest from these test procedures will also be documented along with user friendly software to conduct this analysis. More specifically, this subtask will provide detailed protocols to achieve the following from the test method:

- i) Determine properties of the FAM required as input for micro mechanics and continuum fatigue damage models as well as model crack growth in asphalt mastics and mixtures. For example, procedures developed in subtask 1b to determine the linear and non linear viscoelastic properties will be refined for use with FAM and documented in this subtask.
- ii) Determine fatigue cracking life of FAM with and without rest periods. For example, procedures to assess the fatigue and healing characteristics of FAM developed in subtask 1d-6 will be standardized and documented.

Work Element F2c: Mixture Testing Protocol

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

This work element is intended to develop a mixture testing protocol that will be able to generate mixture parameters of interest for the continuum model with the most optimal level of laboratory testing. The primary characteristics of the comprehensive testing protocol are as follows:

- i) Repeated loading that allows separating the nonlinear viscoelastic, viscoplastic and damage components.
- ii) Different stress levels, temperatures and loading rates in order to determine the linear viscoelastic response, nonlinear viscoelastic response, plastic deformation, and fracture.
- iii) Different stress states (tension and compression) in order to determine the model's parameters under various loading conditions.
- iv) Different confinement levels in order to determine the dependency of model's parameters on confinement.

It is realized that a comprehensive testing protocol might be too elaborate for routine use for mixture design and evaluation. Therefore, we will seek the development of surrogate tests that can potentially lead to determine the necessary model parameters. This, however, can only be done once the comprehensive testing protocol is developed and used to test a variety of mixtures. We will conduct sensitivity analysis using the measurements from the comprehensive testing protocol to determine the parameters that has the significant influence on the mixture performance. It is possible to find that some of the model parameters vary within a small range and they do not have significant influence on performance. These parameters will be assigned

fixed values in the model, and reduce the testing steps that are used to determine these parameters.

Work Element F2d: Tomography and Microstructural Characterization

X-ray CT is a nondestructive test to capture the internal structure of materials. Various applications of this method are discussed by Masad (2004). The X-ray CT step up at Texas A&M University includes two separate systems placed in the same shielding cabinet. The mini-focus system has a 350 kV X-ray source, while the micro-focus system has a 225 kV X-ray source. The required X-ray source power increases as the specimen thickness and density increase, while the micro-focus system can achieve a better resolution than the mini-focus system.

The researchers at Texas A&M University have developed methods for identifying of cracks and their dimensions. Also, they developed mathematical functions of the anisotropic distribution of damage, and statistical functions of these cracks based on size and shape characteristics. The X-ray CT will be used to verify the predictions of the developed models by monitoring evolution of damage at various loading conditions. This is valuable in order expand the model's verification beyond the typical macroscopic measurements to detailed microscopic measurements.

X-ray CT imaging will also be used to obtain microscopic images that are needed for the micromechanical models discussed in Category 3. As discussed later, it is possible to use X-ray CT to capture images at high resolution and then use image processing techniques in order to combine these images for detailed micromechanical analysis.

Work Element F2e: Verification of the relationship between DSR Binder Fatigue Tests and mixture fatigue performance

The current Superpave Binder fatigue parameter has been shown to be insufficient as a predictor of pavement fatigue performance. Recent studies have shown that $G^* \sin \delta$ values obtained from binders used in mixes correlate poorly to laboratory mixture fatigue testing. Progress has been made during the last few years to introduce a more meaningful fatigue parameter for binders, but the extent to which the new test and the parameters derived from it relate to mixture and pavement performance is yet to be determined. The lack of correlation between the binder $G^* \sin \delta$ and performance could be attributed to many factors among which the use of the actual conditions of stress and strain experienced by binders in typical mixtures and the reliance on small strain testing are the most important missing factors.

Recent studies have clearly shown that response of binders to repeated cyclic loading show damage accumulation behavior that cannot be predicted by the few initial cycles used to measure $G^* \sin \delta$. Also, modeling of the strain distribution within the mix has shown that the binder can experience strain levels as high as 90 times those experienced by the mix. By testing binders within the linear viscoelastic region, it is likely that the current specification is not addressing the actual behavior within the mix. These high strains may be indicating that fatigue failure of pavements is, in part, due to the non-linear behavior and subsequent stiffness reduction of binders within the mix.

This work element will focus on comparing binder fatigue results to fatigue performance of mixtures measured in the lab and also pavement fatigue of full scale experiments such as the FHWA-ALF results. The work will include imaging of mixtures to estimate ranges in stress and strains, conducting testing under various loading conditions that mimic the mixture testing of the full scale experiments, and development of specification limits and criteria. The work element will be coordinated with other tasks in the consortium project and also with activities of NCHRP on fatigue. The work is essential for developing an understanding of the role of the binder in fatigue resistance, and in the development of a unified model for fatigue damage. The following tasks will be completed in order to achieve the objectives of this research effort.

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

Data has already been collected on mixture fatigue performance in the laboratory as part of the Pacific Coast Conference on Asphalt Specifications. In this task, the binders used in that study will be tested at various strains and temperature conditions in order to evaluate the results as indicators to mixture fatigue. This will be done using a standard fatigue procedure in the dynamic shear rheometer. The strain levels used for binder testing will be chosen based on the results of the strain distribution modeling research. Number of cycles to failure for the binders (based on the same failure criterion used for mixture testing) will be compared against the same results for mixtures and evaluated for significance.

Subtask F2e-2: Selection of Testing Protocols

Variables relevant to the binder-mix relation, such as asphalt content in the mix, mixture stiffness, and strain and stress levels in the binder domain will be selected and controlled for the testing. Refined binder fatigue protocols that incorporate these conditions will be integrated into the testing plan. The binder and mixture testing will include controlled strain and controlled stress, adding the surrogate stress sweep test for binder testing. Binder test methods will also include limited use of torsion cylinders consisting of binder-sand mixtures for better representation of thin film behavior tested in the DSR. Utilization of the binders used for the FHWA-ALF study will be incorporated into testing for comparison to the fatigue performance results from that study.

Subtask F2e-3: Binder and Mixture Fatigue Testing

Standard fatigue and surrogate stress-sweep testing will be performed on binders and binder-sand torsion cylinder mixtures. Mixture fatigue testing will be performed using axial cyclic fatigue testing in a servo-hydraulic test frame on gyratory samples prepared in the lab. Images of the cross sections of the mixture samples will be taken for analysis of strain distributions.

Subtask F2e-4: Verification of Surrogate Fatigue Test

Data collected during the stress sweep testing of the binders and binder-sand mixtures will be compared to the traditional fatigue testing as well as results from the FHWA-ALF study to verify the stress sweep as a suitable surrogate test for fatigue.

Subtask F2e-5: Interpretation and Modeling of Data

Results from all binder and binder-sand mixture testing will be correlated to the results from gyratory compacted mixture sample testing to evaluate the contribution of binder fatigue characteristics to the fatigue performance of the mixtures. Results from mixture imaging will verify the ranges of stresses and strains experienced by the binder phase.

Subtask F2e-6: Recommendations for Use in Unified Fatigue Damage Model

The results from the previous task will be used to aid in the development of the unified fatigue damage model by providing a more efficient method of evaluating fatigue characteristics of binders, as well as an increased understanding of the behavior of the binder phase within mixtures and its contribution to fatigue performance.

Category F3: Modeling

Work Element F3a: Asphalt Microstructural Model

For nearly a century, heavy crude oil has been viewed by a majority of investigators as colloidal in nature. Although naturally occurring (Trinidad Lake deposit), asphalt is generally defined as the residuum from the distillation of petroleum. Heavier residua such as asphalt consist of a rather grand number of different “petrol” organic compound types (molecules) comprising their chemical makeup. These compound types vary in a complex manner in terms of their molecular composition; hydrogen-to-carbon ratio, shape, molecular weight or size, polarity, density, surface activity, etc. Asphalt molecules are generally thought to range in molecular character from that of non-polar hydrocarbon, waxy and oily type molecules, to condensed poly-aromatic sheet, heteroatom-containing (graphite-like) molecules. Hence, common logic would dictate that a concise description of the composition of the molecules present in heavy residua and their associated interactions with each other and with other foreign materials should directly relate to the physico-chemical properties of asphalts and their propensity to bind with aggregate, polymer, fillers, etc., if used as the gluing agent in pavement construction applications.

A logical approach to take to guide studies which will lead to the most accurate and realistic description of the compositional nature of asphalt binder should rely heavily on theoretical modeling of asphalt nano-structure grounded in such fields of study as that of non-equilibrium statistical mechanics. This type of modeling approach assumes that idealized materials such as polymers, or in the present case, complex petrol-organic molecules found in asphalts, tend to undergo such phenomena as phase separation and nucleate, flocculation/dissolution, crystallizing and melting, all contributing to material softening and embitterment, when characterized as a function of time and temperature. One may then attempt to describe irreversible non-equilibrium thermodynamic processes involving phase ordering vis energy dissipation in asphalt molecular moieties leading to such processes as solidification/melting events by assuming the coupling of material (molecular particles) transport and heat flow between “classes” of petro-chemical molecules to describe diffuse interface dynamics. In these kinds of studies asphalt may be described as a continuum nano-emulsion, that is to say, a solution comprised of a molecular

distribution (M.W., H/C, density, etc.) of petro-chemicals (much like a complex true solution mixture), when defined specifically at temperatures above the material's glass transition temperature, or as an amorphous glass specifically defined through and below the material's glass transition temperature. For an example, past research has demonstrated that the Pal-Rhodes model for concentrated micro-emulsions serves well as a first approximation for quantifying asphalt "micro/nano structuring" events at midrange service temperatures. On the other hand asphalt may be described as an amorphous solid at sub-zero temperatures, but why? This task will attempt to answer this question.

In this task, models of asphalt-binder, coupled with nanotechnology (AFM imaging; friction and morphology, contact-force AFM, nanoindentation AFM, chemical-force AFM, etc.), will continue to be developed or improved that strictly adhere to both quantum mechanical and classical mechanical laws of physics to describe well defined molecular components that accurately represent asphalts as functions of crude source. Phase-field modeling, for example, which may be derived from the theory of extended irreversible thermodynamics (EIT), has been utilized for almost fifty years to describe such phenomena as phase separation in heterogeneous material phases, growth of new phases such as polymer crystals, phase-field modeling has even been utilized to describe brittle fracture in solid materials.

- i) Collaborate with academic and private institutions (Consortium members, NIST, U of RI, TU Delft, etc.) to develop compositional modeling tools. This endeavor may include computational molecular simulations based on *ab initio* calculations, density function theory and Monte Carlo (fluctuation-dissipation theory) simulations, dissipative-structure theory, diffuse interface and phase-field approaches, which stem from the extended irreversible thermodynamics (EIT).
- ii) Collaborate with academic and private institutions to develop physical/rheological modeling tools. These endeavors may include development and utilization of contact and fracture mechanics approaches, strain energy models and other continuum mechanics models, and phase-field modeling grounded in EIT theories, as previously alluded to. It is anticipated that a chemo mechanical model will emerge from these efforts to target direct relationships between material composition and pavement performance.
- iii) Develop approaches (Theoretical) which lead to computational software (e.g., Virtual Asphaltic Concrete Testing Laboratory (VACTL), chemo-metrics, data mining, and neural-networks) to model physico-chemical and chemo-mechanical systems pertinent to continuum mechanics models already in place in current and future asphalt pavement technologies.

Work Element F3b: Micromechanics Model

Subtask F3b-1 Model Development

Micromechanical models are powerful in accounting for the interactions among the mixture constituents. They are capable of explicitly modeling the mixture microstructure geometry and the properties of each of the constituents. In this task, the researchers will pursue the development of several micromechanical modeling approaches.

The first approach will develop the analytical micromechanics models that yield effective mastic and mixture properties given the properties and distribution of the constituents. These analytical micromechanics models will also be able to account for the influence of damage distribution on the effective properties. The analytical models will be developed at Texas A&M University.

The second approach will advance the micromechanics-based computational model that has been developed by researchers at the University of Nebraska (NU). Past work has demonstrated a number of innovative features of the model including (1) bridging the scales between micro-scale (fundamental mixture component properties) and macro-scale (damage-dependent behavior of whole asphalt concrete mixtures), (2) explicit prediction of nonlinear-inelastic material behavior, (3) realistic simulation of rate-dependent microscale fracture damage based on a cohesive zone approach, and (4) microstructure characterization to represent mixture heterogeneity and anisotropy. This modeling approach is directly incorporated into this project in that it employs fundamental materials and mixture properties (outcomes from Category F1) that are obtained from testing methods (Category F2), and will be implemented into other modeling efforts including the unified continuum model (Category F3). The NU model will eventually be calibrated and/or validated through various laboratory performance data and the FHWA-ALF experimental results. More specifically, the NU model will use the thermodynamic/mechanical cohesive-adhesive properties of mixture components, linear-nonlinear viscoelastic properties, and geometric information such as mixture microstructure and aggregate images provided by TAMU and UWM as basic model inputs. Furthermore, the model will be elaborated by taking into account several key fatigue damage-associated factors such as the effects of binder modification, binder aging, additives, damage healing, and moisture to seamlessly explain the complex fatigue damage behavior of asphalt mixtures and pavements. As a subcontractor, NU will take the lead in this particular modeling activity and will collaborate with TAMU who will lead the experimental-analytical part.

The third approach will further develop the multi-scale lattice micromechanical model. Lattice modeling was developed by North Carolina State University (NCSU) with the ultimate goal of linking micromechanical constituent properties with macroscopic damage behavior of asphalt concrete. Past work in this area showed significant promise of this approach, but highlighted several issues, with the most important being the difference between the scale at which experimental measurements are conducted and the scales captured in the model. The extensive experimental program proposed in various work elements in this research would provide rich data that could be used to develop a more robust and reliable lattice model. Specifically, the thermodynamic and mechanical cohesion and adhesion properties as well as the data from aggregate imaging system would provide valuable input to the model. Similarly, any insight gained into asphalt concrete behavior from other microscopic testing by synchrotron and AFM would greatly help refine the lattice model and enhance its predictive capabilities. The lattice model development will be led by NCSU. TAMU will lead the experimental part, providing NCSU with all the data.

Subtask F3b-2 Account for Material Microstructure and Fundamental Material Properties

Previous research efforts have shown that most micromechanical computational models, irrespective of the numerical implementation, underestimated the stiffness and strength of asphalt

mixtures. This was attributed to the lack of realistic representation of the mixture microstructure and the use of bulk properties of the constituents. This finding motivates us to focus some of the research efforts on the use of detailed representation of the microstructure, which can be achieved by using X-ray CT imaging at multiple resolutions. Also, the research will focus on the use of rigorous upscaling methods that are able to incorporate experimental measurements conducted at a small scale into a micromechanical model at a larger scale. For example, the bond energy per unit area calculated from surface energy measurements should be scaled up prior to its use in a micromechanical model. The scaling takes into account the fact that the micromechanical model cannot, due to computational limitations, account for the nanostructural details at which the surface energy is acting. In other words, the actual area of the microstructure can be reduced by orders of magnitudes when transferred to the model scale.

In summary, the research efforts will focus on improving the cohesive zone-based computational micromechanics model and the lattice model in order to better account for the microstructure distribution (asphalt film thickness, realistic shape of aggregates, aggregate size distribution) and to incorporate the fundamental properties measured in Category F1 of the work plan.

Work Element F3c: Development of Unified Continuum Model

Subtask F3c-1 Analytical Fatigue Model for Mixture Design

In this task, a fracture model for predicting the resistance of asphalt mixtures to fatigue loading will be finalized. This model is founded based on the principles of the fatigue model developed during the Strategic Highway Research Program (SHRP) at Texas A&M University. The model accounts for the energy dissipated in fracture, energy dissipated in permanent deformation, physio-chemical properties of mixture (adhesive and cohesive bonds), and viscoelastic properties (Masad et al. 2007). This model is capable of unifying the results from stress-controlled and strain-controlled tests. This model can also be used to analyze experimental measurements conducted on the mastic and fine portions of the mix using the dynamic mechanical analysis and on full mixtures using repeated loading.

The model has been used so far to analyze experimental measurements conducted at a limited range of temperatures and loading frequencies. The research will focus on expanding the use of the model to analyze master curves constructed from comprehensive measurements over wide ranges of temperatures, loading rates, stress levels and strain levels. This is necessary to verify the unified nature of the model for stress controlled and strain controlled tests at all temperatures and loading rates representing different pavement structures.

Subtask F3c-2 Unified Continuum Model

This item constitutes significant part of the research as it will lead to the development of comprehensive viscoelastoplastic continuum damage (VEPCD) model that is applicable for wide ranges of temperatures, different loading rates and complex and realistic mechanical and thermal stresses.

The modeling efforts are based on the following theoretical pillars: (1) the elastic-viscoelastic correspondence principle based on pseudo strain for modeling the viscoelastic behavior of the material; (2) the continuum damage mechanics-based work potential theory for modeling the effects of microcracks on global constitutive behavior; (3) the time-temperature superposition principle with growing damage; (4) the strain hardening viscoplastic model for modeling plastic and viscoplastic behavior; (5) the strain decomposition theory for integrating the nonlinear viscoelastic strain and the viscoplastic strain to describe the total strain; and (6) the anisotropic nature of the aggregates structure..

The fundamentals that govern the model's development have already been established by work at NCSU and TAMU. However, there is still significant work that needs to be done as part of this project in order to:

- (a) integrate all these components in a comprehensive model,
- (b) verify the model predictions under various loading, environmental and boundary conditions,
- (c) relate the model's parameters to fundamental material properties as discussed in section F3c-3, and
- (d) implement the material model in a public domain finite element structural model developed at NCSU.

Subtask F3c-3 Multi-Scale Modeling

A draw back of conventional continuum damage models is that the parameters are determined based on fitting the model to experimental macroscopic parameters. Therefore, these parameters could lose to a certain extent their link to the fundamental properties, and their values could become dependent on the tests used in fitting the model. A major contribution of the research will be to focus on linking the parameters of the continuum model to the fundamental materials properties measured in Category F1. This will be achieved through developing a multi-scale approach in which the micromechanical models described in work element F3b will be used to calculate effective mixture properties based on properties of the mixture constituents. These effective material properties are used as inputs for the continuum model. The multi-scale approach will assist in formulating damage in the continuum model based on the principles of fracture and healing established in work element F1d.

Development of the multi-scale modeling approach has many benefits, including: (1) a more realistic simulation of pavement cracking phenomena by covering the propagation of both microcracks and macrocracks; (2) simpler testing requirements for state highway agencies; (3) a more accurate prediction of performance of asphalt pavements; and (4) a direct relationship between mixture design, material properties and mixture performance.

As part of the multi-scale modeling approach, the results of the computational micromechanical models will be compared to the continuum model results in order to ensure that the macroscopic predictions by the continuum models are explained by the interactions among the mixture constituents in the micromechanical models.

Work Element F3d: Calibration and Validation

The same set of materials will be used in all the Categories discussed above. The researchers will use the materials from the FHWA-ALF experiment and the test sections currently being monitored by WRI. These sections are described in Table 1.

Table 1. A List of mixes used in the field validation study.

Project	Binders
Wyoming HWY 216	PG 58-28 WY1-1 WY-Canadian Blend
	PG 58-28 WY1-2 WY-Rocky Mtn Blend
Nevada I-15	PG 64-22 NV1-1 WY-Rocky Mtn Blend
	PG 64-22 NV1-2 Nevada
	PG 64-22 NV1-3 Venezuelan
	PG 64-22 NV1-4 Canadian
Arizona US 93	PG 76-16 AZ1-1 West Tx Sour & Int Blend
	PG 76-16 AZ1-4 Rocky Mtn Blend B
	PG 76-16 AZ1-3 Rocky Mtn Blend A
	PG 76-16 AZ1-2 Venezuelan
Kansas US 77	PG 64-22 KS1-1 Mid Continent Blend A
	PG 64-22 KS1-2 OK Blend
	PG 64-22 KS1-3 TX/OK Blend
	PG 64-22 KS1-4 KS/UK Blend

In addition to the use of materials with known field performance, the researchers will utilize materials that represent the different combinations of mixtures. It is envisioned that these materials will include the following:

- 1) Asphalt binders:
 - a. Several PG grades: 58, 64, 70, and 76.
 - b. Base binders should be from two different sources
 - c. Modification methods; styrene-butadiene-styrene (SBS), terpolymer (Elvaloy), ethylene vinyl acetate (EVA), and chemical modification
- 2) Different fillers: acidic (quartzite), basic (calcite), and neutral (such as Ottawa sand)
- 3) Aggregates:
 - a. Mineralogy: limestone (with two different moisture-susceptibility histories) and granite (with two different moisture-susceptibility histories)
 - b. Angularity and gradation: one coarse aggregate and one fine aggregate with significant differences in their surface areas.

- 4) Conditioning water: distilled water, sodium chloride solution, and calcium chloride solution.

Mixtures will be designed using the Superpave system to have fine gradation, coarse gradation and stone matrix asphalt (SMA) gradations. The researchers will seek input from the FHWA and ETGs on the selection of mixtures to maximize the comparisons with field performance. We will also seek to coordinate efforts with ongoing national studies (NCHRP and pool fund) in the selection of materials and mixtures.

YEAR 1 PROJECT DIRECTION

In Category F1: Material Properties, the focus of year 1 will be to:

- Conduct a comprehensive literature review to identify the most critical areas that need to be addressed in this project including properties and mechanisms related to cohesive and adhesive bonding, binder oxidative aging, and healing.
- Develop detailed experiment designs to support the relevant areas.
- Begin measuring the thermodynamic work of adhesion and cohesion for a suite of selected asphalt binders, mastics, and aggregates, including modified and unmodified binders.
- Develop a transport model for binder oxidation.
- Determine the relationship between healing and the fatigue endurance limit.

In Category F2: Test Method Development, the focus of year 1 will be to;

- Evaluate fatigue life of polymer modified asphalt binders and prepare modified asphalt binders and investigate the impact of this modification on fatigue life.
- Finalize the mixture design and specimen preparation procedures for the testing of mastics and the fine aggregate matrix using the Dynamic Mechanical Analyzer (DMA).
- Evaluate and define the relationship (or correlation) between fatigue performance of asphalt binder (and/or mastic) to the fatigue performance of the asphalt mixture.

In Category F3: Modeling, the focus of year 1 will be to:

- Refine the micromechanics model using the discrete element and finite element (cohesive zone) approaches for mastics and mixtures.
- Develop an analytical model for fatigue damage that can be used to evaluate the fatigue cracking life of asphalt mixtures during the mixture design process.
- Develop the unified continuum fatigue model to incorporate various material properties.

SCHEDULE

		Year 1	Year 2	Year 3	Year 4	Year 5
Category F1: Material and Mixture Properties						
F1a	Cohesive and Adhesive Properties	X	X	X		
	1a-1 Critical review of literature	X				
	1a-2 Develop experiment design	X				
	1a-3 Thermodynamic work of adhesion and cohesion	X	X	X		
	1a-4 Mechanical work of adhesion and cohesion		X	X		
	1a-5 Evaluate acid-base scales for surface energy		X			
F1b	Viscoelastic Properties	X	X	X	X	
F1c	Aging	X	X	X	X	X
	1c-1 Review of binder oxidative aging	X				
	1c-2 Develop experiment design	X				
	1c-3 Develop transport model for binder oxidation	X	X	X		
	1c-4 Effect of binder aging on properties and performance		X	X	X	X
	1c-5 Polymer modified binders			X	X	
F1d	Healing	X	X	X	X	X
	1d-1 Critical review of literature	X				
	1d-2 Select materials with targeted properties	X	X			
	1d-3 Develop experiment design	X				
	1d-4 Test methods to determine properties relevant to healing		X	X		
	1d-5 Validate contribution of healing using DMA		X	X	X	
	1d-6 Determine relationship between healing and endurance limit	X	X	X	X	X
	1d-7 Coordinate with AFM analysis		X	X		
	1d-8 Develop form for healing parameter to incorporation in models		X	X	X	X
	1d-9 Design experiment on selected binders with synchrotron		X	X		
Category F2: Test Method Development						
F2a	Binder Tests and Effect of Composition	X	X	X	X	X
	2a-1 Analyze existing fatigue data for polymer modified asphalts	X				
	2a-2 Select virgin binders and modifiers to prepare modified binders	X	X			
	2a-3 Subject virgin and modified binders to several aging procedures		X	X		
	2a-4 Collect fatigue test data for all samples			X	X	X
	2a-5 Mechanisms for aging & modification effects on binder fatigue					X
F2b	Mastic Testing Protocol	X				X
	2b-1 Develop specimen preparation procedures	X				
	2b-2 Document test and analysis procedures in AASHTO format					X
F2c	Mixture Testing Protocol				X	X
F2d	Tomography and microstructure characterization		X	X	X	
F2e	Verification: DSR fatigue & Mixture performance	X	X	X	X	X
	2e-1 Evaluate binder fatigue correlation to mixture fatigue data	X				
	2e-2 Selection of mixture testing protocols		X			
	2e-3 Binder and mixture fatigue testing		X	X	X	
	2e-4 Verification of surrogate fatigue test				X	
	2e-5 Interpretation and modeling of data				X	
	2e-6 Recommendations for use in unified model					X

Category F3: Modeling						
F3a	Asphalt Microstructure Model		X	X	X	X
F3b	Micromechanics Model	X	X	X	X	X
	3b-1 Model development	x	x	x	x	x
	3b-2 Account for fundamental material properties in model		x	x	x	x
F3c	Unified Continuum Fatigue Model	X	X	X	X	X
	3c-1 Analytical fatigue model for use during mixture design	x	x	x	x	x
	3c-2 Unified continuum model	x	x	x	x	x
	3d-2 Multi-Scale modeling		x	x	x	x
F3d	Calibration and Validation			X	X	X

RELATIONSHIP TO FHWA FOCUS AREAS

The fatigue work elements support the FHWA Focus Area of Optimizing Pavement Performance by providing a relationship between material property and pavement performance.

BUDGET

		Year 1	Year 2	Year 3	Year 4	Year 5
Category F1: Material and Mixture Properties						
F1a	Cohesive and Adhesive Properties (TAMU)	60,000	100,000	90,000		
F1b	Viscoelastic Properties (TAMU)	70,000	75,000	30,000	25,000	
F1c	Aging (TAMU)	70,000	100,000	110,000	110,000	75,000
F1d	Healing (TAMU)	60,000	105,000	100,000	100,000	75,000
	Healing (UWM)	75,000	75,000	100,000	100,000	50,000
Category F2: Test Method Development						
F2a	Binder Tests and Effect of Composition (UWM)	75,000	100,000	100,000	100,000	50,000
F2b	Mastic Testing Protocol (TAMU)	20,000				20,000
F2c	Mixture Testing Protocol (TAMU)				20,000	20,000
F2d	Tomography and microstructure characterization (TAMU)		70,000	50,000	50,000	
F2e	Verification: DSR fatigue & Mixture performance (UWM)	75,000	100,000	100,000	100,000	100,000
Category F3: Modeling						
F3a	Asphalt Microstructure Model (WRI)		316,000	321,000	321,000	319,000
F3b	Micromechanics Model (TAMU)	60,000	125,000	125,000	125,000	110,000
F3c	Unified Continuum Fatigue Model (TAMU)	60,000	125,000	125,000	125,000	110,000
F3d	Calibration and Validation*			90,000	95,000	140,000
TOTAL		625,000	1,291,000	1,341,000	1,271,000	1,069,000
				5,597,000		

Note* Tentatively only budget from TAMU is reflected here but this element will involve coordination from all agencies.

REFERENCES

- Bhasin, A., and D. N. Little (2006). "Characterization of aggregate surface energy using the universal sorption device." *Journal of Materials in Civil Engineering (ASCE)*, Accepted for publication.
- Della Volpe, C., and S. Siboni (2000). "Acid base surface free energies of solids and the definition of scales in the Good van Oss Chaudhury theory." *Journal of Adhesion Science and Technology*, 14(2), 235-272.
- Hefer, A. W., A. Bhasin, and D. N. Little (2006). "Bitumen surface energy characterization using a contact angle approach." *Journal of Materials in Civil Engineering (ASCE)*, 18(6), 759-767.
- Huang, C. W., E. Masad, A. Muliana, and H. Bahia (2007). "Development and Numerical Implementation of a Nonlinear Viscoelastic Model for Hot Mix Asphalt." *Mechanics of Time Dependent Materials*, (In Review).
- Little, D. N., and A. Bhasin (2006). "Using Surface Energy Measurements to Select Materials for Asphalt Pavement." *Final Report for Project 9-37*, Texas Transportation Institute.
- Masad, E. (2004). "X-ray Computed Tomography of Aggregates and Asphalt Mixes," *Materials Evaluation Journal, American Society for Nondestructive Testing*, Vol. 62, No. 7, pp. 775 – 783.
- Masad, E., V. Castelo Branco, D. Little, and R. Lytton (2007). "A Unified Method for the Analysis of Controlled-Strain and Controlled-Stress Fatigue Testing." *International Journal of Pavement Engineering* (Accepted for Publication).
- Sharon, E., S. P. Gross, and J. Fineberg (1996). "Energy Dissipation in Dynamic Fracture." *Physical Review Letters*, 76(12), 2117-2120.

Appendix F1

Flow Chart Illustrating Integration of Elements for Fatigue Work Area

