## TABLE OF ASPHALT RESEARCH CONSORTIUM DELIVERABLES

| Deliverable | Description | Draft Delivery Date | Final Delivery Date | ARC Partner | Staff Assignment | Notes |
|---|---|---|---|---|---|---|
| Summary Report | Comprehensive Summary Report (Level 1)<br><br>(Report summarizing all work elements in significant detail to provide a single source documentation of ARC accomplishments) | 4/30/2013 | 12/15/2013 | TAMU | All | Reference level 2 and 3 deliverables for details |
| Report A | Summary report on Moisture Damage (Level 2) | 1/31/2013 | 9/30/2013 | TAMU | Masad | Sent to FHWA for review, Reference level 3 deliverables for details |
| Report B | Characterization of Fatigue Damage and Relevant Properties (Level 2) | 5/31/2013 | 10/31/2013 | TAMU | Bhasin | Reference level 2 and 3 deliverables |
| Report C | PANDA: Pavement Analysis using a Nonlinear Damage Approach (Level 2) | 5/31/2013 | 11/30/2013 | TAMU | Darabi | Summary of PANDA methodology including descriptions of methods for indentifying model parameters |
| Report D | Microstructural Characterization of the Chemo-Mechanical Behavior of Asphalt in Terms of Aging and Fatigue Performance Properties (Level 2) | 5/31/2013 | 10/31/2013 | TAMU | Little | Summary report on methodology for characterizing the phases of asphalt binder with description of composite |

| Deliverable | Description | Draft Delivery Date | Final Delivery Date | ARC Partner | Staff Assignment | Notes |
|---|---|---|---|---|---|---|
| | | | | | | implications |
| Report E | Lattice Model and Continuum Damage to Fracture (Level 2) | 5/31/2013 | 9/30/2013 | NCSU | R. Kim | Comprehensive report on lattice model |
| Report F | Microstructure Cohesive Zone Modeling for Moisture Damage and Fatigue Cracking (Level 2) | 1/31/2013 | 8/31/2013 | UNL | Y.R. Kim | Sent to FHWA for review Comprehensive report of cohesive zone model |
| Report G | Design System for HMA Containing a High Percentage of RAP Material | 12/31/2013 | 3/31/2014 | UNR | Sebaaly Hajj | |
| Report H | Critically Designed HMA Mixtures | 5/31/2013 | 11/30/2013 | UNR | Hajj Sebaaly | Comprehensive report describing the developed mechanistic-based approach for critically designed mixtures |
| Report I | Thermal Cracking Resistant Mixes | 8/31/2013 | 12/31/2013 | UNR | Hajj Sebaaly | |

| Deliverable | Description | Draft Delivery Date | Final Delivery Date | ARC Partner | Staff Assignment | Notes |
|---|---|---|---|---|---|---|
| Report J | Pavement Response Model to Dynamic Loads 3D Move | 9/30/2013 | 12/31/2013 | UNR | Hajj Sebaaly | Delayed. Research team focused on addressing and solving the various bugs reported by the users for newly released Ver. 2 of the software. |
| Report K | Development of Materials Database | 6/30/2013 | 12/31/2013 | UNR | Hajj Ekedahl | |
| Report L | Development and Validation of the Bitumen Bond Strength Test (BBS) | Completed 10/31/11 | 6/30/2013 | UWM | Hanz | Extended to incorporate new information from NCHRP 9-50 |
| Report M | Development of Test Procedures for Characterization of Asphalt Binder Fatigue and Healing | Completed 10/31/11 | 6/30/2013 | UWM | Tabatabaee | Final pending receipt of peer review comments |
| Report N | Guideline for Selection of Modification Techniques | 9/30/2013 | 3/31/2014 | UWM | Tabatabaee | On schedule |
| Report O | Characterization of Binder Damage Resistance to Rutting | 6/30/2013 | 12/31/2013 | UWM | Tabatabaee | On schedule |
| Report P | Quantifying the Impacts of Warm Mix Asphalt on Constructability and Performance | 9/30/2013 | 12/31/2013 | UWM | Hanz | Draft extended 6 months |
| Report Q | Improvement of Emulsion Characterization and Mixture Design for Cold Bitumen Applications | 9/30/2013 | 3/31/2014 | UWM | Hanz | On schedule |

| Deliverable | Description | Draft Delivery Date | Final Delivery Date | ARC Partner | Staff Assignment | Notes |
|---|---|---|---|---|---|---|
| Report R | Studies on Tire-Pavement Noise and Skid Response | Completed 12/31/11 | 6/30/2013 | UWM | Roohi | On schedule |
| Report S | Molecular dynamics results for multiple asphalt chemistries | 5/31/2013 | 12/31/2013 | URI | Greenfield | |
| Report T | Progress Toward a Multi-scale Model of Asphalt Pavement- Including Test Methods for Model Input Parameters | 9/30/2013 | 3/31/2014 | WRI | Pauli | Delayed because fo Delft finite element work |
| Report U | Design Guidance for Fatigue and Rut Resistance Mixtures | 9/30/2013 | 3/31/2014 | AAT | Bonaquist Christensen | NTIS format report with Technical Brief |
| Report V | Continuum Damage Permanent Deformation Analysis for Asphalt Mixtures (Level 2) | 5/31/2013 | 10/31/2013 | TAMU | Lytton/Luo | Reference appropriate level 3 deliverables |
| Report W | Characterization of Fatigue and Healing Properties of Asphalt Mixtures (Level 2) | 5/31/2013 | 10/31/2013 | TAMU | Lytton/Luo | Reference appropriate level 3 deliverables |
| Report X | Characterization of Field Cores of Asphalt Pavements (Level 2) | 5/31/2013 | 10/31/2013 | TAMU | Lytton/Luo | Reference appropriate level 3 deliverables |
| Report Y | Water Vapor Diffusion in Pavement and Its Effects on the Performance of Asphalt Mixtures (Level 2) | 5/31/2013 | 11/30/2013 | TAMU | Lytton/Luo | Reference appropriate level 3 deliverables |
| Report Z | Effect of Extraction Methods on the Properties of Aggregates in Reclaimed Asphalt Pavement (NTIS format) | Completed 3/1/2013 | | UNR | Hajj Sebaaly | Final pending receipt of peer review comments |

| Deliverable | Description | Draft Delivery Date | Final Delivery Date | ARC Partner | Staff Assignment | Notes |
|---|---|---|---|---|---|---|
| AASHTO Method | Simplified Continuum Damage Fatigue Analysis for the Asphalt Mixture Performance Tester | 5/31/2013 | 9/30/2013 | AAT | Bonaquist Christensen | Development documented in Report U |
| AASHTO Method | Wilhelmy Plate Test (Level 3) | 1/31/2013 | 6/30/2013 | TAMU | Bhasin | Sent to FHWA for review Referenced in Reports A & B |
| AASHTO Method | Universal Sorption Device (Level 3) | 1/31/2013 | 6/30/2013 | TAMU | Bhasin | Sent to FHWA for review Referenced in Reports A & B |
| AASHTO Method | Dynamic Mechanical Analysis (Level 3) | 1/31/2013 | 6/30/2013 | TAMU | Kassem | Sent to FHWA for review Referenced in Reports A & B |
| ASTM Method | Automated Flocculation Titrimetric Analysis | Completed | | WRI | Pauli | ASTM D-6703 |
| AASHTO Method | Determination of Polymer in Asphalt | Completed | | WRI | Harnsberger | |
| AASHTO Method | A Method for the Preparation of Specimens of Fine Aggregate Matrix of Asphalt Mixtures (Level 3) | 1/31/2013 | 6/30/2013 | TAMU | Kassem | Sent to FHWA for review Referenced in Reports A & B |
| AASHTO Method | Measuring intrinsic healing characteristics of asphalt binders | 1/31/2013 | 6/30/2013 | TAMU/ UT | Bhasin | Sent to FHWA for review Referenced in Report B |
| AASHTO Method | Test Methods for Determining the Parameters of Material Models in PANDA (Pavement Analysis Using Nonlinear Damage Approach) (Level 3) | 5/31/2013 | 7/31/2013 | TAMU | Kassem Darabi | Referenced in Report C |
| Test Method & | Continuum Damage Permanent Deformation Analysis for Asphalt Mixtures | 5/31/2013 | 10/31/2013 | TAMU | Lytton/Luo | Referenced in Report V |

| Deliverable | Description | Draft Delivery Date | Final Delivery Date | ARC Partner | Staff Assignment | Notes |
|---|---|---|---|---|---|---|
| Model | (Level 3) | | | | | |
| Test Method & Model | Characterization of Fatigue and Healing Properties of Asphalt Mixtures (Level 3) | 5/31/2013 | 9/30/2013 | TAMU | Lytton/Luo | Referenced in Report W |
| Test Method Analysis Program | Nondestructive Characterization of Tensile Viscoelastic Properties of Undamaged Asphalt Mixtures (Level 3) | 5/31/2013 | 10/31/2013 | TAMU | Lytton/Luo | Referenced in Reports W & Y |
| Test Method & Model | Characterization of Field Cores of Asphalt Pavements (Level 3) | 5/31/2013 | 10/31/2013 | TAMU | Lytton/Luo | Referenced in Reports W & X |
| Test Method Analysis Program | Nondestructive Characterization of Anisotropic Viscoelastic Properties of Undamaged Asphalt Mixtures under Compressive Loading (Level 3) | 5/31/2013 | 10/31/2013 | TAMU | Lytton/Luo | Referenced in Report V |
| AASHTO Practice | Mix Design for Cold-In-Place Recycling (CIR) | 12/31/2013 | | UNR | Sebaaly Hajj | Detailed in Report Q |
| AASHTO Practice | Mix Design for Cold Mix Asphalt | 9/30/2013 | 3/31/2014 | UWM | Hanz | On schedule |
| AASHTO Practice | Evaluation of RAP Aggregates | 12/31/2012 | | UNR | Sebaaly | Detailed in Report G |
| AASHTO Practice | Identification of Critical Conditions for HMA mixtures | 5/31/2013 | | UNR | Hajj Sebaaly | Detailed in Report H |
| AASHTO Method | Determining Thermal Crack Properties of Asphalt Mixtures Through Measurement of Thermally Induced Stress and Strain | Completed 5/31/2012 | | UNR | Hajj Velasquez | Detailed in Report I |
| AASHTO Method | Determining Asphalt Binder Bond Strength by Means of the Bitumen Bond Strength Test ( BBS) | Completed | 6/30/13 | UWM | Hanz | Approved as AASHTO TP-91 |
| AASHTO Method | Measurement of Asphalt Binder Elastic Recovery in the Dynamic Shear Rheometer (DSR ) | Completed 1/31/2013 | 6/30/2013 | UWM | Tabatabaee | On schedule |
| AASHTO | Estimating Fatigue Resistance of Asphalt | Completed | 6/30/2013 | UWM | Tabatabaee | Approved as |

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|---|---|---|---|---|---|---|
| Method | Binders Using the Linear Amplitude Sweep (LAS) | | | | | AASHTO TP-101 |
| AASHTO Method | Binder Yield Energy Test ( BYET) | Completed 1/31/2013 | Complete | UWM | Tabatabaee | Combine with ER-DSR, BYET |
| AASHTO Method | Measurement of Rigden Voids for fillers | Completed 1/31/2013 | 6/30/2013 | UWM | Roohi | Pending review comments |
| AASHTO Method | Measurement of Asphalt Binder Lubricity Using the Dynamic Shear Rheometer (DSR) | 6/30/2013 | 12/31/2013 | UWM | Hanz | |
| AASHTO Method | Procedure for Evaluation of Coating for Cold Mix Asphalt | 4/30/2013 | 9/30/2013 | UWM | Hanz | |
| AASHTO Method | Cold Mix Laboratory Specimen Preparation Using Modified SGC Molds | 6/30/2013 | 12/31/2013 | UWM | Hanz | |
| AASHTO Method Software | RAP Binder PG True Grade Determination | Completed 9/30/2012 | 6/30/2013 | UWM | Hanz | Action pending ETG comments |
| AASHTO Method | Measurement of Asphalt Binder Fracture Properties Using the Single Edge Notch Bending Test | Completed 9/30/2012 | 6/30/2013 | UWM | Tabatabaee | Action pending ETG comments |
| AASHTO Method | Test Method for Measurement of the Glass Transition Temperature of Asphalt Binders | Completed 1/31/2013 | 6/30/2013 | UWM | Tabatabaee | Action pending FHWA/ETG comments |
| AASHTO Method | Test Method for Measurement of the Glass Transition Temperature of Asphalt Mixtures | 4/30/2013 | 6/30/2013 | UWM | Tabatabaee | Combined with UNR TSRST procedure |
| AASHTO Method Software | Analysis of Asphalt Mixture Aggregate Structure through Use of Planar Imaging and Image Processing & Analysis System (IPAS) | 4/30/2013 | 9/30/2013 | UWM | Roohi | Submission pending |
| AASHTO Method | Determining the Resistive Effort of Asphalt Mixtures during Compaction in a Gyrator Compactor using an Internal Device | Completed ASTM | 9/30/2013 P&B testing | UWM | Hanz | ASTM Standard approved |
| AASHTO | Micromechanical Properties of Various | 3/31/2013 | 8/31/2013 | TAMU | Little | Sent to FHWA |

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|---|---|---|---|---|---|---|
| Method | Structural Components in Asphalt using Atomic Force Microscopy (AFM) (Level 3) | | | | | for review, Referenced in Report D |
| AASHTO Method | Test Method for Fatigue of Binder and Mastics: A cyclic direct tension test that can provide direct evaluation of fatigue for binder and mastic. It can also provide model validation and model parameter inputs. | 4/30/2013 | 10/31/2013 | VT | Wang | |
| AASHTO Method | Evaluate Healing using Continuum Damage Approach (Level 3) | 5/31/2013 | 8/31/2013 | TAMU/ UT | Bhasin | Appendix in Report B |
| Test Method & Analysis Program | Self-Consistent Micromechanics Models of Asphalt Mixtures (Level 3) | 5/31/2013 | 10/31/2013 | TAMU | Lytton/Luo | Referenced in Report W |
| AASHTO Method & Analysis Program | Nonlinear Mechanical Behavior of Asphalt Binders and Prediction of Rutting Susceptibility (Level 3) | 5/31/2013 | 9/30/2013 | TAMU | Little | References to Dissertation & journal papers |
| AASHTO Method | Method to determine surface roughness of aggregate and fines based on AFM | 9/30/2013 | 4/30/2014 | WRI | Grimes | Will be subject of Tech. Pub. |
| AASHTO Method | A method to determine ductile-brittle properties via AFM measurements | 4/30/2013 | 11/30/2013 | WRI | Grimes | Will be subject of Tech. Pub. |
| AASHTO Method | AFM-based micro/nano-scale cyclic direct tension test | 3/31/2013 | 10/31/2013 | WRI | Grimes | Will be subject of Tech. Pub. |
| AASHTO Method | Measurement and Texture Spectral Analysis of Pavement Surface Profiles Using a Linear Stationary Laser Profiler (SLP) | Completed 9/30/2012 | 3/31/2013 | UWM | Roohi | Pending FHWA review |
| Model | HMA Thermal Stresses in Pavement | 3/31/2014 | | UNR | Hajj | Detailed in Report I |
| Software | Dynamic Model for Flexible Pavements 3D-Move | 9/30/2013 | | UNR | Hajj Siddharthan | Detailed in Report J |

| Deliverable | Description | Draft Delivery Date | Final Delivery Date | ARC Partner | Staff Assignment | Notes |
|---|---|---|---|---|---|---|
| Model & Test Method | Improved Oxygen and Thermal Transport Model of Binder Oxidation in Pavements (Level 3) | 5/31/2013 | 10/31/2013 | TAMU | Glover | Part of Report B & Summary Report References to Dissertations and Journal Papers |
| Model & Test Method | Pavement Air Voids Size Distribution Model for use in an Oxygen and Thermal Transport Model of Binder Oxidation in Pavements (Level 3) | 5/31/2013 | 10/31/2013 | TAMU | Glover | Part of Report B & Summary Report References to Dissertations and Journal Papers |
| Model | Approaches to interpret MD simulation results and experimental data to quantify the composition and temperature dependence of free energy. | 3/31/2013 | | URI | Greenfield | Detailed in Report S |
| Model and Software | Phase-Field Model of Asphalt Binder Fracture and COMSOL Code for Model | 9/31/2013 | 3/31/2014 | VT | Wang | Detailed in Report T |
| Software | PANDA Software (Pavement Analysis using a Nonlinear Damage Approach) | 12/31/2013 | 6/20/2014 | TAMU | Sun-Myung Kim | |
| Model & Software | Lattice Micromechanical Model for Virtual Testing of Asphalt Concrete in Tension | 3/31/2013 | | NCSU | Richard Kim | Part of Report E |

A brief description of each deliverable follows:

**Summary Report: Comprehensive Executive Report of Principal Contributions of Texas A&M University to Asphalt Research Consortium Program**

*Report Summary*

This report overviews the wide range of research deliverables produced by the Texas A&M University (TAMU) team for the Asphalt Research Consortium (ARC) program. These deliverables include ten major technical topical reports; sixteen test methods (nine of which are presented in the format of AASHTO recommended methods of practice); a finite element model of asphalt pavement in which damage can be assessed at either the continuum or micromechanical scale; a micromechanical, cohesive zone model of asphalt behavior; and a lattice model of asphalt behavior that can either be evaluated at either the micromechanical or continuum scale. These deliverables are the culmination of a blend of basic, developmental and applied research conducted under the ARC program.

This comprehensive report is presented in three parts. Part I is an overview of the ARC program that defines TAMU's contributions along with TAMU's collaborators (the University of Texas – Austin, the University of Illinois- Urbana-Champaign, North Carolina State University and the University of Nebraska-Lincoln). Part II addresses key issues regarding viscoelastic characterization of asphalt materials with emphasis on damage accumulation and with a specific focus on moisture damage, oxidative aging, fracture and healing, nonlinear and three-dimensional stress states, and micro-rheological properties of asphalt binders. Part III addresses the computational models as asphalt performance with primary focus on the Pavement Analysis using Non-Linear Damage Analysis (PANDA) model but also including cohesive zone and lattice models of the asphalt mixture.

Within the topical area of moisture damage, Report 0 concentrates on fundamental mechanisms of moisture damage, moisture transport over the range of length scales included in the asphalt mixture, characterization of material properties resulting from moisture damage, the driving forces for moisture movement over these various length scales, and methods to assess moisture damage over the various length scales. Within the topical areas of binder and mixture aging, an oxygen transport model is proposed, and both fast-rate and constant-rate kinetics are considered as well as the impact of the structure of the asphalt mixture on oxidation and the impact of oxidation on mixture properties.

Within the wide-ranging topical area of damage in the asphalt pavement, the report addresses tensile and compressive viscoelastic properties of asphalt mixtures, anisotropic properties of the mixture, permanent deformation, and fatigue and healing. Particular emphasis is given to the impact of fracture healing both at the binder and mixture scale. A viscoelastic continuum damage based approach to fatigue that incorporates healing is also presented.

An approach toward micro-rheological assessment of the asphalt binder is presented with focus on atomic force microscopic (AFM) methods to scan the binder in order to identify phases present within the asphalt binder and to, with the same AFM tip used to scan for the presence, form and quantity of phases; assess viscoelastic properties of each binder phase. The impact of aging on alteration of asphalt phases and their evolution through aging is also addressed with evidence of the impact of aging on a range of binders.

The PANDA model is overviewed with both its continuum damage and micromechanical capabilities. The cohesive zone model and the lattice micromechanical models are reviewed and the appropriate detailed technical reports are referenced for a more complete description and details of each model.

**REPORT A: Moisture Damage of Asphalt Pavements: Mechanisms, Characterization, Prediction and Numerical Modeling**

*Report Summary*

An important area that the Asphalt Research Consortium (ARC) has focused on is fundamental characterization and modeling of moisture damage. Moisture damage contributes significantly to the premature deterioration of asphalt pavements. It is a complex phenomenon that is defined as the degradation of the mechanical properties of the material due to the presence of moisture in its microstructure. It involves thermodynamic, chemical, physical, and mechanical processes. This report describes these processes and fundamental material properties that influence them. In addition, special attention is given to better understand the moisture diffusion mechanism and develop experimental methods to measure the diffusivity of moisture through asphalt mixtures, mortars, and asphalt binders. The diffusion coefficient is needed to relate material properties to the ability of asphalt mixtures to retain and release moisture. It is also an essential material property for the development of numerical models of moisture transport and moisture damage.

The moisture diffusion analysis and measurements are used to develop a method of predicting and quantifying the amount of water that can enter into a pavement system by vapor transport. In addition, they are used to identify to what extent the fatigue crack growth of pavement would result from such moisture accumulation. This report includes novel methods to characterize moisture damage in both fine aggregate mixtures (FAM) and full mixtures.

During the past decade, significant research at Texas A&M University and other institutions have shown surface free energy of aggregates and asphalt binders are very important in determining the resistance of asphalt mixture to moisture damage. This report includes a comprehensive characterization of the minerals that make up aggregates in order to explain the interactions between the aggregates and materials: asphalt binder, water, and chemical additives. The result is a catalog of mineral properties that influence aggregate-asphalt adhesion. This is a significant contribution because it allows engineers to select aggregate-binder combinations that are compatible and have high resistance to moisture damage.

One of the major contributions of the ARC work on moisture damage is the development of numerical models for moisture damage. These models are efficient tools to identify the dynamics of the different damage mechanisms, understand the initiation and evolution of these deterioration processes, and relate these processes to the mixture response at the macroscale level. The first modeling approach relies on the application of the Cohesive Zone Model (CZM). The second modeling approach uses a continuum moisture-mechanical damage mechanics framework, which is part of the Pavement Analysis using Nonlinear Damage Approach (PANDA). Both models are implemented in the commercial Finite Element (FE) software Abaqus® and were used to perform 2-D and 3-D simulations of moisture damage at the microscale level and to understand material factors that affect moisture damage.

**REPORT B: Characterization of Fatigue Damage and Relevant Properties in Asphalt Binders and Composites**

*Report Summary*

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 binder*, 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*.

This report presents the findings from a study conducted to better understand and characterize the properties of asphalt binders, mortars (FAM) and mixtures that affect the fatigue life of asphalt mixtures. Fatigue cracking and tensile fracture in asphalt mixtures originates in asphalt binders or at the interface of asphalt binders with aggregates. Chapter 2 of this research report demonstrates the relationship between the work of cohesion to the practical work of fracture. Chapter 3 of this report presents a mechanism that describes micro-damage healing at a micrometer length scale and a test method to measure the inherent healing capacity of asphalt binders. The inherent healing capacities of asphalt binders were measured as a function of temperature and aging condition. In summary, Chapters 2 and 3 discuss the fundamental mechanisms associated with the nucleation and growth of micro fracture and healing in asphalt binders. These chapters also present test and analytical methods to characterize the ideal and practical work of fracture as well as the inherent healing ability of asphalt binders. Such tools can be used for materials screening or engineering and designing better performing modified binders.

Oxidative aging in asphalt binders is a continuous process that affects the properties of the asphalt binder. As binders oxidize, loose their ability to relax with time, and become more susceptible to cracking. Predicting the rate at which binders oxidize in pavements is essential to predicting changes to mixture properties over time. Chapter 4 of this report describes recent developments in a thermal and oxygen transport model to estimate binder oxidation in pavements as a function of time and depth.

Chapter 5 of this report presents test methods and associated mechanistic analytical methods to characterize permanent deformation, fracture and healing in asphalt mixtures. A repeated direct tension test (RDT) is used along with a combination of correspondence principles and Paris' law to characterize the properties of the asphalt mixture, including its resistance to fatigue cracking. This methodology can be effectively used with asphalt mortars and mixtures to understand the affect of material and mixture properties, or external factors such as moisture, on their performance.

Chapter 6 approaches characterization of healing in a composite from a continuum standpoint. In particular, this chapter presents a test and analytical method that uses the viscoelastic continuum damage (VECD) approach to determine the healing characteristics of asphalt composites as a function of the level of damage immediately prior to the rest period as well as the duration of the rest period.

Most mechanistic analysis of material response is based on a uniaxial stress state or multi-axial stress state. Chapter 7 of this report investigates the influence of multi-axial stress state on the viscoelastic properties of asphalt binders. In particular, the chapter investigates the presence of interaction nonlinearity, i.e. nonlinearity due to the interaction of different stresses in the specimen. The understanding of these interaction effects is especially important while considering damage in asphalt pavement, such as near surface cracking, that is induced by a multi-axial stress state.

In summary, this report documents a comprehensive study conducted to develop a thorough understanding of the viscoelastic properties and performance of asphalt mixtures at different length scales. This knowledge can be employed to:

- better understand mechanisms that dictate performance in asphalt mixtures,
- develop test methods to evaluate material or mixture performance that may be used for material screening or mixture design, respectively, and
- used in conjunction with mechanistic models to predict the behavior of a mixture based on material properties or the behavior of a pavement structure based on mixture properties under a variety of different conditions (e.g. PANDA).

A unifying theme for the research documented in this report was to use mechanistic or physical models to characterize viscoelastic properties and performance of materials (including mixtures) independent of the conditions under which the material was tested. In other words, the goal was to seek material properties that are truly dependent on the material and not the method used to measure the property (e.g. geometry, mode of loading).

## REPORT C: PANDA: Pavement Analysis using Nonlinear Damage Approach

*Report Summary*

Accurate prediction of response of asphalt concrete pavements during their service life requires the consideration of deformation and distress mechanisms and environmental conditions that pavements experience over time. To move toward achieving this goal, the ARC team at Texas A&M University focused on implementing the state-of-the-art computational techniques and constitutive models in Pavement Analysis using Nonlinear Damage Approach (PANDA) finite element code. PANDA has the potential to serve as the next-generation tool for better pavement design and analysis; incorporating fundamental deformation and distress mechanisms. PANDA is a powerful tool to utilize/manage available resources to gain optimum pavement performance.

Most of the available models in the literature for asphalt pavements have been developed to predict the responses under specific test conditions or design problem, and therefore, are usually ad hoc and do not represent the behavior of asphalt concrete under general three dimensional stress states and realistic environmental conditions that actually happens in the field. PANDA incorporates temperature-dependent viscoelastic, viscoplastic, viscodamage, micro-damage healing, moisture-induced damage, and oxidative aging constitutive models to provide a robust model that can be used to predict the response of asphalt pavements subjected to general and realistic loading and environmental conditions.

This report details the description of deformation and distress mechanisms occurring in asphalt concrete materials. The key equations of nonlinear viscoelastic, viscoplastic, hardening-relaxation, viscodamage, micro-damage healing, moisture-induced damage, and oxidative aging components of PANDA are presented. The developed numerical algorithms for the proposed constitutive models are implemented in finite element software Abaqus through the user defined material subroutine PANDA-UMAT.

Another objective of this report is to provide a robust and simple protocol to calibrate and validate the PANDA model. A standard AASHTO testing procedure is developed to cover the test methods required to determine PANDA model parameters.  In addition, it presents straightforward and novel procedures that allow systematic identification of the parameters associated with each component of the model. Once calibrated, PANDA is validated against several experimental data including Nottingham data, Accelerated Loading Facility (ALF) data, ARC data, and Waterway Experiment Station data. Results show that PANDA model is capable of predicting time-, rate-, and temperature-dependent response of asphalt concrete materials subjected to different mechanical and environmental loading conditions.

Finally, this report presents PANDA as a powerful tool with research and analytical applications that can be used by both researchers and practitioners.  It is demonstrated that PANDA is a “living” model serving as a platform that can continually be improved and updated.

**Report D: Microstructural Characterization of the Chemo-Mechanical Behavior of Asphalt in Terms of Aging and Fatigue Performance Properties**

*Report Summary*

The study of asphalt chemo-mechanics requires a basic understanding of the physical properties and chemical composition of asphalt and how these properties are linked to changes in performance induced by chemical modifications. This report presents the findings from a study conducted to characterize the microstructure and the micro-rheology of asphalt binders using an Atomic force microscope (AFM). More specifically, this study demonstrates the application of AFM imaging to extract the microstructure of the asphalt binder while simultaneously measuring the nano-scale engineering properties or micro-rheology (e.g. creep compliance) of these structures. The study also demonstrates the use of AFM imaging to measure the surface free energy of the asphalt binders as well as surface interactions with specific functional groups using functionalized tips. This work also uniquely implements the framework of chemo-mechanics by investigating two types of chemical modification processes, natural (oxidative aging) and synthetic (chemical doping) as they relate not only to macro-scale properties of asphalt binder but also to the asphalt microstructure and micro-rheology.

The findings from this study indicate that *oxidative aging* induces substantial changes to the microstructure and micro-rheology of the asphalt binder. Prior to aging, binders typically demonstrated two distinctive phases: a dispersed phase and a continuous phase. The micro-rheology of these phases, measured using the AFM, revealed that the dispersed phase was stiffer than the continuous phase. Long-term oxidative aging of the binder affected the clustering / dispersion of the phases in the asphalt binder. It was also observed that long-term aging not only induced changes in phase structure and distribution, but also in the micro-rheology of each phase. For a given binder, aging increased the stiffness of the dispersed phase by 14 to 50 percent and stiffness of the continuous phase by 25 to 60 percent.

This study also demonstrated that certain asphalt *chemical parameters* have a consistent and measureable effect on the asphalt microstructure that is observed with AFM. In fact, certain microstructural features that emerged via chemical doping were very similar to the microstructures observed after *oxidative aging* of the asphalt binder.

By implementing a *crack initiation* model – which requires measureable microstructural characteristics as an input parameter – it was demonstrated that microstructural flaws (depending on the extremity) can have a profound impact on asphalt performance than the properties of the material located between the flaws. This approach was used to determine the internal stresses in the asphalt binder that drive the formation of the microstructure as observed using the AFM.

Overall, this body of work provides experimental and analytical methods that can be used to determine the microstructure and micro-rheology of asphalt binders as well as to quantify the effect of chemical modifications, aging and other factors on these properties. Researchers envision that these methods and properties can be used to (i) better understand and model the mechanisms that drive fatigue cracking and self-healing in asphalt binders and (ii) engineer better performing asphalt binders via chemical and/or polymer modifications.

**REPORT E: A Multiscale Virtual Fabrication and Lattice Modeling Approach for the Fatigue Performance Prediction of Asphalt Concrete**

*Report Summary*

Predicting the ultimate performance of asphalt concrete under realistic loading conditions is the main key to developing better-performing materials, designing long-lasting pavements, and performing reliable life cycle analysis for pavements. Therefore, much attention has been directed towards developing a model that can predict asphalt concrete performance. The fatigue performance of asphalt concrete depends on the mechanical properties of the constituent materials, namely, asphalt binder and aggregate. This dependent link between performance and mechanical properties is extremely complex, and experimental techniques often are used to try to characterize the performance of hot mix asphalt. However, given the seemingly uncountable number of mixture designs and loading conditions, it is simply not economical to try to understand and characterize the material behavior solely by experimentation. It is well known that analytical and computational modeling methods can be combined with experimental techniques to reduce the costs associated with understanding and characterizing the mechanical behavior of the constituent materials.

This study aims to develop a multiscale micromechanical lattice-based model to predict cracking in asphalt concrete using component material properties. The proposed algorithm, while capturing different phenomena for different scales, also minimizes the need for laboratory experiments. The proposed methodology builds on a previously developed lattice model and the viscoelastic continuum damage model to link the component material properties to the mixture fatigue performance. The resulting lattice model is applied to predict the modulus values for different scales. A framework for capturing the so-called *structuralization effects* is introduced that significantly improves the accuracy of the modulus prediction. Furthermore, air voids have been added to the model to help capture this important micromechanical feature that affects the fatigue performance of asphalt concrete as well as the modulus value. The effects of rate dependency are captured by implementing the viscoelastic fracture criterion. In the end, an efficient cyclic loading framework is developed to evaluate the damage accumulation in the material that is caused by long sustained cyclic loads.

**REPORT F: Microstructure Cohesive Zone Modeling for Cracking and Moisture Damage**


*Report Summary*

This report details the activities and findings of research on microstructure cohesive zone modeling for cracking and moisture damage of asphaltic mixtures. The primary objective of this study was to develop computational microstructure cohesive zone models to predict cracking and moisture damage of heterogeneous-inelastic asphalt mixtures where the complex microstructure characteristics were incorporated in the modeling process.

To meet the objective, the complex microstructure characteristics of asphalt mixtures were reproduced in the model, such that they would allow model users to efficiently evaluate the effects of individual constituent properties and volumetric characteristics of the mixtures. Additionally, the model was designed to account for the fracture process zone of the mixtures with and without moisture damage via the use of appropriate cohesive zone fracture approaches.

The model developed in this study was verified and validated. In order to validate the model, experimental programs were also designed for model inputs and outputs, and microstructural simulations of multiphase mixture specimens were conducted. Model simulation results agreed well with test results, which demonstrated that the microstructure cohesive zone model was properly developed. Various parametric analyses were also conducted to investigate how each model parameter affected the material-specific fracture mechanism and damage resistance potential of the mixtures. Model simulation results clearly presented the significance of mechanical properties of mixture components and geometric characteristics of microstructures for the better design of asphaltic paving mixtures and roadway structures.

This study can be used by practitioners and researchers as an efficient tool to quantitatively and/or qualitatively estimate the effects of small-scale design variables (such as mixture components, their interactions and volumetric characteristics) on overall mixture performance with significant savings in experimental cost and time.

**Report G: Design System for HMA Containing a High Percentage of RAP Material**

*Report Summary*

This report details the work in developing a design system for high levels of recycled asphalt pavement (RAP) material. The overall goal of the mix design process of hot mixed asphalt (HMA) is to recommend a mix that can withstand the combined actions of traffic and environment. Therefore, it is critical to assess the impact of the various mix components on the performance of the constructed pavement (i.e. resistance to rutting, fatigue, and thermal cracking). The existence of RAP in the mix presents a challenge to the design engineer due to the complex interaction among the new and recycled components of the mix. The inclusion of RAP materials in the HMA mix can improve its resistance to rutting while it may greatly jeopardize its resistance to fatigue and thermal cracking. The key to successfully include RAP in the HMA mix is to be able to assess its impact on pavement's performance while recognizing the uniqueness of each project with respect to both materials and loading conditions.

Hence, the use of RAP materials in HMA can be highly beneficial from both the economical and long-term performance aspects if the appropriate testing and analysis procedures are used to design the final mixtures. The overall objective of this research effort is to develop testing and analysis procedures that can be effectively used to evaluate RAP materials and optimize the performance of HMA mixtures containing High RAP content. The research effort will cover the various aspects of the design process starting with the evaluation of the RAP materials (binders and mixtures) through the mix design process and the performance evaluation of the final HMA mixture containing RAP materials.

**Report H: Critically Designed HMA Mixtures**


*Report Summary*

Hot mix asphalt (HMA) mixtures are believed to have a critical combination of temperature and traffic loading rate which will result in excessive permanent deformation. Designing the appropriate mixture type and properties are significantly important tasks that pavement engineers make on a routine basis. For many years this key decision has been made relying upon empirical procedures that lack fundamental characterization that might not be representative to the specific project condition. In light of this limitation, there is a need to develop an advanced, yet realistically simplified approach to assess, based on closely simulated field conditions, the rutting susceptibility of HMA mixtures under a given set of traffic loads and environmental conditions that are applicable to the project.

This study presents a new mechanistic-based approach that consists of evaluating asphalt mixtures using the repeated load triaxial (RLT) test at field representative testing conditions to determine the critical temperature of the HMA beyond which the mixture becomes unstable. An HMA was considered appropriate for a specific project location if the determined critical temperature was greater than the effective asphalt pavement temperature for rutting determined using the Mechanistic-Empirical Pavement Design Guide (MEPDG) software.

Predictive equations for estimating the anticipated deviator and confining stresses along with the equivalent deviator stress pulse duration as a function of pavement temperature, vehicle speed, and asphalt mixture's stiffness for RLT testing have been developed using 3D-Move. Additionally, predictive equations that account for the actual project characteristics such as climate conditions, material characteristics, operational speed, and traffic loading were developed in this study to estimate the effective asphalt pavement temperature. Flow number criteria as a function of traffic level were also developed for HMA mixtures. The proposed approach was validated using independent set of mixtures with known field performance. Very good agreement between laboratory results and field performance was achieved supporting the appropriateness of the proposed approach.

## Report I: Thermal Cracking Resistant Mixes

*Report Summary*

Thermal cracking is one of the main types of distresses in flexible pavements usually occurring in cold regions or location with high temperature fluctuation. Historically, the resistance of asphalt mixtures to thermal cracking was mainly related to the performance grade (PG) of the asphalt binder. However, field performance of asphalt mixtures reveals that only PG of the asphalt binder cannot ensure appropriate resistance to thermal cracking. Currently, the evaluation of the thermal cracking resistance of an asphalt mixture is not a part of the mix design process. Therefore, development of a practical mechanistic-based approach is required to assess the potential resistance to thermal cracking of an asphalt mixture while considering the material properties, pavement structure, and environmental conditions at the location of interest.

Due to the noted influence of oxidative aging on the mixture properties and pavement performance, it is becoming imperative to have a more complete understanding of the influence of asphalt binder aging on the viscoelastic behavior of asphalt mixtures. Traditionally, aging studies of asphalt materials have been conducted primarily on asphalt binders only, omitting any potential influence of the aggregate. These results are commonly extrapolated to the mixture behavior without a comprehensive understanding of how the mixture characteristics may potentially influence the aging of the binder within the mixture. A comprehensive experimental plan was conducted to evaluate the effects of mixture parameters, namely different aggregate and asphalt binder sources, air voids, and binder contents on the aging characteristics of asphalt binders aged in mixtures. Furthermore, a new approach was proposed to correlate the oxidative aging of an asphalt binder in terms of carbonyl functional groups to the viscoelastic behavior of asphalt mixtures in terms of a continuous relaxation spectrum. Such correlations permitted the incorporation of the long-term oxidative aging directly into the constitutive equation utilized in pavement response analyses.

A comprehensive analysis model will be developed in order to assist researcher and practitioners in a better selection of thermal crack resistant mixtures. The proposed approach will need further validation using independent set of mixtures with known field performance.

**Report J: Pavement Response Model to Dynamic Loads 3D Move**

*Report Summary*

The analytical model (3D-Move) adopted to undertake the pavement response computation uses a continuum-based finite-layer approach. The 3D-Move Analysis model can account for important pavement response factors such as the moving traffic-induced complex 3D contact stress distributions (normal and shear) of any shape, vehicle speed, and viscoelastic material characterization for the pavement layers. This approach treats each pavement layer as a continuum and uses the Fourier transform technique; therefore, it can handle complex surface loadings such as multiple loads and non-uniform tire pavement contact stress distribution. Since the tire imprint can be of any shape, this approach is suitable to analyze tire imprints, including those generated by wide-base tires. The finite-layer method is much more computationally efficient than the moving load models based on the finite element method. This is because often times the pavements are horizontally layered and pavement responses are customarily required only at a few selected locations and for such problems the finite layer approach of 3D-Move Analysis is ideally suited. Since rate-dependent material properties (viscoelastic) can be accommodated by the approach, it is an ideal tool to model the behavior of asphalt concrete (AC) layer and also to study pavement response as a function of vehicle speed. Frequency-domain solutions are adopted in 3D-Move Analysis, which enables the direct use of the frequency sweep test data of HMA mixture in the analysis. The 3D-Move Analysis (ver. 2.0) also includes Pavement Performance Models, using which many important pavement distress modes can be investigated. In addition, a variety of non-highway vehicles (e.g., End-Dump Truck and Forklift et.) can also be considered.

## Report K: Development of Materials Database

*Report Summary*

The ARC database was designed with two primary goals in mind. The first goal was to provide a Web-based database management system and application that will allow Consortium members to store research results related to materials, material properties, material measures and results of laboratory and field testing. The second goal was to make the data available to the general public via a searchable Web-based interface. It is expected that university researchers and students, along with industry professionals and public agencies, will benefit from this data. The system is implemented using well-adopted technologies including Microsoft SQL Server 2008 and Microsoft ASP.NET. The database and application are currently being hosted at the University of Nevada, Reno.

This report will summarize the database architecture, structure, and various functions. The report will document the software and maintenance procedures and will provide the necessary deployment and maintenance plans. Proposed future improvements will also be presented. The report will include a chapter on the data quality act.

**REPORT L: Evaluation of the Binder Bond Strength Test (BBS) for Moisture Damage Characterization**


*Report Summary*

This report summarizes the development and implementation of the Binder Bond Strength (BBS) test to evaluate the moisture susceptibility of asphalt-aggregate systems. The BBS test is a significant modification of the PATTI (Pneumatic Adhesion Tension Testing Instrument) test specified in ASTM D4541 and used in the coatings industry. This research details development of the test procedure and a sensitivity analysis of the factors influencing moisture damage. To conduct the sensitivity study an experimental test matrix, which considered the effects of different modifiers, aggregate mineralogy, and conditioning media was developed to assess the effects of different chemical and physical conditions at the aggregate-asphalt interface on bond strength of binders from various asphalt sources.

Development of the test procedure resulted in significant changes to ASTM D4541 including improvements to the equipment and changes to guidance for sample preparation and conditioning to provide a procedure specific to asphalt-aggregate systems. The test was found to be reproducible and the recommended conditions in the procedure sufficient to demonstrate the adverse effects of moisture. Results of the sensitivity analysis indicate that both bond strength and change in bond strength due to the presence of moisture are sensitive to asphalt binder modification, presence of anti-stripping additives, and the mineralogy of the substrate used in the test. Values of bond strength were also found to be related to asphalt binder stiffness. As a result, it is recommended that the test be applied to the materials intended for use in the field and be conducted at multiple test temperatures to fully understand the potential for moisture damage in mixes. Findings from the BBS test were verified through comparison to cyclic shear loading in the DSR and values of surface free energy estimated based on contact angle measurements. Results found similar ranking between the moisture resistance of binders tested in the BBS (tension) and those subjected to cyclic shear loading. Furthermore, general agreement was observed between BBS results and work of cohesion/debonding estimated from surface free energy calculations. A comparison between BBS results and mixture testing using Tensile Strength Ratio (TSR) indicate that both methods rank materials similarly under wet conditions. Overall, results indicate that the BBS is a repeatable and reproducible test recommended as a practical method to directly measure bond strength in dry and moisture conditions.


*Related Products:*

AASHTO Test Method TP-91: Determining Asphalt Binder Bond Strength by Means of the Binder Bond Strength (BBS) Test

**REPORT M: Development of Test Procedures for Characterization of Asphalt Binder Fatigue and Healing**

*Report Summary*

The fatigue resistance and self-healing capabilities of asphalt binders can have a significant effect on the service life of an asphalt pavement. Sole use of the G* sinδ fatigue parameter currently specified by Superpave, is not sufficient to estimate fatigue performance as it only represents asphalt binder properties in the linear visco-elastic range of behavior. This study introduces two test procedures for measuring asphalt binder resistance to damage; an accelerated monotonic procedure (called Binder Yield Energy Test, BYET), and a cyclic procedure (called Linear Amplitude Sweep, LAS) as better indicators of fatigue resistance. In both procedures fatigue resistance is estimated through application of Visco-elastic Continuum Damage (VECD) concepts to the response measured by the DSR. Research found that use of the VECD analysis approach for the monotonic mode of loading used in the BYET test was a challenge for polymer modified asphalts due to the strain hardening and non-uniform response at high strains. As a result the LAS test, a cyclic loading procedure that includes a linear increase in applied strain was developed to address these challenges. The LAS test was found to be highly repeatable, able to characterize both conventional and modified binders, and practical to use. In regards to performance, LAS results were found to correlate to laboratory mixture fatigue performance and in-service performance from Long Term Pavement Performance (LTPP) program test sections.

The development DSR test procedure for measuring self-healing of asphalt binders is also summarized. The procedure includes two tests: a strain controlled test with continuous cyclic loading and a second test with cyclic loading that has a single rest period, inserted at a specified damage level. The procedure was used to evaluate the effects of changing materials properties, test conditions, and the timing and duration of rest periods on healing. Results indicate that binder modification and oxidative aging have greater effects on fatigue life than healing. However, if temperature is increased during the rest period the effect of healing on fatigue law parameters can be significant. The end result of this work is an AASHTO standard procedure along with recommendations for application of the LAS as a specification test. Recommendations to develop further understanding and improved laboratory evaluation of healing are also provided.

*Related Products:*

AASHTO Test Method TP-101: Standard Method of Test for Estimating Damage Tolerance of Asphalt Binders Using the Linear Amplitude Sweep
AASHTO Test Method: Measurement of Asphalt Binder Elastic Recovery and Ductility in the Dynamic Shear Rheometer (DSR)

**REPORT N: Guidelines for Selection of Modification Techniques, Extenders, and Biobinders**

*Report Summary*

This report utilizes the large database of modification types, methodologies and test results collected to estimate the expected effect of various types of modification techniques on performance grade and damage behavior of asphalt binders. Based on these results suggested modification techniques and procedures will be provided. The report will also introduce a simple spreadsheet tool to estimate the effect of various modification types on base binder performance grade and other binder properties. The tool uses an MS Excel™ platform, and applies an incremental approach to estimating effects on performance. This approach is intended to appeal to a wide range of users by minimizing the amount of user-generated input required and providing default values for all performance categories. The software includes the option to allow users to input design assumptions and reliability information if more detailed or project specific information is desired.

The second phase of the report addresses bio-binders and binder modification using extender oils. This research is both timely and important as while these materials present potential performance and environmental benefits, they have not been tested widely and their effects on short and long term performance are not well documented. The report will provide a current state of the practice through synthesis of an extensive literature review on bio-binders and extender oils and includes further performance evaluation of materials deemed high priority through peer review. The selected materials will be investigated in terms of rheological, chemical, and mechanical properties of the extender oil and blended binder. Furthermore, the need for modification of mix design procedures when using aforementioned binders and additives, in particular the effects on mixing and compaction procedures will be investigated. The results will be used to provide guidelines for use of bio-binders and asphalt extenders, and to define future research needs to better integrate use of these materials into practice.

*Related Products:*

Spreadsheet Tool for Modification Selection

**REPORT O: Characterization of Binder Damage Resistance to Rutting**

*Report Summary*

This report investigates methods to better understand the mechanisms driving mixture rutting resistance through use of modeling, image analysis, and performance testing of asphalt binders and mixtures. To achieve this objective mixes prepared with a variety of binder and aggregate combinations were subjected to repeated load-permanent deformation testing. Binder performance properties including stiffness, compliance, and elasticity were measured to quantify the effects of binder grade and/or modification. A planar imaging analysis software, identified as IPas in the report was used to assess the effects of use of different binders or aggregate gradations on the aggregate skeleton developed during compaction. In combination the aggregate structure and binder performance data serves as a means to define the interaction between the binder and aggregate during loading and to quantify the role of the aggregate structure in overall rutting resistance.

The aggregate structure data obtained from imaging is further extended to support development of a multi-scale micromechanical finite element model for detailed analysis of the behavior of solely asphalt binder and asphalt binder combined with various fractions of fine aggregate (mastic and mortar) and applying the behavior to estimate the performance of the overall asphalt mixture structure. This approach defines the role of each phase in the overall rutting performance and provides an estimate of the expected stress and strains experienced in the binder phase due to traffic loading at high temperatures. These results were found to have significant practical applications in selecting the appropriate stress levels and other conditions for experimental characterization of asphalt binder rutting resistance.

The study provides an assessment of the MSCR test and uses the new information generated through this research to recommend revisions to the test procedure to reduce variability and improve reproducibility. To meet this objective, a multi-faceted approach to evaluation of the MSCR including mechanical testing of binders and mixtures as well as analytical modeling procedures was implemented.

*Related Products:*

AASHTO Test Method: Analysis of Asphalt Mixture Aggregate Structure through use of Use of Planar Imaging and Analysis System (IPas)
Software: Image Process and Analysis System (IPas)

**REPORT P: Quantifying the Impacts of Warm Mix Asphalt on Constructability and Performance**

*Report Summary*

The intent of this research is to promote effective use of WMA through developing an improved understanding of the impacts of WMA additives and reduced production temperatures on workability and performance. To pursue this objective an experiment was designed to evaluate the effects of various WMA technologies on the workability and performance properties of asphalt binders and mixtures using existing standards and new test methods developed during the study. In regards to workability use of WMA requires the mix to demonstrate comparable workability at lower temperatures relative to HMA and to maintain workability at temperatures below the design target. Preliminary results found that evaluating these two requirements in the laboratory is not a straight forward process as the relationship between density and compaction temperature is not a linear function and is influenced by many factors related to properties of the mix components. This relationship is not adequately explained by viscosity, thus two new test methods adapted from the lubricating oils industry will be introduced to characterize asphalt binder as a lubricant using the coefficient of friction parameter. The report summarizes theory behind these tests and the steps taken in their development. It also presents the concept of estimating mixture workability through use of mastic viscosity as a means to incorporate consideration of filler type and concentration on workability using a standard DSR geometry.

Experiments were also designed to assess the impact reduced production temperatures on asphalt binder performance and potential for moisture damage through use of the DSR and Binder Bond Strength Test. Results indicate that the lower aging temperatures associated with production of WMA are detrimental to asphalt binder performance properties, however the effect is WMA additive specific and is most prominent in high temperature performance tests. These results are consistent with mixture performance results published in the literature. The conditions associated with WMA production, both reduced temperatures and incomplete drying of aggregate are detrimental to resistance to moisture damage. The contributions of both factors were assessed through dynamic modulus testing after multiple freeze thaw cycles and varying aggregate application temperature in the BBS test. Results indicate that these detrimental effects can be mitigated through WMA additive selection. The study also includes comparison of performance properties of laboratory and field produced mixes using the materials from the Manitoba WMA project.

*Related Products*

AASHTO TP-XX: Measurement of Asphalt Binder Lubricity Using the Dynamic Shear Rheometer

**REPORT Q: Improvement of Emulsion Characterization and Mixture Design for Cold Bitumen Applications**

*Report Summary*

Reducing the environmental impacts of construction and optimizing the service life of asphalt pavements are motivating factors in development of guidance for use of emulsions in pavement preservation and cold mix applications. Barriers to implementation exist for use of emulsion technologies in both spray and mixing applications that are preventing their expanded use. Specifically, there is a need to develop a performance based system for evaluation of emulsions and mix design procedures for cold mix asphalt (CMA) and cold-in-place recycling (CIR) that are consistent with the framework used for hot applied binders and mixes. The intent of this study is to address the short-comings of current specifications through providing a performance-based grading system for emulsions and mix design guidelines for CMA and CIR.

Similar to hot-applied binders asphalt emulsion technology has evolved to meet the increasing needs for superior performance through use of modified emulsions. The current specification framework to accept emulsions is not capable of quantifying the benefits of modified emulsions or comparing modification types. Furthermore, surface treatments have varying functions and serve a different purpose than structural layers, thus different failure modes must be considered in materials evaluation. The goal of this task is to leverage the technology developed for hot-applied binders in the SuperPave system to assess emulsion residue properties related to the critical failure modes associated with a given surface treatment and to apply conventional binder evaluation methods to emulsions used in CIR and CMA.

Relative to the conventional HMA design procedure, use of CMA and CIR presents a research challenge because a 4-phase system exists in the mix consisting of water, aggregate, asphalt, and air voids. To accommodate this system mix design procedures are required to provide a means to select an appropriate emulsion content and develop sufficient voids in mineral aggregate (VMA) to promote curing while in place. There is also a need to adapt the concepts and technology, specifically the SuperPave Gyratory Compactor (SGC) and recently developed performance tests prevalent in design of HMA to design of CIR and CMA.

*Related Products*

AASHTO Practice: Mix Design for Cold Mix Asphalt (CMA)
AASHTO Practice: Mix Design for Cold In-Place Recycling (CIR)
AASHTO Method: Procedure for Evaluation of Coating of Cold Mix Asphalt
AASHTO Method: Cold Mix Laboratory Specimen Preparation Using Modified SGC Molds

**REPORT R: Studies on Tire-Pavement Noise and Skid Response**

_Report Summary_

Pavement surface texture affects functional characteristics related to skid resistance and noise generation of HMA. Texture spectral analysis (TSA) methods derived from signal processing theories show promise for improving surface texture characterization. Texture parameters measured with a stationary linear profiler (SLP) and processed using TSA methods represent a means for quantifying surface properties and asperity distributions. Current methods to analyze pavement surface texture typically rely on mean profile depth (MPD) or mean texture depth (MTD) values, but fail to capture the distribution of asperities at the pavement surface. This report investigates the applicability of laser profiling systems for measuring surface texture of laboratory and field samples, and considers appropriate applications. Models that account for aggregate and mixture properties are developed and related to texture parameters by analyzing constructed field sections and laboratory Superpave Gyratory Compactor (SGC) samples. Results indicate that stationary laser profiling systems are capable of capturing macro-texture and micro-texture properties of laboratory and field samples, suggesting that a comprehensive friction characterization of asphalt mixture surfaces can be obtained using laboratory test methods and TSA techniques. Furthermore, samples prepared using standard laboratory compaction techniques can be used to estimate field surface texture, resulting in a method that is attractive for rapid deployment. With this system, it is believed that asphalt mixture designers will have an improved tool by which to estimate pavement surface texture and the resulting frictional and acoustic properties.

*Related Products:*

AASHTO Test Method: Measurement and Texture Spectral Analysis of Pavement Surface Profiles Using a Linear Stationary Laser Profiler (SLP)

## REPORT S: Molecular Dynamics Results for Multiple Asphalt Chemistries


*Report Summary*

Research within the ARC has noted that asphalts that differ in crude oil source can demonstrate differences in mechanical properties over time, even when initially matching the same complex modulus specifications. This has created a need to understand the origins and mechanisms by which the asphalt chemistry can influence mechanical properties. This chemo-mechanics relationship arises in several materials. Understanding the impacts of chemo-mechanics on asphalt properties and aging is of practical importance for understanding how asphalts that meet mechanical specifications can be anticipated to differ as a result of their chemistry.

Molecular-scale models provide a means to quantify how different molecule types contribute to the overall mechanical response of a system. Comparing differences in model systems that arise from differences in chemical composition then provide a mechanistic basis for interpreting experiments that use asphalts differing in broad chemical composition. In this report, detailed chemical compositions are proposed for three SHRP core asphalts that are similar in crude oil source to asphalts used throughout the ARC. Compositions are represented by integral numbers of specific molecules and are intended for use in asphalt models, rather than experiments. The compounds were chosen to be consistent with the sizes and chemistries that have been measured during experimental characterizations. They are inspired by molecules proposed by others in the literature and identified by geochemists in petroleum source rocks.

Molecular dynamics simulations have been employed to predict properties of the model asphalt systems. Thermodynamic properties include the density and thermal expansion coefficient. Dynamics results include the rates that individual molecules relax within the model asphalts. These indicate the basis for chemo-mechanics: mechanical properties that depend on the chemical nature of the material. Predictions of complex modulus are also made and are compared to experimental results for SHRP asphalts.

One objective is to use results from molecular dynamics simulations of asphalts that differ in their fundamental chemistry to guide models that apply at larger length scales, such as phase field models. A model for interpreting the molecular dynamics results in terms of temperature- and composition-dependent free energies is discussed. The thermodynamics results thus provide a route to using molecular dynamics to guide the free energies used in phase field models.
In total, the results from these simulations directly indicate how molecules of different chemical families and sizes relax within an overall model asphalt system. The results can be used indirectly to interpret the reasons and mechanisms by which differences in chemical composition can affect asphalt mechanical properties. Future molecular dynamics simulations of asphalts should use the proposed compositions and should incorporate additional chemistries by applying the approaches that were used to choose these compositions.

## REPORT T: Progress Toward a Multi-scale Model of Asphalt Pavement


*Report Summary*

Asphalt chemo-mechanics is a fundamental theory and predictive model of asphalt concrete properties which relies on a multiscale, multiphysics approach. This bold endeavor investigates the behavior of the asphalt binder and the mixture at multiple length scales from molecular, nano-, meso-, micro-, and continuum (macro-) scales, and as such, provides a coordinated effort that ultimately links the molecular composition of asphalt to actual pavement performance. This type of modeling approach is presently used in many other high-tech industries (e.g., concrete, metals, polymers, and composites) to explain and predict performance of materials based on fundamental material properties. This approach should have an enormous impact on the knowledge available to researchers; state DOTs, and the paving industry in general who are seeking to improve pavement performance life in a cost effective manner.

Asphalt binder, which constitutes a vital component material in pavements, has historically been modeled by more traditional empirical analyses such as Finite Element Methods (FEM) and Discrete Element Methods (DEM). Considering the advantages of these methods, there still exist many shortcomings. Recently, the Phase Field Method (PFM) has emerged as a powerful computational way to simulate and forecast the microstructure evolution of asphalt binder. Unlike the traditional analysis methods mentioned above, which may be classified as predominately mechanics approaches, PFM analyzes the problems from the material constituent energy aspect and can provide a view of the whole microstructure evolution process as it impacts the mechanical response of the material. Model input in this type of approach may stem from physicochemical properties of the materials; which may be derived from experimentation as well as fundamental computational sources such as molecular dynamics simulations. In this report the PFM approach will be discussed in detail in regard to how it may be utilized to study asphalt mechanical responses pertinent to thermal and load related fatigue and healing. Links or bridges are made between molecular mechanics processes, at the small scale, and between classical finite element methods, at the higher scale. In short, this report discusses the progress made to date to begin implementation of the multiscale, multiphysics approach to predicting pavement performance from fundamental material compositional properties.

## REPORT U: Design Guidance for Fatigue and Rut Resistance Mixtures

*Report Summary*

This report will be prepared in NTIS format with an accompanying FHWA Technical Brief. The NTIS report will thoroughly document the research performed to improve four empirical models relating engineering properties of asphalt mixtures to composition that were developed in previous National Cooperative Highway Research Program studies: (1) the Hirsch model for dynamic modulus, (2) the resistivity rutting model, (3) the continuum damage fatigue model, and (4) the permeability model. For each model, the report will describe the following:

- The original model, its shortcomings and the required improvements.
- The design of the experiment for the improvements.
- The materials and test methods used.
- Statistical engineering analysis of the resulting data.
- The final improved model.
- Applications for the improved model.

The FHWA Technical Brief will demonstrate applications of the models. The technical brief will include the following:

- Brief description of the models.
- Using the models to evaluate and improve mix design specifications.
- Using the models to design mixtures for specific applications.

Engineers and experienced technicians who design asphalt concrete mixtures will benefit from using the improvements in the models.

*Related Products*
A standard method in AASHTO format "Simplified Continuum Damage Fatigue Analysis for the Asphalt Mixture Performance Tester (AMPT)"

## REPORT V: Continuum Damage Permanent Deformation Analysis for Asphalt Mixtures


*Report Summary*

Permanent deformation (i.e., rutting) is one of the major distresses in asphalt pavements and it consists of the irrecoverable deformation due to viscoplastic flow and viscofracture fatigue damage. The fundamental mechanisms of rutting have not been well addressed due to the complexity of asphalt mixtures especially in a destructive compressive load. A comprehensive characterization of the asphalt mixtures was accomplished in this report by mechanistically modeling the inherent anisotropy, anisotropic viscoelasticity, anisotropic viscoplasticity and anisotropic viscofracture of the asphalt mixtures.

The inherent anisotropy due to preferentially oriented aggregates was characterized by a microstructural parameter which could be rapidly and accurately measured by lateral surface scanning (i.e., Hot-dog) tests and physically related to anisotropic modulus ratio. The anisotropic viscoelasticity was represented by complex moduli and Poisson's ratios in orthogonal directions that were determined by an efficient testing protocol. Master curve models were proposed for the magnitude and phase angle of these complex variables. An innovative and robust strain decomposition method was proposed to separate the viscoplastic and viscofracture responses from the viscoelastic components. Based on this, the viscoplastic deformation and the viscofracture fatigue that occurs simultaneously during rutting can be accurately and efficiently modeled and predicted.

The viscoplasticity were intensively modeled by an anisotropic viscoplastic damage model which incorporated 1) modified effective stresses to account for the inherent and stress-induced anisotropy; 2) a new model to provide a smooth and convex yield surface and address the material cohesion and internal friction; 3) a non-associated flow rule to consider the volumetric dilation; and 4) a temperature and strain rate dependent strain hardening function. The viscofracture resulting from the crack growth in compression led to the stress-induced anisotropy and was characterized by anisotropic damage densities, the evolution of which was modeled by the anisotropic pseudo J-integral Paris' laws.

Results indicated that the undamaged asphalt mixtures were inherently anisotropic and had vertical to horizontal modulus ratios from 1.2 to 2.0 corresponding to microstructural parameter from 0.2 and 0.5. The rutting would be underestimated without considering the inherent anisotropy. Viscoelastic and viscoplastic deformation developed simultaneously while the viscofracture deformation occurred only in the tertiary flow, which was signaled by the increase of phase angle. Rutting was accelerated by the viscofracture damage and the asphalt mixture had a brittle (splitting cracks) or ductile (diagonal cracks) fracture when the air void content was 4% and 7%, respectively. The testing protocol that produced the fundamental material properties is very efficient and can be completed in one day with simple and affordable testing equipment. The developed constitutive models can be effectively implemented for the rutting prediction of asphalt pavements under various traffic, structural, and environmental conditions.

**REPORT W: Characterization of Fatigue and Healing Properties of Asphalt Mixtures**

*Report Summary*

Fatigue cracking is one of the most common distresses of asphalt pavements, whereas healing is a counter process to cracking which alleviates cracking damage and extends fatigue life of asphalt pavements. Most of existing methods to characterize fatigue cracking and healing are generally empirical or phenomenological in nature, which does not satisfy the need to develop mechanistic-based pavement design methods. The objective of this study is to characterize fatigue cracking and healing of asphalt mixtures using a robust mechanistic approach.

A controlled-strain repeated direct tension (RDT) test is selected to generate both fatigue cracking and permanent deformation in an asphalt mixture specimen. Fatigue cracking is separated from permanent deformation from a mechanical viewpoint. The development of fatigue cracking is described by the evolution of the damage density and the increase of the average crack size with the increase of loading cycles.

A creep and step-loading recovery (CSR) test is designed to measure the internal stress in the recovery phase of an asphalt mixture specimen. The internal stress and the strain measured in the recovery phase are used to conduct the mechanistic analysis of recovery and healing of the asphalt mixture specimen. Then healing is described using the decrease of the damage density and average crack size with time.

The proposed approach is able to demonstrate distinctly different fatigue cracking and healing characteristics of different types of asphalt mixtures. The entire series of tests for fatigue, permanent deformation and healing can be completed in one day, with the healing part requiring only a matter of minutes. The obtained healing rates are predicted using undamaged material properties, which facilitates the decision-making process in pavement design. The proposed methods produce practical results from simple tests using basic measurements and theoretical properties, such as surface energy. Fatigue cracking and healing are characterized by their essential cause and effect relationships based on true mechanical behaviors and true material properties.

## REPORT X: Characterization of Field Cores of Asphalt Pavements

*Report Summary*

The distribution of viscoelastic properties in field layers is not uniform because of nonuniform air void distribution and aging. Therefore, characterization of field specimens is more challenging compared to that of laboratory compacted specimens. Formerly, characterization of field asphalt mixtures was based on binder tests which are useful but do not represent the properties of the asphalt mixtures because binder is only a component in the asphalt mixture.

This study uses linear viscoelastic theory and numerical modeling to obtain the undamaged and damaged viscoelastic properties of both laboratory-mixed-laboratory-compacted and field compacted asphalt concrete. Additionally, it uses fracture mechanics principles to find the fracture and healing properties of aged asphalt specimens.

The analytical models presented in this research have been successfully verified by testing the actual field specimens of different ages. The model developed in this dissertation is suitable to track the viscoelastic, fracture and healing properties of the field specimen with time and depth. The test protocols and analytical models described in this study can be used for the development of reliable performance models for field-aged asphalt layers.

**REPORT Y: Water Vapor Diffusion in Pavement and Its Effects on the Performance of Asphalt Mixtures**

*Report Summary*

In general, moisture damage in pavement can be defined as progressive degradation of asphalt mixture material and is influenced by a variety of factors such as: aggregate type, mixture design, environment and traffic. The occurrence of moisture damage in asphalt pavement is a rather complex phenomenon, which involves chemical, physical, mechanical and thermodynamic processes. Moisture damage can occur either within the asphalt mastic (cohesive failure) due to water weakening the material or it can occur at the asphalt-aggregate interface (adhesive failure) by water penetrating into the asphalt-aggregate interface. Fatigue cracking is the major form of distress in asphalt pavement and the key material property that affects fatigue cracking is the bond energy between the asphalt binder and aggregates. Because the affinity of aggregates for water is far greater than their affinity for the asphalt binder, regardless of whether water is in the form of liquid or vapor, the presence of moisture tends to soften the asphalt mastic and strip the asphalt binder from the aggregate surface, which significantly reduces the tensile strength of asphalt mixture and consequently accelerates the pavement deterioration. Although it remains unclear to what extent the permeation of water vapor from the subsurface will affect the asphalt mixture performance, the moisture vapor in asphalt mixture plays an essential role in accelerating fatigue crack growth of the asphalt mixture.

This report describes two key objectives: the first objective is to develop a method of predicting and quantifying the amount of water that can enter into a pavement system by vapor transport; the second objective is to identify to which extent the fatigue crack growth of pavement would result from such moisture accumulation. To fulfill these two objectives, a diffusion model was first established to illustrate the wetting process of the surface asphalt layer due to the vapor migration from subgrade soil into the upper layer. Secondly, in order to quantify the degree of moisture damage induced by water vapor diffusion, fine aggregate mixture (FAM) specimens were fabricated and conditioned at different levels of relative humidity (RH) in closed vacuum desiccators that allows little temperature fluctuation. Moreover, the moisture conditioned specimens were tested using a newly developed repeated direct tension (RDT) test method to evaluate the fatigue crack growth. The RDT test greatly reduced the stress state complexity within the specimens by evenly distributing stress over the cross section area of the cylindrical specimen. Compared to the previous torsional test, the newly proposed test protocol was more efficient in characterizing the moisture susceptibility of the asphalt mixture. A major finding in this chapter is that the higher level of RH in as asphalt surface layer will induce significantly higher crack growth rates.

**Report Z: Effect of Extraction Methods on the Properties of Aggregates in Reclaimed Asphalt Pavement**

*Report Summary*

Evaluating the RAP materials consists of measuring the properties of the binder and aggregates of the reclaimed mix. Several research studies have been conducted to identify the best methods for separating and testing the binder and aggregates of the RAP materials but there have not been any standard procedures that agencies can use on a routine basis. This report presents the findings from a joint study conducted by University of Nevada, Reno (UNR) and National Center for Asphalt Technology (NCAT) to investigate the influence of centrifuge, reflux, and ignition oven methods on recovered RAP aggregate properties. Laboratory-produced (simulated) RAP materials were prepared with aggregates from four different sources in the United States. Properties (gradation, specific gravities, Superpave consensus properties and others) of the virgin aggregates were compared to those from the recovered RAP aggregates. The study also evaluated the effect of the bulk specific gravity of the RAP aggregate on voids in mineral aggregates (VMA), which is the most important volumetric criteria to ensure mix durability

This findings from this study can be applied by practitioners (such as state DOTs) and researchers to better design mixtures with high percentage of RAP material. The material presented here is the final report for the aforementioned subtask of the work element E2b: "Design System for HMA Containing a High Percentage of RAP Material."

**Deliverable Brief**

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

**Format**

Standard Practice

**ARC Partner**

Advanced Asphalt Technologies, LLC

**Product Description**

A standard practice for conducting and analyzing cyclic direct-tension fatigue tests in the Asphalt Mixture Performance Tester (AMPT) will be prepared. The practice will consist of two components: (1) analysis of cyclic direct tension fatigue tests using continuum damage principles to characterize damage accumulation in a mixture, and (2) analysis of simple fracture energy tests to characterize the damage tolerance of a mixture. The testing and analysis to be included in this practice will produce a comprehensive fatigue relationship for an asphalt concrete mixture using a limited number of tests. The resulting fatigue relationship can be used in mixture design to characterize the load associated cracking potential of a mixture. It can also be used in mechanistic-empirical pavement design to estimate the cracking performance of a pavement.

**Equipment Availability and Cost**

The fatigue test method would be an add-on to the currently available AMPT which costs approximately $75,000. Both current AMPT manufacturers have developed prototype hardware and software for cyclic tension fatigue testing. The fracture energy test is a simple monotonic test on a notched specimen that can also be conducted in the AMPT. The additional cost for an AMPT with fatigue capability is estimated to be approximately $5,000 to $10,000.

**Potential Applications**

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

**Targeted Users**

Engineers and experienced technicians who design asphalt concrete mixtures.

**Time and Skill Requirements**

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

**Deliverable Brief**

Wilhelmy Plate Method

**Format**

Test Method

**ARC Partner**

TTI

**Product Description**

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

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

**Equipment Availability and Cost**

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

**Potential Applications**

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

**Targeted Users**

DOT, especially centralized labs, and other transportation agencies.

**Time and Skill Requirements**

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

**Recommended Next Steps**

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

**Deliverable Brief**

Universal Sorption Device

**Format**

Test Method

**ARC Partner**

TTI

**Product Description**

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

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

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

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

**Equipment Availability and Cost**

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

**Potential Applications**

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

**Targeted Users**
DOT, especially centralized labs, and other transportation agencies.

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

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

**Deliverable Brief**

Dynamic Mechanical Analysis

**Format**

Test Method

**ARC Partner**

TTI

**Product Description**

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

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

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

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

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

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

**Equipment Availability and Cost**

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

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

**Targeted Users**

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

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

**Recommended Next Steps**
This test method is available in AASHTO format.

**Deliverable Brief**

Automated Flocculation Titrimetric (AFT) Analysis

**Format**

Test Method

**ARC Partner**

Western Research Institute

**Product Description**

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

**Equipment Availability and Cost**

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

**Potential Applications**

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

**Targeted Users**

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

**Time and Skill Requirements**

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

**Recommended Next Steps**

None.

**Deliverable Brief**

Determination of Polymer in Asphalt

**Format**

Test Method

**ARC Partner**

Western Research Institute

**Product Description**

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

The draft AASHTO format method has been delivered.

**Equipment Availability and Cost**

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

**Potential Applications**

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

**Targeted Users**

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

**Time and Skill Requirements**

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

**Recommended Next Steps**

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

**Deliverable Brief**

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

**Format**

AASHTO Test Method

**ARC Partner**

Texas A&M

**Product Description**

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

**Equipment Availability and Cost**

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

**Potential Applications**

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

**Targeted Users**

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

**Time and Skill Requirements**

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

**Recommended Next Steps**

Develop an AASHTO procedure for DMA specimen preparation.

**Deliverable Brief**

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

**Format**

Test Method

**ARC Partner**

Texas A&M

**Product Description**

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

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

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

**Equipment Availability and Cost**

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

**Potential Applications**

Screening for intrinsic healing potential of asphalt binders

**Targeted Users**
DOT and other transportation agencies

**Time and Skill Requirements**
One day including binder specimen preparation and testing.

Skill level required is similar to that for binder DSR testing.

**Deliverable Brief**

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

**Format**

AASHTO Test Procedure

**ARC Partner**

TTI

**Product Description**

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

**Equipment Availability and Cost**

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

**Potential Applications**

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

**Targeted Users**

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

**Time and Skill Requirements**

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

**Recommended Next Steps**

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

**Deliverable Brief**

Continuum Damage Permanent Deformation Analysis for Asphalt Mixtures

**Format**

Test Method

**ARC Partner**

Texas A&M University

**Product Description**

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

**Equipment Availability and Cost**

1. MTS machine or equivalent with temperature chamber, LVDTs and load cell; and
2. Sample rotation equipment ($50) and scanner ($100) for determining inherent anisotropy.

**Potential Applications**

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

**Targeted Users**

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

**Time and Skill Requirements**

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

**Recommended Next Steps**

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

**Deliverable Brief**

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

**Format**

Test Method and Data Analysis Program

**ARC Partner**

Texas A&M University

**Product Description**

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

**Equipment Availability and Cost**

1. MTS machine or equivalent with temperature chamber, LVDTs and load cell programmable loading; and
2. Same sample as used in nondestructive characterization, no sample-to-sample variance.

**Potential Applications**

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

**Targeted Users**

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

**Time and Skill Requirements**

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

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

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

**Recommended Next Steps**

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

**Deliverable Brief**

Nondestructive Characterization of Tensile Viscoelastic Properties of Undamaged Asphalt Mixtures

**Format**

Test Method and Data Analysis Program

**ARC Partner**

Texas A&M University

**Product Description**

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

**Equipment Availability and Cost**

1. MTS machine or equivalent with temperature chamber, LVDTs and load cell;
2. Sample saw for parallel ends;
3. Coring machine for a sample with uniform composition;
4. Gluing jig; and
5. Universal fixture for the base of the testing sample.

**Potential Applications**

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

**Targeted Users**

Material engineers and lab technicians.

**Time and Skill Requirements**

1. Materials engineers: fitting the lab data with the master curve functions for modulus, Poisson's ratios and their phase angles; and

2. Lab technicians: data for a complete tensile master curve for a mixture can be determine in one day.

**Recommended Next Steps**

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

**Deliverable Brief**

Nondestructive Characterization of Field Cores of Asphalt Pavements

**Format**

Test Method and Data Analysis Program

**ARC Partner**

Texas A&M University

**Product Description**

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

**Equipment Availability and Cost**

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

**Potential Applications**

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

**Targeted Users**

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

**Time and Skill Requirements**

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

**Recommended Next Steps**

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

**Deliverable Brief**

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

**Format**

Test Method

**ARC Partner**

Texas A&M University

**Product Description**

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

**Equipment Availability and Cost**

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

**Potential Applications**

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

**Targeted Users**

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

**Time and Skill Requirements**

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

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

**Recommended Next Steps**

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

**Deliverable Brief**

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

**Format**

Practice

**ARC Partner**

University of Nevada, Reno

**Product Description**

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

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

**Equipment Availability and Cost**

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

**Potential Applications**

Mix Design Process

**Targeted Users**

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

**Time and Skill Requirements**

Design can be conducted within 3-5 days and will require technician level skills to conduct.

**Recommended Next Steps**

Submit to AASHTO

**Deliverable Brief**

Mix Design for Cold Mix Asphalt

**Format**

Practice

**ARC Partner**

University of Wisconsin – Madison, Modified Asphalt Research Center (UWMARC)

**Product Description**

Cold mix asphalt consists of producing a mixture of asphalt emulsion and mineral aggregate for use as a surface course on a flexible pavement. Use of emulsion eliminates the need for heating of aggregates during mixing, thus a substantial reduction in energy consumption and emissions is realized relative to conventional HMA. Other potential benefits include reduced production cost and improved work safety. However, given these possible benefits use of CMA is limited due to the absence of a standard mix design procedure. This product will leverage technology and concepts developed in the SuperPave mix design for HMA to develop a similar procedure for Cold Mix Asphalt. Specifically the method will provide a means to select an optimum fluids (emulsion + water) content based on volumetric criteria. The procedure will also include recommended practices for SGC compaction, curing, and performance evaluation of CMA mixes.

**Equipment Availability and Cost**

SGC is available at the cost of $30,000 - $40,000. Perforated molds are also commercially available, cost unknown.

**Potential Applications**

Mix Design Process

**Targeted Users**

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

**Time and Skill Requirements**

Design can be conducted within 4-5 days and will require technician level skills to conduct.

**Recommended Next Steps**

Develop draft practice in AASHTO format by 9/30/2013 and submit to FHWA, ETG, or other groups for peer review.

**Deliverable Brief**

Evaluation of RAP Aggregates

**Format**

Practice

**ARC Partner**

University of Nevada, Reno

**Product Description**

As reclaimed asphalt pavement (RAP) usage becomes more common throughout the industry, the differences in handling RAP materials as compared to virgin aggregates are becoming more significant. These differences include RAP aggregate properties, such as specific gravity, absorption, and aggregate gradation, along with other aggregate properties of the virgin and RAP blends. In recent years, there have been many recommendations regarding the measurement and usage of these RAP properties. However, there has not been a consistent recommendation for assessing the RAP aggregate properties. Both the solvent extraction and the ignition oven methods can be used to recover RAP aggregates for specific gravity testing and for determining other properties of the aggregate blend. The solvent extraction method may leave a residue of asphalt on the aggregate while the ignition oven method may cause aggregate degradation. This practice will recommend the most effective methods for extracting RAP aggregates based on their impact on the various properties of the RAP aggregates and the volumetric calculations for the Superpave mix design. The practice utilizes the equipment being currently used in the Superpave volumetric mix design method.

**Equipment Availability and Cost**

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

**Potential Applications**

Mix Design Process

**Targeted Users**

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

**Time and Skill Requirements**

Tests can be conducted within 3-5 days and will require technician level skills to conduct.

**Recommended Next Steps**

Submit to AASHTO or ASTM

**Deliverable Brief**

Identification of Critical Conditions for HMA mixtures

**Format**

Practice

**ARC Partner**

University of Nevada, Reno

**Product Description**

Field performance data from the WesTrack project and other pavements indicate that every HMA mix has a critical temperature and a critical loading rate beyond which the mixture will become highly unstable that must be identified during the design process. Once these two critical conditions are identified, they must be checked against the expected field conditions where the HMA mix will be placed. Furthermore, it is believed that the critical conditions of an HMA mix can be significantly influenced through changes in binder content, binder properties, and aggregates gradation. This process will allow the mix design engineer to design excellent performing HMA mixtures for mainline traffic and traffic on off-ramps and at intersections with changes that can be accommodated in the production process without major interruptions, such as slightly modify the binder properties or slightly reduce the binder content as the construction approaches the intersection. The final product will be in the form of a recommended practice to identify the critical condition of an HMA mix at the mix design stage to avoid accelerated rutting failures of HMA pavements. An interim report (Characteristics of Dynamic Triaxial Testing of Asphalt Mixtures) has been completed which summarizes the state of stresses under the various loading conditions that were calculated using the pavement analysis software 3D-Move.

**Equipment Availability and Cost**

Commercial grade equipment is available at the cost of $70,000- $80,000.

**Potential Applications**

Mix Design Process and Mix Performance Evaluation.

**Targeted Users**

State Highway Agencies and Research Laboratories.

**Time and Skill Requirements**

Test can be conducted within 48 hours and will require technician level skills to operate.

**Recommended Next Steps**

Conduct Round Robin Testing

**Deliverable Brief**

Determining Thermal Crack Properties of Asphalt Mixtures through Measurement of Thermally Induced Stress and Strain

**Format**

Test Method

**ARC Partner**

University of Nevada, Reno

**Product Description**

The thermal stress restrained specimen test (TSRST) was enhanced by adding a modular feature to measure the thermal strain from an unrestrained specimen concurrently with the standard stress measurements from the restrained specimen while both are thermally loaded by decreasing the temperature in the test chamber. These measurements were then used to calculate the relaxation modulus as a function of temperature. Five distinguished characteristic stages were defined to describe the behavior of the asphalt mixture: (1) Viscous softening; (2) Viscous-Glassy Transition; (3) Glassy Hardening; (4) Crack Initiation; and (5) facture. These stages allowed for the determination of the thermo-viscoelastic properties of the mixture. Furthermore, some improvements were introduced to increase testing repeatability, in particular stress build-up curve, by replacing the restrained standard beam specimens with cylindrical specimens cored horizontally (57 mm diam. x 140 mm height) from a SGC compacted sample. The new improved TSRST device is called the Uniaxial Thermal Stress and Strain Test (UTSST).

The UNR researchers have been conducting laboratory experiments to assess the impact of sample size and variable cooling and warning rates on the thermo-viscoelastic properties. The testing method has also been used to assess the influence of high RAP contents as well as different warm-mix additives on mixture properties. The final version of the test method will be practical to use with the current Superpave mix design method and will produce mix properties that are directly incorporated into the Thermal Stress Model currently being developed.

**Equipment Availability and Cost**

Commercial grade equipment is available at the cost of $60,000- $80,000.

**Potential Applications**

Mix performance evaluation and generate input to analysis/performance models

**Targeted Users**

State Highway Agencies, Research Laboratories, and Commercial Laboratories

**Time and Skill Requirements**

Test can be conducted within 48 hours and will require technician level skills to operate.

**Recommended Next Steps**

Conduct Round Robin Testing

**Deliverable Brief**

Binder Bond Strength (BBS) Test.

**Format**

Test Method. Complete – AASHTO TP-91

**ARC Partner**

University of Wisconsin – Madison, Modified Asphalt Research Center (UWMARC)

**Product Description**

The Binder Bond Strength (BBS) test is a relatively quick and repeatable approach for evaluating the integrity of the bond at the asphalt-aggregate interface and the effects of moisture. The BBS is a significantly modified version of the Pneumatic Adhesion Tensile Testing Instrument (PATTI) specified in ASTM D4541. The main components of the BBS equipment are: portable pneumatic adhesion tester, pressure hose, piston, reaction plate and a metal pull-out stub. The pull-out stub has a rough surface that can prevent asphalt debonding from the stub surface by providing mechanical interlock and larger contact area between the asphalt binder and stub. For testing, the stub is attached to an aggregate substrate. To start the test, the piston is placed over the pull-out stub and the reaction plate is screwed on it. Compressed air is introduced to the system creating a tensile force in the direction normal to the substrate. Failure occurs when the applied stress exceeds the strength of the bond, failure can occur within the binder, at the asphalt/aggregate interface, or in a mixed mode. Research has shown that the BBS test is sensitive to conditioning time, conditioning medium, substrate mineralogy, and type of binder modification. The test is also sensitive to asphalt binder stiffness, requiring control of temperature and use of multiple temperatures for testing.

**Equipment Availability and Cost**

The BBS Test equipment is commercially available as the "P.A.T.T.I. Quantum Gold" sold by SEMicro Corp. The cost of the device is approximately $6000. The specially designed pull-out stubs are also commercially available.

**Potential Applications**

Evaluate the effect of anti-stripping or other modifications on the moisture susceptibility of asphalt-aggregate systems. Evaluate curing of emulsions as a means to estimate aggregate loss in chip seals.

**Targeted Users**

State Highway Agencies, Research Institutions, Asphalt Producers, and Consulting Laboratories.

**Time and Skill Requirements**

Sample preparation requires cutting of aggregates from quarry to produce aggregate plates with parallel faces. Time to conduct the dry BBS testing is approximately 4 hours (includes sample preparation). Additional time, 24 hours is needed for moisture conditioning of samples tested in the wet condition. Minimal technician training is required.

**Recommended Next Steps**

None planned at this time. The research team will address comments from AASHTO SCOM or other groups as needed.

**Deliverable Brief**

Measurement of Asphalt Binder Elastic Recovery and Ductility in the Dynamic Shear Rheometer (DSR)

**Format**

Test Method

**ARC Partner**

University of Wisconsin – Madison, Modified Asphalt Research Center (UWMARC)

**Product Description**

This product provides a test procedure to measure the ductility and elastic recovery of asphalt binders in the Dynamic Shear Rheometer (DSR). The current protocol measures these properties in a ductility bath which has both technical and practical shortcomings. From a technical perspective the geometry of the sample in the ductility bath changes with extension of the sample. As a result the sample is subjected to varying strain rates throughout the test, thus confounding the effects of modification on performance with the changing binder properties due to the variable strain rate. Practical limitations of the ductility bath include poor repeatability, the need for manual data collection, and the time required to conduct the test. The proposed DSR-based tests can be performed on any rheometer using the standard 8 mm parallel plate geometry.

In the procedure for ductility the sample is tested in monotonic shear using a constant shear strain rate. The sample is continuously loaded to a predetermined strain value and the peak shear stress and the corresponding strain is recorded as the sample yields. The procedure for measuring the elastic recovery in the DSR consists of two steps: a constant shear strain rate is applied for two minutes followed by a zero constant stress for an hour. The main difference from the current protocols can be seen in the last step where instead of cutting the sample a constant zero shear stress is applied. The elastic recovery in the ductility bath and elastic recovery in the DSR correlates very well, in addition the ER-DSR test provides a time savings relative to current methods.

**Equipment Availability and Cost**

Dynamic Shear Rheometer (DSR) equipment is common within industry and state agencies. New machines range in cost from $50,000-80,000.

**Potential Applications**

Improved "PG Plus" test methods for modified binders. Replace highly variable results from ductility and elastic recovery tests with ductility bath with DSR-based methods.

**Targeted Users**

Asphalt Producers, State Highway Agencies, and Contractors.

**Time and Skill Requirements**

Testing time is approximately 2 hours. Standard DSR training is required. A technician with minimal training can perform the test.

**Recommended Next Steps**

Present draft AASHTO method to the Binder ETG and revise for submission to AASHTO.

**Deliverable Brief**

Estimating Fatigue Resistance of Asphalt Binders Using the Linear Amplitude Sweep (LAS) Test

**Format**

Test Method. Complete – AASHTO TP-101

**ARC Partner**

University of Wisconsin – Madison, Modified Asphalt Research Center (UWMARC)

**Product Description**

The Linear Amplitude Sweep (LAS) test quantifies fatigue damage accumulation of asphalt binders using a short procedure in the DSR. The results from the test are analyzed by using either a fracture mechanics based approach or by using the Viscoelastic Continuum Damage (VECD) framework to derive a relation between number of cycles to failure and strain. Thus, from a single test one can account for both traffic loading (i.e., number of cycles to failure) and pavement structure (i.e., strain), which are known to affect fatigue resistance of pavements. It has been shown that binder fatigue performance as estimated by the LAS test correlates well to mixture performance in the laboratory and to fatigue performance in the field.

The test is conducted using the standard 8 mm parallel plate geometry DSR. The procedure consists of two tests; the first is a frequency sweep to obtain an undamaged material response, the second consists of cyclic loading at a constant frequency of 10 Hz, with systematically, continuously linearly increasing strain amplitudes and is run directly following the frequency sweep. Loading begins with 0.1% strain to obtain an undamaged material response, followed by strain steps increasing from 0.1% up to 30% applied strain.

**Equipment Availability and Cost**

Dynamic Shear Rheometer (DSR) costs between $50,000-80,000 depending upon the manufacturer and capabilities of the machine.

**Potential Applications**

Rank asphalt binders based on fatigue damage resistance and determine the effect of modification on the fatigue performance. Select modification types and dosages to engineer asphalt binders for fatigue resistance.

**Targeted Users**

Asphalt Producers, State Highway Agencies, Contractors, Research Institutions, and Consulting Laboratories.

**Time and Skill Requirements**

Total testing time with conditioning is approximately 30 minutes. Standard DSR training is required.

**Recommended Next Steps**

Complete inter-laboratory ruggedness testing to establish repeatability and reproducibility of test and robustness of settings. Revise AASHTO TP-101 to reflect results of ruggedness testing and comments received from FHWA Binder ETG.

**Deliverable Brief**

Binder Yield Energy (BYET) Test
(this test method has now been combined with the method "Measurement of Asphalt Binder Elastic Recovery and Ductility in the Dynamic Shear Rheometer (DSR)")

**Format**

Test Method

**ARC Partner**

University of Wisconsin – Madison, Modified Asphalt Research Center (UWMARC)

**Product Description**

This test method has been integrated into the product for Measurement of Asphalt Binder Elastic Recovery and Ductility in the Dynamic Shear Rheometer (DSR). Please refer to the referenced Deliverable Brief for further information.

**Deliverable Brief**

Measurement of Rigden Voids for Fillers

**Format**

Test Method

**ARC Partner**

University of Wisconsin – Madison, Modified Asphalt Research Center (UWMARC)

**Product Description**

This test method determines the voids in a dry, compacted filler sample using the Rigden apparatus. The void content is estimated by compacting dry fillers using specified mold size and compaction effort. The Rigden Voids parameter is a measure of packing found sensitive to filler type for both natural and manufactured materials. Given it's relation to packing and filler shape/size the Rigden Voids directly relates to the amount of volume available in the filler to accommodate asphalt binder. Furthermore, research results indicate that due to the relation between packing and asphalt free volume, the Rigden Voids parameter has found to relate well to the filler stiffening effect on binders. As a result, the change in mastic performance relative to that of a conventional binder varies based on the Rigden Voids of the filler. Changes in mastic properties were found to correlate well with mixture workability and performance properties through laboratory testing.

The Rigden Voids apparatus consists of a sample container attached to a base plate seated between two vertical rods. The vertical rods control the drop height of the standard hammer used to compact the filler. With the weight and height of drop constant, the filler is compacted at a standard compactive effort using100 blows. The %Rigden Voids in the filler is calculated using the specific gravity and height/weight of the compacted filler.

**Equipment Availability and Cost**

Rigden Apparatus costs approximately $3000.

**Potential Applications**

Classify filler based on Rigden voids as a means to estimate impacts of fillers on HMA workability and performance properties. Tool to screen and select fillers to allow mixes to achieve certain performance properties.

**Targeted Users**

Aggregate producers, contractors, and state highway agencies.

**Time and Skill Requirements**

Testing time is approximately 1 hour. A technician with minimal training can perform the test.

**Recommended Next Steps**

Submit draft AASHTO standard and revise based on FHWA/ETG review.

**Deliverable Brief**

Measurement of Asphalt Binder Lubricity Using the Dynamic Shear Rheometer (DSR)

**Format**

Test Method

**ARC Partner**

University of Wisconsin – Madison, Modified Asphalt Research Center (UWMARC)

**Product Description**

The current measure of asphalt binder workability, viscosity does not relate directly to mixture workability as the relationship between density and temperature is not a linear function. There is a need to better understand the role of binder in workability through application of the basic concepts used to characterize lubricating oils. Lubricating oils experience two extreme conditions; hydrodynamic lubrication and boundary lubrication, operation in these regimes is based on film thickness, viscosity, and surface roughness. To capture both behaviors two geometries were developed; a four ball apparatus for hydrodynamic lubrication and a pin-on-disk geometry for boundary lubrication. The four ball apparatus consists of three steel ball bearings clamped in a cup, with a fourth ball held in a chuck and loaded against them. The pin on disk geometry consists of an aggregate plate (disk) contacted by a fixture that includes two square aggregate blocks (pins). In both tests the normal force is controlled and torque monitored as the fixture rotates at a constant speed, the test output is binder coefficient of friction.

Research results indicate that the coefficient of friction is sensitive to the presence of WMA additives, asphalt binder modification, and test temperature. Furthermore, boundary lubrication testing found significant influences of surface roughness and mineralogy for the coefficient of friction of a given binder. As a result the conclusion was drawn that it is necessary to include effects of the aggregate surface to obtain a complete understanding of the influence on WMA additives on binder and mixture workability.

**Equipment Availability and Cost**

Both test methods have been adapted to fit the dimensions of the DSR. However, non-standard test geometries are specified for both tests. Total cost of these fixtures is approximately $8000.

**Potential Applications**

Evaluation of WMA additives to select additive types and dosage rates. Understanding of the asphalt binder role in mixture compaction to select of WMA production temperature ranges.

**Targeted Users**

Research Laboratories and Materials Suppliers

**Time and Skill Requirements**

Testing time is approximately 3 hours each for the Lubricity Test. Standard Superpave testing equipment training is needed (DSR). Specific training on preparation of non-standard test geometries, sample preparation procedure, test procedure, and analysis of data required.

**Recommended Next Steps**

Submit draft AASHTO test method by 3/31/2013 and address outstanding comments.

**Deliverable Brief**

Procedure for Evaluation of Coating for Cold Mix Asphalt

**Format**

Test Method

**ARC Partner**

University of Wisconsin – Madison, Modified Asphalt Research Center (UWMARC)

**Product Description**

For CMA to perform in the field, it is required that sufficient aggregate coating is achieved during mixing and that the emulsion film remains intact after curing and while in-service. Ensuring high degree and quality of coating is not a straightforward process as it is required that the emulsion is able to coat moist aggregate. Therefore in addition to sufficient viscosity the emulsion chemistry selected must be compatible with the job aggregate. Research indicates that the coating achieved during mixing has a direct impact on the moisture damage resistance of CMA, as demonstrated in the laboratory by a substantial reduction in TSR. Given the additional factors to consider in producing CMA, a coating test serves the purpose of verifying the materials selected will achieve adequate coating and perform well in the field.

The proposed test method evaluates the degree and quality of coating through use of digital imaging conducted before and after the boiling test on the same 3000 g sample. After mixing the loose CMA sample is placed in a frame on the surface of a flatbed scanner. The degree of coating, expressed as a percent is obtained using the thresholding analysis function common to many available image processing software tools. The thresholding is calibrated through scanning of the bare aggregate to define the limit the software will define as "uncoated" in the analysis. To evaluate quality of coating the sample is then subjected to a boiling test and image analysis is used again after conditioning. A high quality of coating will exhibit a limited decrease in %coated due to the boiling test.

**Equipment Availability and Cost**

Available – Test uses an office grade flatbed scanner ($50) and use of readily available image processing software. Two examples of free products are Image J 1.46m (NIH) and iPas (UW-Madison).

**Potential Applications**

Materials selection and mix design tool.

**Targeted Users**

Materials suppliers, contractors, state highway agencies

**Time and Skill Requirements**

Coating and boiling test take approximately 1.5 hours. HMA Technician or similar skills needed for mix preparation. Minimal training required for use of scanner and image processing software.

**Recommended Next Steps**

Submit draft AASHTO test method by 3/31/2013 to FHWA, address all comments, and submit final procedure 9/30/2013.

**Deliverable Brief**

Cold Mix Asphalt Laboratory Specimen Preparation Using Modified SGC Molds

**Format**

Test Method

**ARC Partner**

University of Wisconsin – Madison, Modified Asphalt Research Center (UWMARC)

**Product Description**

The objective of the previously presented CMA Mix Design Procedure (#20) is to adapt the concepts, test methods, and equipment currently used for HMA to CMA. This requires use of the SuperPave Gyratory Compactor (SGC) to prepare samples and measurement of various mixture performance properties after a given level of curing. The presence of water necessitates development of a separate test procedure to account for impacts on both compaction and performance. The procedure will also provide an initial range of compactive effort (# of gyrations) to use in preparation of cold mix samples and will introduce new equipment necessary for compaction and curing times for sample priors to measurement of volumetric and performance properties.

The presence of water requires a use of a perforated SGC mold during compaction to provide a pathway for drainage of water in the mix. The dimensions and other aspects of the mold remain unchanged. Sample preparation procedures will recommend a waiting time between mixing and compaction and curing time and temperature with sample confinement prior to volumetric and performance testing. Confinement is required to minimize the change in dimensions experienced by the sample during curing.

**Equipment Availability and Cost**

Commercial grade SGC designed for compaction of CMA is available at the cost of $30,000 - $40,000, perforated molds are available at an additional cost.

**Potential Applications**

Materials selection and mix design tool.

**Targeted Users**

Materials suppliers, contractors, state highway agencies

**Time and Skill Requirements**

HMA Technician or similar skills needed for mix preparation and compaction. Curing requires 72 hours.

**Recommended Next Steps**

Submit draft AASHTO test method by 6/30/2013 to FHWA, address all comments, and submit final procedure 12/31/2013.

**Deliverable Brief**

RAP Binder PG True Grade Determination

**Format**

Test Method and Software

**ARC Partner**

University of Wisconsin – Madison, Modified Asphalt Research Center (UWMARC)

**Product Description**

This test method presents the procedure to estimate the effect of recycled asphalt pavement (RAP) or recycled asphalt shingles (RAS) on binder performance grade. The procedure measures the Superpave PG properties of asphalt binders and mortars in order to estimate the performance properties of the blended binder. Due to the use of mortars, extraction of binders from recycled materials is not required. Mortars are prepared by combining the base binder at varying levels of aging and RAP (RAP Mortar) and aggregates obtained from the field RAP after sieving and burning in the ignition oven (Aggregate Mortar). The level of base binder aging used in mortar preparation is adjusted based on the performance property measured.

The procedure has two outputs, the continuous grade of the blended binder and the rate in grade improvement as a function of % binder replacement. To obtain these parameters it is necessary to test both RAP and Aggregate mortar to estimate the properties of the recycled binder. This estimation is based on the assumption that any difference in performance between the two mortars is attributed to the effect of the RAP/RAS binder. To obtain the continuous grade of the blended material, the effect of the RAP/RAS binder is used as a shift factor to adjust the properties of the base binder. Given the continuous grade of the base and blended binder and the level of %Binder replacement in the prepared RAP mortar, the rate of grade increase per %Binder Replacement (PBR), expressed as °C/%PBR is determined. A draft procedure has been submitted that details preparation of mortars, adjustments to AASHTO M320 methods, and calculations for the rate of grade increase in final continuous grade. A software tool has also been developed to automate the calculations detailed in the standard.

**Equipment Availability and Cost**

Procedure makes used of equipment required for SuperPave grading. Only additional item required is an ignition oven. The ignition oven is commercially available at a cost of ~$20,000.

**Potential Applications**

Improving mix durability through application of a materials specific, performance related selection of maximum levels of binder replacement that can be allowed without adjusting the performance grade of the base binder.

**Targeted Users**

State Highway Agencies, Contractors, and Research Institutions.

**Time and Skill Requirements**

Requires grading of three materials using skills similar to those of a binder testing technician.

**Recommended Next Steps**

Address FHWA Mixture ETG comments on draft AASHTO Standard and deliver software tool.

**Deliverable Brief**

Measurement of Asphalt Binder Fracture Properties using the Single-Edge Notch Bending (SENB) Test

**Format**

Test Method

**ARC Partner**

University of Wisconsin – Madison, Modified Asphalt Research Center (UWMARC)

**Product Description**

The Single Edge Notch Bending (SENB) test measures the low temperature fracture properties of asphalt binders and mastics at low temperatures. The test geometry consists of a beam prepared with a notch of pre-determined depth at the center of the beam. During testing the beam is subjected to three point bending and the load is applied in a displacement control mode. The test apparatus makes use of the Bending Beam Rheometer device currently used in standard SuperPave testing with modification to the load frame to produce loads sufficient to induce fracture and the a motor capable of applying the load in displacement control mode. During loading the machine software monitors the applied load and sample displacement. Analysis of the test method assumes that conditions of Linear Elastic Fracture Mechanics (LEFM) are met. Given this assumption known solutions derived in LEFM for Mode I loading are applied to estimate binder fracture energy ($G_f$) and fracture toughness ($K_{IC}$).

Preliminary results indicate that this test method is capable of differentiating between materials resistant to fracture and those that are not for both asphalt binders and mastics. The test is also sensitive to the presence of recycled binders and demonstrates the effects of modification on crack initiation and propagation.

**Equipment Availability and Cost**

Bending Beam Rheometer (BBR) - $40,000. Motor Step-Loading frame to apply load using displacement control - ($12,000). Both items are readily available.

**Potential Applications**

Asphalt binder grading based on fracture properties. Ranking of asphalt materials based on fracture toughness Effect of modification and recycled binders on low temperature cracking of asphalt binders.

**Targeted Users**

Asphalt Producers, State DOT’s, Contractors, Research Institutions, and Consultants.

**Time and Skill Requirements**

The time required for testing one specimen is approximately 2 hours. This includes sample preparation and sample conditioning at specified temperature for 1 hour. A technician with minimal training can perform the test.

**Recommended Next Steps**

Revise draft AASHTO test method based on FHWA Binder ETG comments and submit to AASHTO for consideration as a provisional standard.

**Deliverable Brief**

Test Method for Measurement of the Glass Transition Temperature of Asphalt Binders

**Format**

Test Method

**ARC Partner**

University of Wisconsin – Madison, Modified Asphalt Research Center (UWMARC)

**Product Description**

This test assesses the thermo-volumetric properties of asphalt binders by determining the glass transition temperature ($T_g$) and the coefficients of thermal expansion/contraction by means of a dilatometric test system. The dilatrometic system consists of cells made of aluminum and sealed with cryogenic o-rings, and precise capillary tubes instrumented with automated pressure sensors. To conduct the test an asphalt sample is inserted in the cell and the cell is filled with alcohol through the capillary tube. The device is enclosed in an environmental chamber and subjected to a prescribed temperature range and rate of change. During the test the volume change of the asphalt sample is monitored using the change in level of alcohol in the capillary tubes, as the change in height is proportional to total sample volume. For analysis, the specific volume vs. temperature data recorded by the software is fit using a non-linear model to obtain the glass transition temperature ($T_g$) and the thermal coefficients of contraction/expansion. In its current state the apparatus includes a monitoring system that is fully automated through regulation of temperature and measurement of volume change through use of pressure cells instrumented on the capillary tubes.

**Equipment Availability and Cost**

Total estimated cost of equipment and assembly is approximately $2,500. The system is comprised of insulated chamber ($100), dilatometric cell ($1000), pressure sensor ($250), capillary tube ($100), and a cooling system with solenoid valve ($200). Liquid nitrogen is currently been used as cooling agent. A tank of nitrogen costs $70 (for 5 tests).

**Potential Applications**

Comparison of measured values of $T_g$ to expected service temperatures to assess thermal cracking risk. Use of coefficient of thermal expansion/contraction for pavement design purposes.

**Targeted Users**

Material Suppliers, Research Institutions

**Time and Skill Requirements**

Testing time is approximately 4 hrs for 1°C/min of cooling rate. A significant level of training is required to ensure proper sample preparation. Proper sample preparation is imperative to obtain quality data.

**Recommended Next Steps**

Revise standard based on comments received from FHWA Binder ETG (if necessary) and submit final standard to AASHTO.

**Deliverable Brief**

Asphalt Mixture Glass Transition Test

(This test has been combined with the modified Thermal Stress Restrained Specimen Test)

**Format**

Test Method

**ARC Partner**

University of Wisconsin – Madison, Modified Asphalt Research Center (UWMARC)

**Product Description**

This product has been integrated into the test method for the modified Thermal Stress Restrained Speciment Test for simultaneous measurement of thermal strain and thermal stress in asphalt mixture. Please refer to the referenced Deliverable Brief.

**Deliverable Brief**

Analysis of Asphalt Mixture Aggregate Structure through Use of Planar Imaging Processing and Analysis (iPas)

**Format**

Test Method / Software

**ARC Partner**

University of Wisconsin – Madison, Modified Asphalt Research Center (UWMARC)

**Product Description**

The Image Processing and Analysis System (iPas) has been developed to as a means to quantify the aggregate structure in asphalt mixtures through use of planar imaging. To conduct the analysis laboratory compacted samples or field cores are cut in the vertical direction, scanned with a conventional office grade flatbed scanner, and input into the software. The software applies a series of well established image processing techniques including filtering and thresholding to identify the aggregate matrix in the mix and identify aggregates and their orientation. Using this information the software identifies aggregates that are in contact and the amount of surface that is in contact (contact length). As a result, the effective aggregate skeleton within the mix is identified. The iPas system includes quality control measures to ensure that the images processed are representative of the actual mix through comparison of iPas estimates to actual values of mix gradation and volumetric properties.

Research has shown that sole use of volumetrics are an insufficient means to ensure mixture performance, as various mixes compacted to the same level of density demonstrate significantly different performance. In contrast, the aggregate structure parameters resulting from the image analysis conducted by iPas have been shown to correlate well with both mixture resistance to rutting and thermal cracking. These results highlight the importance of achieving a quality aggregate skeleton during compaction to achieve in-service performance. Further research is ongoing to identify the mix design properties that influence formation of the aggregate skeleton and potential for integrating these concepts into current mix design procedures.

**Equipment Availability and Cost**

Saw, Standard flatbed scanner ($50), Version of iPas software is currently available at no cost.

**Potential Applications**

Assess effects of different compaction methods (laboratory and field) on aggregate structure. Evaluate mix segregation. Mix design tool to ensure components selected result in a quality aggregate structure that will perform well in the field.

**Targeted Users**

State Highway Agencies, Research Laboratories, and Contractors.

**Time and Skill Requirements**

Basic computer skills and asphalt mixture design knowledge. Analysis is approximately 30 minutes per image.

**Recommended Next Steps**

Finalize draft AASHTO standard and submit to FHWA Mix ETG for review. Revise standard based on input and assess potential for submission to AASHTO.

**Deliverable Brief**

Determining the Resistive Effort of Asphalt Mixture during Compaction in a Gyratory Compactor using an Internal Device

**Format**

Test Method. Completed – ASTM approved standard.

**ARC Partner**

University of Wisconsin – Madison, Modified Asphalt Research Center (UWMARC)

**Product Description**

The Gyratory Pressure Distribution Analyzer (GPDA) monitors the internal forces of a mix during compaction through use of three load cells oriented at 120°C, an internal data collection unit to monitor load cell response during compaction, and a software tool to convert load cell readings to values of load and eccentricity. To conduct testing the device is activated and placed in the SGC mold prior to compaction. After compaction the device is connected to a computer via USB cable and the software uses readings from all three load cells to determine the reactive force exerted by the mix during compaction and its effective location with respect to the center of the sample. The output of the testing device, load and eccentricity, can be used to calculate the resistive effort of the mix as a function of SGC gyrations. In combination with mixture volumetric data, the resistive effort at different levels of density has been used to evaluate mixture workability and stability through use of the construction force index (CFI) and traffic force index (TFI) respectively. Application of these indices can be used to identify aggregate gradation and asphalt binder combinations that exhibit workability during construction and in-service stability. The TFI measured using the GPDA data has been found to correlate well to mixture Flow Number.

**Equipment Availability and Cost**

Super Pave Gyratory Compactor and Gyratory Pressure Distribution Analyzer (GPDA) required. The GPDA is currently being marketed by Troxler and sells for approximately $8000.

**Potential Applications**

This technology has most use as a mix design tool to identify aggregate gradation, binder grades, and types of modification that will results in a mixture that exhibits workability during construction and adequate aggregate interlock for in-service stability. The GPDA also has potential use as a QC tool by specifying a minimum mixture eccentricity or level of resistive effort for a given gyration.

**Targeted Users**

Research Laboratories, Contractors, and State Agencies.

**Time and Skill Requirements**

Testing time is approximately 1 hour. Standard Superpave mix design training is required. Specific training related to use of the GPDA and analysis of the data collected is also required.

**Recommended Next Steps**

Complete precision and bias statement for incorporation into ASTM Standard that has been approved. Introduce newly developed software tool for analysis and training materials.

**Deliverable Brief**

Micromechanical Properties of Various Structural Components in Asphalt using Atomic Force Microscopy (AFM)

**Format**

Test and Analysis Method

**ARC Partner**

TAMU/TTI

**Product Description**

The purpose of this test and analysis method is to characterize the micromechanical properties of various structural components in asphalt using Atomic Force Microscopy (AFM) and to quantify mechanical, viscoelastic properties of the phase components of asphalt binders before and after various degrees of oxidative aging. Nano-indentation experiments have been performed under work element F2d on a micro-grid of asphalt. TAMU has been successful in determining micromechanical properties such as stiffness, adhesion and elastic/plastic behavior. TAMU has noted a substantial difference in these mechanical properties between unaged and aged binders. The binders tested to date are AAB, AAD and ABD from the Materials Reference Library (MRL) of the Strategic Highway Research Program (SHRP). These binders were chosen based on the variation in crude source, chemical composition and elemental analysis that represent.

This product will be a test method in AASHTO recommended practice format to used nano-indentation to quantify viscoelastic properties of the phases of the asphalt binder as well as the composite asphalt binder before and after aging. These properties will ultimately be used to predict the fracture, hardening, fatigue, permanent deformation and fracture healing potential of asphalt binders and their performance in asphalt mixtures. The recommended standard practice will address the testing methodology and the methods by which to extract the viscoelastic properties as well as the utility of using these viscoelatic properties to screen for performance potential in terms of facture, fatigue, permanent deformation and compatibility with aggregate of all size fractions within the asphalt mixture.

**Equipment Availability and Cost**

An AFM capable of performing this function can be purchased for approximately $35,000 and is available from Agilent Technologies among other manufacturers.

**Potential Applications**

This methodology should be used as a screening tool for asphalt binder fracture, fatigue, and permanent deformation potential and development of adhesive (with aggregate) and cohesive bond energy in a mixture and thus compatibility with a selected aggregate as well as moisture susceptibility.

**Targeted Users**

Central laboratories of the FHWA and state DOTs as well as consultancies will be likely to immediately benefit.

**Time and Skill Requirements**

Use of the AFM requires a dedicated technician, knowledgeable in the science and use of the AFM. The testing protocol will be sufficiently specific, however, to make this a reasonable and beneficial effort.

**Recommended Next Steps**

Complete the testing protocol and develop methods of analysis to define viscoelastic properties.

**Deliverable Brief**

Fatigue assessment method of asphalt binder and asphalt mastic

**Format**

AASHTO Method

**ARC Partner**

Virginia Tech

**Product Description**

The purpose of this project is to establish an AASHTO standard test method for the use of a cyclic tensile test system to measure the fatigue resistance of asphalt binder and mastic. A cyclic tensile test system is fabricated from modification of Direct Tension Tester (DTT) provided by Interlaken Inc. for the fracture properties assessment of asphalt binder at low temperature. (ASTM 6723). Cyclic tensile test specifications, calibration procedure, sample preparation procedure, detailed test procedure and data interpretation methodology will be included in the product.

**Equipment Availability and Cost**

DTT will be altered using commercial software Test Builder which is also provided by Interlaken Inc. The cost of DTT unit is standard market price and the Test Builder Software Package is around $1000 extra with purchase of DTT equipment.

**Potential Applications**

The developed test system is capable of applying cyclic tensile loadings to small asphalt material specimens including not only asphalt binder but also mastic which is the mix of binder and fine sands. The fatigue resistance of specimen is measured directly by the number of loading cycles for a specimen to fail under cyclic loading. The axial strain of specimen can be measured by the system automatically. The test builder system can be used to develop new test procedure depending on the users' specific needs. Cyclic tensile test results of asphalt binder were used to calibrate the material property parameters of an elasto-plastic model in this project.

**Targeted Users**

Asphalt pavement researchers and highway engineering communities.

**Time and Skill Requirements**

The sample preparation and installation are the same with the procedure for direct tension test of asphalt binder which will require one hour for sample preparation and one hour for sample conditioning. Time of cyclic tensile test varies depending on loading magnitude, frequency and test temperature. Operation of Test Builder requires two hours of training. An experienced technician is qualified to assure proper operation of the instrument.

**Recommended Next Steps**

The test is a newly developed procedure which requires further calibration. Application of the test procedure to validate specific material properties for constitutive model development should also be further investigated.

**Deliverable Brief**

Evaluate Healing using Continuum Damage Approach

**Format**

Test Method

**ARC Partner**

UT Austin / Texas A&M

**Product Description**

A test method to measure the rate of overall healing in asphalt mortars (or fine aggregate matrix / FAM) as a function of the duration of rest period and extent of damage prior to the rest period. This test method can also be applied to full asphalt mixtures subjected to dynamic loading in shear or tension.

Self-healing in asphalt composites can be regarded as the reversal of micro-damage. Under isothermal conditions, overall healing in asphalt composites (mortars or mixtures) is a function of the duration of the rest period as well as the extent of damage immediately preceding the rest period. Typically healing is quantified using direct measurement of stiffness as a function of the rest period. However this approach is confounded by several factors. For example, the viscoelastic recovery of the composite can be misconstrued as healing. Also the results are dependent on experimental factors such as the loading amplitude and mode of loading. The proposed procedure overcomes these limitations by using the viscoelastic continuum damage approach (VECD) to quantify healing as a material property. In summary, the experimental method involves applying cyclic loads (controlled stress or strain) and measuring the stiffness of the test specimen as a function of time or number of load cycles. Rest periods of varying durations are introduced when the stiffness of the specimen reduces to different predetermined levels. The resulting data are analyzed using the viscoelastic continuum damage approach to quantify healing in terms of the recovery of the state variable, S, that represents damage in the test specimen. The resulting data can also be analyzed to produce the characteristic stiffness versus damage (C vs. S) curve based on the viscoelastic continuum damage method. The proposed test method was demonstrated to be effective in quantifying the healing characteristic of asphalt mortars using a dynamic shear rheometer (DSR).

**Equipment Availability and Cost**

- Dynamic Shear Rheometer ($50,000 – DSR is already in use for other binder tests)
- The asphalt materials performance tester (AMPT) can also be modified and used with this same protocol to evaluate healing characteristics of full asphalt mixtures.

**Potential Applications**

- Comparing the healing potential of different asphalt mortars and mixtures.
- Evaluating the influence of additives on the healing capacity of different asphalt mixtures.
- Evaluating the influence of mixture variables (e.g. gradation, fines content) on improving healing characteristics via mechanisms such as crack pinning etc.

**Targeted Users**

DOT and other research agencies.

### Time and Skill Requirements

One day for testing excluding specimen fabrication.
Skill level required is similar to that for mixture testing.

### Recommended Next Steps

Validating the efficacy of this protocol with full asphalt mixtures subjected to cyclic tension-compression loading.

**Deliverable Brief**

Self-Consistent Micromechanics Models of Asphalt Mixtures

**Format**

Analytical Model and Data Analysis Program

**ARC Partner**

Texas A&M University

**Product Description**

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

**Equipment Availability and Cost**

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

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

Cost of personal computer.

**Potential Applications**

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

**Targeted Users**

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

**Time and Skill Requirements**

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

**Recommended Next Steps**

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

**Deliverable Brief**

Nonlinear Mechanical Behavior of Asphalt Binders and Prediction of Rutting Susceptibility

**Format**

Test Method

**ARC Partner**

Texas A&M

**Product Description**

The mechanical behavior of asphalt binders is nonlinear. Asphalt binders exhibit shear thinning/thickening behavior in steady state shear tests and non-proportional behavior in other standard viscoelastic tests such as creep-recovery or stress relaxation tests. Moreover, they develop normal stress differences even in simple shear flow – a characteristic feature of nonlinear viscoelastic behavior.

Many researchers have asserted the importance of considering the nonlinearity of the mechanical behavior of asphalt binders in order to accurately approximate field performance and to compare and rank their performance under field conditions. In order to do so, a reliable, robust viscoelastic model is necessary. Most of the models in the literature do not accurately capture the various features of nonlinear response, and those that do are too complicated to use routinely and still possess shortcomings.

Considering these issues, a new, nonlinear viscoelastic model was developed under ARC at Texas A&M University using a Gibbs-potential based thermodynamic framework. This model has been corroborated with data from experiments in which shear-thinning behavior and the non-proportional creep recovery behavior was observed together. The model was also used to evaluate the various criteria currently used to predict the rutting susceptibility of asphalt binders: Superpave parameter ($G^*/\sin\delta$), zero shear viscosity, and the multiple stress creep recovery or (MSCR) test. Results of the analysis of rutting prediction criteria show that each criterion characterizes the resistance to permanent strain in asphalt binders over a different range of applied stresses. The zero shear viscosity applies at very low stress levels, $G^* \sin\delta$ applies at very high stress levels and MSCR applies at intermediate stress levels.

While evaluations studies proved a rough equivalence in the ranking of unmodified binders based on the zero shear viscosity, $G^* \sin\delta$ and MSCR tests, this was not true with modified binders where changes in stress state often impacted relative rankings. In these cases the necessity of a protocol that ranks performance over a range of potential stress levels is necessary. The proposed protocol meets this need.

**Equipment Availability and Cost**

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

**Targeted Users**

DOT and other research agencies.

**Time and Skill Requirements**

One day for testing excluding specimen fabrication.  Skill level required is similar to that for dynamic shear rheometer testing.

**Recommended Next Steps**

Validate the efficacy of this protocol with full asphalt mixtures with various asphalt binders, especially those containing substantial levels of polymer modification using elastomers and plastomers, and subjected to cyclic compression loading.

**Deliverable Brief**

Method to determine the surface roughness of aggregate and fines based on AFM

**Format**

AASHTO Method

**ARC Partner**

WRI

**Product Description**

The purpose of this project is to establish an AASHTO standard test method for the use of an Atomic Force Microscope (AFM) to measure the surface roughness of aggregates and fines. The test method will include AFM system specifications, probe tip and cantilever specifications, calibration procedure, sample preparation procedure, detailed test procedure, and data interpretation methodology.

**Equipment Availability and Cost**

The test method can use just about any available AFM. Standard cantilevers and tips are used. Suitable image analysis software is included with many AFM packages, but is also available separately. The cost of this system can vary considerably depending upon the manufacturer and selected options for the AFM instrument.

**Potential Applications**

Information relative to the surface roughness of aggregates is used for modeling and understanding the asphalt/aggregate adhesive bond which is the fundamental basis of pavement performance.

**Targeted Users**

Asphalt pavements research and highway engineering communities.

**Time and Skill Requirements**

This is a relatively simple test. However, due to the nature of AFM, an experienced technician is needed to assure proper operation of the instrument. Testing, including sample preparation will require one to two hours per sample depending upon the type of saw and the initial size and shape of the aggregate sample. Cut sample are typically oven-dried over night prior to imaging. Imaging and image analysis takes about one hour per sample.

**Recommended Next Steps**

This new tool should be used to conduct definitive testing regarding the importance of aggregate surface roughness on the asphalt/aggregate adhesive bond.

**Deliverable Brief**

Method to determine ductile-brittle properties via AFM measurements

**Format**

AASHTO Method

**ARC Partner**

WRI

**Product Description**

The purpose of this project is to establish an AASHTO standard test method for the use of an Atomic Force Microscope (AFM) to quantitatively measure ductile-brittle properties for asphalt adhesives relative to temperature and stress rate using a direct tension type of measurement. The energy needed to fracture a visco-elastic material such as asphalt has both a thermodynamic and a dissipative component. An AFM-based direct tension test is used to measure fracture energy in terms of these components. In this test method we equate the brittle fracture energy with the thermodynamic energy. The difference between the measured fracture energy and the thermodynamic fracture is the dissipative energy which we equate with ductile behavior. The test method thus provides a quantitative measure of both ductile and brittle properties with respect to temperature and stress-rate as well as the total fracture energy and the relative significance of the ductile and brittle components.

**Equipment Availability and Cost**

The test method utilizes an AFM with environmental chambers, a nano-positioning stage, and modified cantilever probes. Equipment suitable for conducting these measurements is readily available 'off-the-shelf' from a variety of manufacturers. The cost of this system when assembled from available components will vary considerably depending upon the manufacturer and selected options for the various instruments.

**Potential Applications**

This test method provides a tool which can be used to predict the fracture properties of an asphalt pavement as it ages relative to the service environment and the particular binder used.

**Targeted Users**

Asphalt research and highway engineering community

**Time and Skill Requirements**

Characterizing the fracture energy of an asphalt binder involves testing as a function of both rate and temperature. An individual sample can typically be characterized in three to four working days. This includes time for sample preparation, testing, and analysis of the data. The equipment can be operated by a conscientious technician. The information obtained is targeted to engineers with knowledge of pavement design and asphalt mixture characterization.

**Recommended Next Steps**

We recommend that development and verification of this test method should be continued with additional testing and that descriptions of this work should be readied for publication.

**Deliverable Brief**

AFM-based micro/nano-scale cyclic direct tension test

**Format**

AASHTO Method

**ARC Partner**

WRI

**Product Description**

The purpose of this project is to establish an AASHTO standard test method for the use of an Atomic Force Microscope (AFM) to quantitatively measure fracture energy (i.e. strain energy release rate) at micro/nano-scale for asphalt adhesives relative to temperature and stress rate using a direct tension type of measurement. Visco-elastic materials such as asphalt tend to exhibit fracture energies that are dependent upon both the temperature and the stress rate. To quantify the fracture energy for this type of material a test procedure that allows for the control of both the temperature and stress rate is needed. Fracture energy is quantified in terms of a strain energy release rate that is, the energy required to extend a crack by a unit of length and/or to create a new unit of crack surface. Fracture energy is typically measured in a direct tension-type fixture which measures the force needed to rupture an axially-loaded notched beam of specified dimensions. A similar type of testing can be conveniently conducted at micro/nano-scale using an appropriately configured AFM and colloidal-tipped probes. The test method will include detailed AFM system specifications including a dedicated nano-positioning stage and environmental chamber, probe tip and cantilever specifications, sample preparation procedure, detailed test procedure, and data interpretation methodology.

**Equipment Availability and Cost**

AFMs with environmental chambers, nano-positioning stages, and modified cantilever probes suitable for conducting these measurements are all readily available 'off-the-shelf' from a variety of manufacturers. The cost of this system when assembled from available components will vary considerably depending upon the manufacturer and selected options for the various instruments.

**Potential Applications**

This test method provides a tool which can be used to predict the fracture properties of an asphalt pavement as it ages relative to the particular binder used.

**Targeted Users**

Asphalt research and highway engineering community

**Time and Skill Requirements**

Characterizing the fracture energy of an asphalt binder involves testing as a function of both rate and temperature. An individual sample can typically be characterized in three to four working days. This includes time for sample preparation, testing, and analysis of the data. The equipment can be operated by a conscientious technician. The information obtained is targeted to engineers with knowledge of pavement design and asphalt mixture characterization.

**Recommended Next Steps**

We recommend that development and verification of this test method should be continued with additional testing and that descriptions of this work should be readied for publication.

**Deliverable Brief**

Measurement and Texture Spectral Analysis of Pavement Surface Profiles Using a Linear Stationary Laser Profiler (SLP)

**Format**

Test Method

**ARC Partner**

University of Wisconsin – Madison, Modified Asphalt Research Center (UWMARC)

**Product Description**

This test method describes a means to measure and analyze pavement surface profiles using a linear Stationary Laser Profiler (SLP) and Texture Spectral Analysis (TSA) methods, respectively. The stationary laser profiler (SLP) relies on the principle of optical triangulation to measure surface texture characteristics. The laser sensor projects a laser beam on the sample surface, which is diffusely reflected to a receiver and translated into amplitude values. The SLP triangulates surface amplitude as it travels laterally at low speeds along the rail of the test assembly. Surface amplitude is coupled with horizontal displacement to define the surface profile. The test frame supports the laser and draw-wire sensor devices on one end and a small motor at the other. The laser sensor is connected to the frame-mounted counter-balance assembly by two screws. Connected by a thin cable, the motor pulls the laser assembly across the frame at a controlled rate while it registers horizontal displacement measurements. The combined amplitude-displacement measurement is registered in the computer's data acquisition card, which is transmitted to the software interface. After recording the raw surface profile with the SLP, several transformation algorithms are applied to the profile data. Discrete Fourier Transform can be applied to the conditioned data to determine the texture level distribution. Using techniques outlined in related ISO standards, allow for calculation of mean profile depth (MPD) and power spectral density (PSD). Data generated using TSA methods can be used to define the pavement surface texture spectrum, which can be used to estimate friction and noise generation characteristics of pavement. This method is applicable to both laboratory and field compacted mixes.

**Equipment Availability and Cost**

Stationary Laser Profiler is required, cost is unknown.

**Potential Applications**

SLP can be used as a supplement to current mix design procedures to evaluate surface texture and to adjust gradation and other factors to maximize texture and minimize noise generation.

**Targeted Users**

Research Laboratories, Consultants, State Highway Agencies.

**Time and Skill Requirements**

Testing time is approximately 1 hour. Knowledge of laser and mathematics used to analyze data required.

**Recommended Next Steps**

Revise draft standard based on FHWA recommendations.

**Deliverable Brief**

HMA Thermal Stresses in Pavement

**Format**

Model

**ARC Partner**

University of Nevada, Reno

**Product Description**

Low temperature cracking is a common type of failure in asphalt pavements that occurs particularly in cold regions or locations with significant temperature fluctuations. It can also occur in climates with higher temperatures where harder asphalt binders are typically used to combat hot weather pavement problems such as rutting. A comprehensive method for designing an asphalt mixture that is resistant to low temperature cracking at the location of interest is under development. The proposed method accounts for the following parameters which are critical to thermal cracking analysis: 1) the temperature profile within the asphalt layer; 2) the change in the chemical composition, as measured by the carbonyl area (CA) of the asphalt binder in the mixture due to oxidation with time; 3) the change in the asphalt mixture mechanical properties such as relaxation modulus and tensile strength with binder oxidative aging over time; and 4) the change in the asphalt mixture thermal properties such as coefficient of thermal contraction/expansion and glassy transition temperature with binder oxidative aging over time.

The final product will be in the form of a thermal cracking model that can effectively simulate the long-term properties of HMA mixtures and assess the impact of such properties on the resistance of HMA mixtures to thermal crack initiation.

**Equipment Availability and Cost (Select one)**

Commercial grade equipment is available at the cost of $60,000- $70,000.

**Potential Applications**

Mix Design Process and Mix Performance Evaluation

**Targeted Users**

State Highway Agencies, Research Laboratories, and Commercial Laboratories

**Time and Skill Requirements**

Modeling can be completed within 48 hours and will require engineering level skills.

**Recommended Next Steps**

Validate the model using field performance.

**Deliverable Brief**

Dynamic Model for Flexible Pavements: 3D-Move

**Format**

Software

**ARC Partner**

University of Nevada, Reno

**Product Description**

The loads generated by the moving vehicle are dynamic in nature, and they invoke a dynamic response from the pavement structure which is greatly impacted by the inertia of the pavement structure and the viscoelastic behavior of the hot mix asphalt (HMA) layer. The normal and shear dynamic stresses that are generated at the tire-pavement interface control the pavement response in terms of the stresses, strains, and deformations that are generated throughout the pavement structure. The tensile strains generated at the bottom of the HMA layer control the fatigue performance of the HMA pavement. The compressive stresses and strains generated throughout the various pavement layers greatly influence the rutting performance of the HMA pavement. The shear stresses and strains generated within the HMA layer greatly control the shoving performance of the HMA pavement at intersections, on off-ramps, and at facilities that service slow moving heavy loads such as seaports and airports. The final product will be in the form of a pavement analysis software that incorporates the viscoelastic properties of the HMA layer with the non-circular/non-uniform two dimensional pressure distributions at the tire-pavement interface along with vehicle speed. The model will also be capable of predicting pavement performance in terms of rutting and fatigue.

**Equipment Availability and Cost**

Computer hardware at the cost of $2,000.

**Potential Applications**

Mix Performance Evaluation, Pavement Analysis.

**Targeted Users**

State Highway Agencies, Researchers, Consulting Agencies, Contractors.

**Time and Skill Requirements**

Modeling can be completed within 24 hours and will require engineering level skills.

**Recommended Next Steps**

Validate the software.

**Deliverable Brief**

Improved Oxygen and Thermal Transport Model of Binder Oxidation in Pavements

**Format**

Methodology, Publication

**ARC Partner**

TAMU

**Product Description**

An improved oxygen and thermal transport model of binder oxidation in pavements will be developed. Improvements will include both fast-rate and constant-rate binder oxidation kinetics; an air void size distribution model based upon CT imaging determinations of air voids; consideration of limiting cases of oxygen levels in the air voids (provided either by convective flow or by diffusion through the pores only); and an improved pavement temperature model (each of these elements is described in a separate product description.) The improved model will use input data (pavement location for use in determining environmental data that impacts temperature over time, pavement air voids structure, binder kinetics parameters) to calculate binder oxidation and hardening in pavements as a function of time an depth. These results can be used with mixture models to estimate changes in mixture properties such as fatigue resistance that occur due to binder oxidation.

**Equipment Availability and Cost**

N/A. This product is a methodology and not test equipment.

**Potential Applications**

The model will provide essential information for an improved pavement design method. Current methods provide only empirical estimates of binder oxidation in pavements that are quite imprecise and in addition overlook some important effects of binder oxidation on mixture properties and performance.

**Targeted Users**

Pavement researchers, pavement design and maintenance engineers

**Time and Skill Requirements**

Researchers with background in thermal and mass transport, binders, mixtures, and computational methods will incorporate the methodology into design, maintenance, and forensic activities.

**Recommended Next Steps**

Validation of the pavement oxidation model using field locations across the country is ongoing with more planned. Longer term, plans should be made to incorporate the model into a new generation pavement design guide.

**Deliverable Brief**

Pavement Air Voids Size Distribution Model for use in an Oxygen and Thermal Transport Model of Binder Oxidation in Pavements

**Format**

Methodology, Publication

**ARC Partner**

TAMU

**Product Description**

Using a distribution of air void pore sizes, instead of a single average size, in the oxygen and thermal transport model for binder oxidation in pavements, will provide more accurate estimates of binder oxidative aging in pavements. The methodology will determine a distribution of air void pore sizes from CT imaging techniques which will be used to calculate upper and lower limits on binder oxidation rate estimates for two limiting cases: convective air flow through interconnected pores in the pavement versus diffusive flow only. In reality, probably both mechanisms contribute to supplying oxygen to pavement pores.

**Equipment Availability and Cost**

**Potential Applications**

This product will allow improved modeling of binder oxidation in pavements, essential for accurate prediction of pavement performance over time and in the presence of deterioration due to oxidative embrittlement of binders.

**Targeted Users**

**Time and Skill Requirements**

**Recommended Next Steps**

Validation with additional pavement sites.

**Deliverable Brief**

Approaches to interpret MD simulation results and experimental data to quantify the composition and temperature dependence of free energy

**Format**

Model

**ARC Partner**

University of Rhode Island (subcontract from Western Research Institute)

**Product Description**

Molecular-scale models provide a means to quantify how different molecule types contribute to the overall mechanical response of a system. Comparing differences in model systems that arise from differences in chemical composition then provide a mechanistic basis for interpreting experiments that use asphalts differing in broad chemical composition. Molecular dynamics simulations have been employed to predict properties of these distinct model asphalt systems.

A model for interpreting the molecular dynamics results in terms of temperature- and composition-dependent free energies is provided. The model comprises a sequence of steps to use for interpreting simulation results and experimental data. In this way, the model provides a method for using results from molecular dynamics simulations of model asphalts that differ in their fundamental chemistry to guide models that apply at larger length scales, such as phase field models. Thermodynamics results obtained using molecular dynamics simulations thus provide a route to guide the free energies that are used in phase field models.

**Equipment Availability and Cost**

Running new molecular dynamics simulations requires multiprocessor computer systems and fast inter-computer communications, such as gigabit Ethernet. The programs are open source and can be obtained without cost, though using them properly requires significant expertise.

**Potential Applications**

The results from these simulations directly indicate how molecules of different chemical families and sizes relax within an overall model asphalt system. The results can be used indirectly to interpret the reasons and mechanisms by which differences in chemical composition can affect free energies and asphalt mechanical properties.

**Targeted Users**

- Pavement and materials engineers/researchers;
- Asphalt / bitumen developers

**Time and Skill Requirements**

Applying the methods used to conduct the research requires experience and computational skills in applied physical and asphalt chemistry. Applying phase field models also requires skills (see that Model and Software brief). Engineers with some experience with asphalts and asphalt chemistry can understand and discuss the results.

**Recommended Next Steps**

Future molecular dynamics simulations of asphalts should use the proposed compositions or should incorporate additional chemistries by applying the approaches that were used to choose these compositions.

**Deliverable Brief**

Numerical approach to model the asphalt binder fracture properties based on phase field theory

**Format**

Computer Module: COMSOL Finite Element Code

**ARC Partner**

Virginia Tech

**Product Description**

The function of this product is to employ the new modeling and computational method, i.e. the phase-field method to analyze the complex fracture properties of asphalt binder (including Mode I, II & III cracking and crack interactions). A companion experiment procedure is also developed to use the Direct Tension Tester machine for testing the critical stress and fracturing paths of the specimens under different cracking modes.

**Equipment Availability and Cost**

The numerical simulation is by using the mathematical module of the Finite Element Software COMSOL Multiphysics and the test method uses the Direct Tension Tester from the Interlaken Company with the cooling machine named Julabo. The costs are mainly in two aspects:1. Advanced computation system and the license fee for the finite element software COMSOL Multiphysics; 2. The operation and maintenance fee of the Direct Tension Tester since asphalt cracking experiments are conducted on this machine.

**Potential Applications**

Information relative to the surface energy and the potential free energy (local free energy based on asphalt chemistry, elastic energy and etc.) of asphalt binder is used for numerical simulation and understanding the fracture properties of asphalt binder which is the fundamental property of asphalt performance.

**Targeted Users**

Highway engineering communities and asphalt pavement researchers

**Time and Skill Requirements**

This is system work that requires an experienced researcher familiar with both of the asphalt structure and mathematical and mechanical fundamentals: the former refers to the mastering of the mechanical behavior of asphalt binder while the latter refers to the knowledge of theory of finite element. The researcher should be skillful in solving partial differential equations using COMSOL software. Making of the asphalt cracking specimens usually takes 1~2 hours based on the specific design. Conducting fracture experiments on the Direct Tension Tester usually takes about one hour for 6 specimens.

**Recommended Next Steps**

This new tool should be able to simulate complex cracking problem such as crack interactions. And it should be better connected with the Molecular Dynamic Simulation for a Multi-scale modeling. The next steps will focus on developing such modules.

**Deliverable Brief**

Pavement Analysis Using Nonlinear Damage Approach (PANDA)

**Format**

Subroutines in the Abaqus finite element program

**ARC Partner**

TTI

**Product Description**

The ARC team at Texas A&M University will deliver a mechanistic model in the form of a User defined MATerial subroutine (PANDA-UMAT) within the finite element software Abaqus. This model will incorporate several constitutive relationships to predict response of asphalt concrete materials subjected to mechanical and environmental loading conditions. PANDA-UMAT includes viscoelastic, viscoplastic, mechanical damage, micro-damage healing, moisture damage, and oxidative aging models. These constitutive relationships will contribute to the overall ability of the mechanistic model to make reliable predictions of the appearance of important forms of damage to asphalt pavements. The final deliverables of the continuum damage modeling effort will be as follows:

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

(2) The second part is the PANDA User Interface (PUI) that allows the user to access the capabilities of the model implemented in Abaqus finite element software without requiring in-depth experience in Abaqus pre-processing functions. Abaqus provides wide flexibilities in terms of analysis type, material properties, mesh type, load and boundary conditions etc. In order to allow users to utilize these versatile features without having in-depth knowledge in Abaqus pre-processing functions, the PUI will be developed at Texas A&M University by a team of researchers who are familiar with Abaqus and have expertise in the development of user friendly interfaces. PUI will be customized for pavement applications such that users can conduct performance simulations of pavements without having the in-depth knowledge of using Abaqus. In the PUI, users will be required to specify the thickness of each layer, the properties of each layer, the wheel load magnitude, the type of loadings (e.g. pulse, equivalent, or moving load), and the mode of analysis (e.g. 2D plane strain, 2D axisymmetric, or 3D). The PUI will translate these inputs into Abaqus language and creates the input file that can be used directly by Abaqus to perform the simulations. Therefore, users will benefit from all pre-processing and post-processing capabilities of Abaqus through the PUI.

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

- guidelines to estimate or measure the material constants associated with the constitutive relationships implemented in the UMAT.
- a theory manual which documents the constitutive equations implemented in the UMAT.
- guideline to use the PANDA User Interface (PUI) to create pavement structures that can be analyzed using PANDA-UMAT.

**Equipment Availability and Cost**

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

**Potential Applications**

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

**Targeted Users**

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

**Time and Skill Requirements**

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

**Recommended Next Steps**

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

**Deliverable Brief**

Lattice Micromechanical Model for Virtual Testing of Asphalt Concrete in Tension

**Format**

Analysis Program

**ARC Partner**

North Carolina State University

**Product Description**

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

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

**Time and Skill Requirements**

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

**Recommended Next Steps**

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