WESTERN RESEARCH INSTITUTE

Providing solutions to highway building materials problems

FIRST YEAR WORK PLANS

June 18 – December 25, 2007

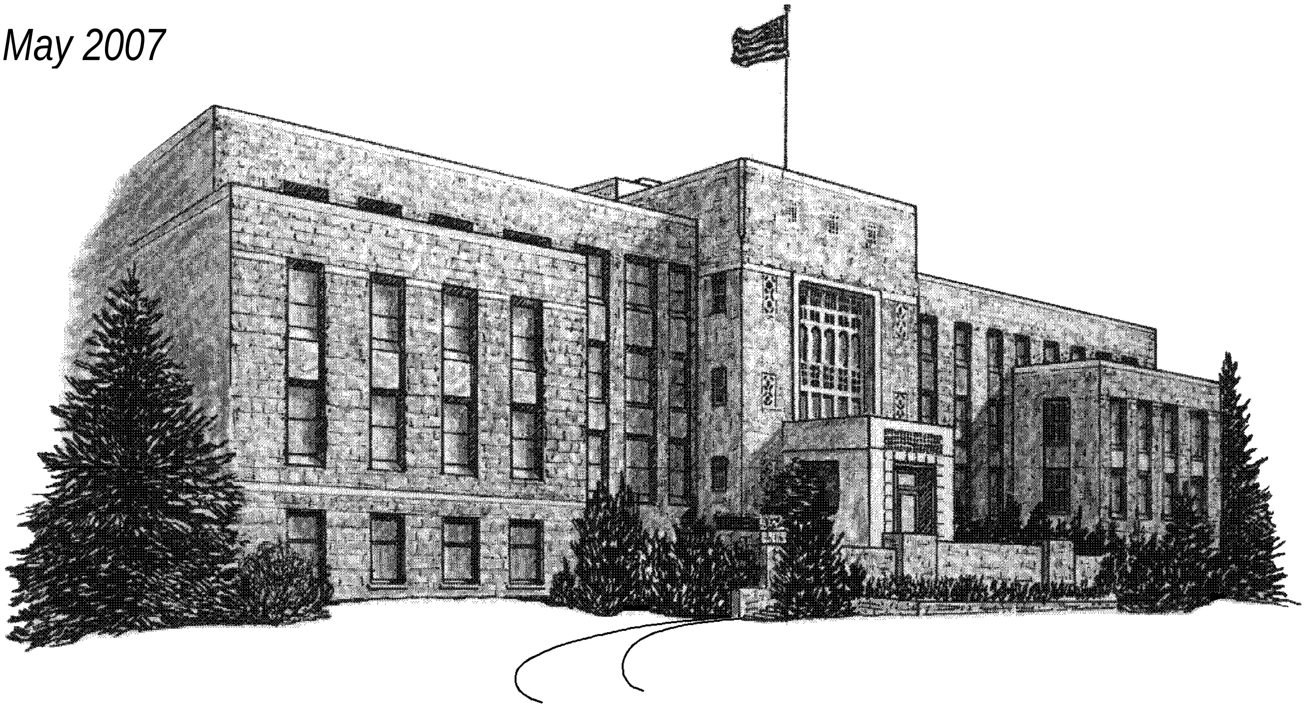
ASPHALT RESEARCH CONSORTIUM

PROGRAM AREA:

ENGINEERED MATERIALS

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

May 2007



www.westernresearch.org

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

FOREWORD

This document is the proposed Research Plan for Year 1 of the Federal Highway Administration (FHWA) Contract DTFH61-07-H-00009, the Asphalt Research Consortium. The Consortium is coordinated by Western Research Institute with partners Texas A&M University, the University of Wisconsin-Madison, the University of Nevada Reno, and Advanced Asphalt Technologies.

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

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

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

The Asphalt Research Consortium members strongly believe that the proposed research is responsive to the needs of asphalt engineers and technologists, state DOT's, and supports the FHWA Strategic Goals and the Asphalt Pavement Road Map.

TABLE OF CONTENTS

PROGRAM AREA: ENGINEERED MATERIALS..59

PROGRAM AREA: ENGINEERED MATERIALS

INTRODUCTION

The Need for Engineered Paving Materials

Demands on flexible pavements in terms of traffic loadings and service life are rapidly increasing. Recent published transportation statistics indicate that between 1993-2002 truck traffic has increased by more than 33% while lane miles have increased by only 2%. The total vehicle mile travel in the United States is expected to increase by 50% in the next 20 years and, more importantly, freight movement is expected to double by 2025. Figure 1 shows the estimated growth in truck traffic on various sections of the National Highway System between 2000 and 2020.

In addition to increased traffic demands, the escalating increase in crude oil prices as well as cost of energy in general, are expected to result in increased production costs of asphalts. The use of recycled asphalt pavements (RAP) is known to reduce the quantity of required asphalt, resulting in a reduction of the energy required for asphalt production. Currently, the use of RAP is limited by state agencies due to risks involved in using it at higher levels in the mix. It is well recognized that more knowledge is needed to allow for effective use of higher percentage of RAP in HMA mix designs.

Engineered Paving Materials (EPMs) are developed for specific performance-related purposes such as extended fatigue lives, moisture or rut-resistance, or durability against thermal and fatigue cracking, and aging. These materials can be designed for ease of construction, quality control/quality assurance, or of maintenance and rehabilitation activities. They can also be designed for many of the other functional and structural objectives that all pavements must satisfy. The process of engineering of materials requires an understanding of the engineering properties of the constituent materials of HMA and how they contribute to the composite properties of asphalt concrete. The performance of HMA is dependent on the response of the properties of this composite under the varying conditions imposed by traffic and weather including the stiffness under rapidly applied loads and slowly applied thermal stresses, thermal expansion and contraction, permeability, thermal conductivity, time-temperature shift, time-aging shift, anisotropy due to the shape of aggregates used, fracture, healing, and plastic properties. Engineering these properties requires the use of materials property models to provide reliable and accurate estimates of the desired properties of the composite. The selection of the precise set of required composite properties is attained as the result of an optimization process in which all of the properties are considered in a prediction of the pavement performance given specific traffic, weather, drainage and subgrade support conditions at the project site. Thus, the engineering design of the pavement structure is not considered as a separate process from the engineering design of the composite material to be used as its surface.

Materials property models have been developed and used successfully in other engineering disciplines such as mechanical engineering, plastics and polymers, and aerospace composites. Admittedly, the materials used in pavements are recognized as being more difficult to model and inherently more variable largely because of the huge volumes of materials that are constructed annually. However, recent successful developments in micromechanics and analytical modeling in these other fields and recent success in FHWA-sponsored research in pavement construction materials have demonstrated that it is now possible to engineer materials that are better able to satisfy the multiple performance requirements that are placed on pavement surfacing.

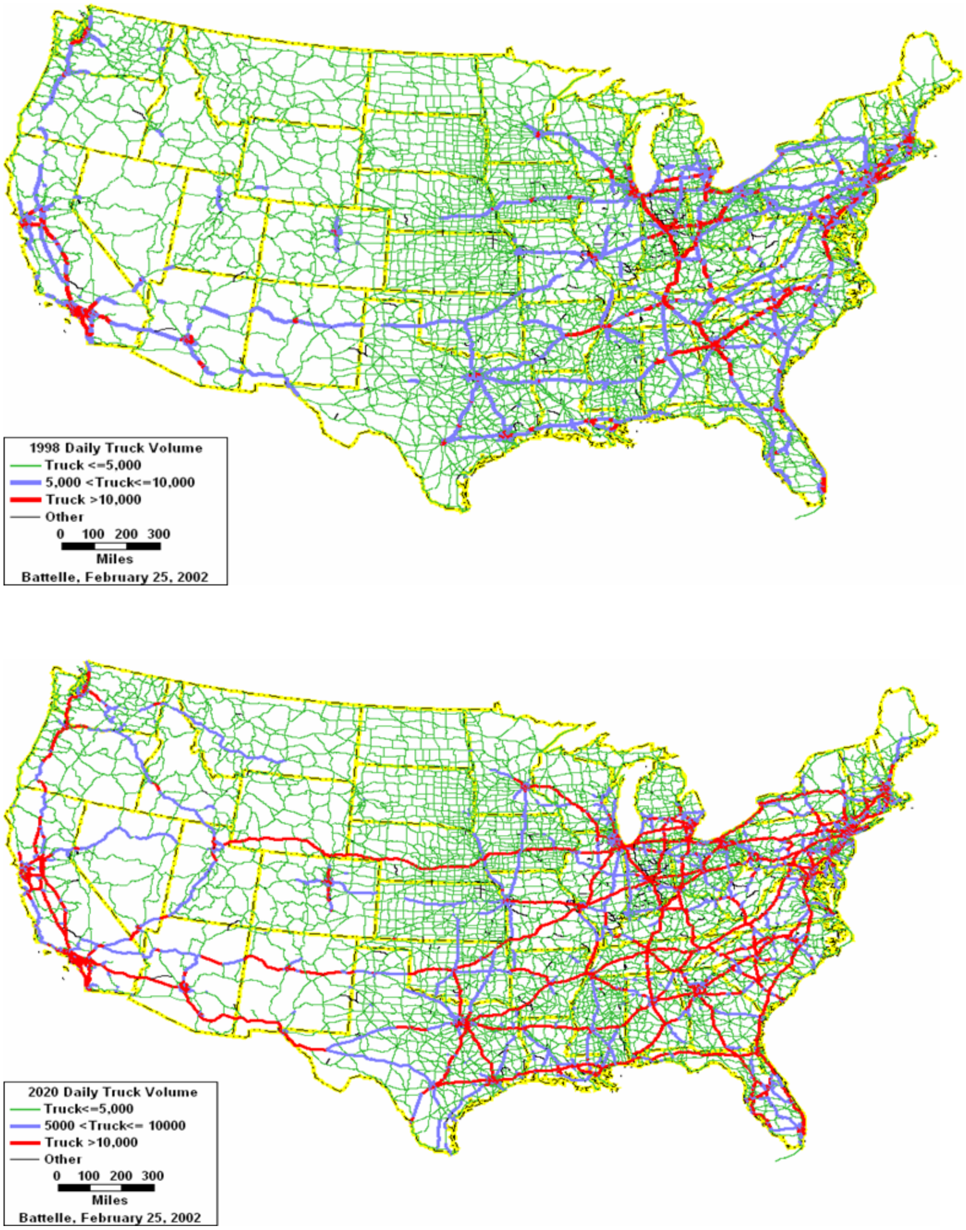


Figure 1. Expected growth of truck traffic on the national highway system. Source: FHWA office of asset management.

Functional Requirements of Engineered Paving Materials

Since the introduction of Superpave, the types of materials that can satisfy the Superpave performance criteria have changed. The use of modified asphalt, as an example, has increased from 5% of the market to more than 15% today. The aggregate gradation and characteristics, such as angularity, have also changed significantly. The request for special types of mixtures to deliver specific functions, such as improved friction, less noise, and drainage has increased significantly. All these changes reflect the reaction of the industry to increased traffic and environmental demands. Superpave also introduced more performance-based tests and design systems and enhanced the level of knowledge regarding relationships between material characteristics and pavement performance. These systems have allowed industry to be more effective in choosing materials, have encouraged more innovation in selecting mixtures, and increased the competition on warranted pavements.

Utilizing Engineered Paving Materials (EPMs) is an essential requirement for resistance of damage from increased demands and for reducing cost or increasing reuse of resources. Design and modeling of EPMs for flexible pavements is one of the main focus areas for the research of the consortium. EPMs for the purpose of this project can be classified into two groups based on their function.

I. High performance to resist damage from the following critical conditions:
   - High Traffic Volume
   - Extreme Heavy Loads and Slow Traffic Speed
   - Extreme Climate
   - Increased friction and reduced noise
   - Perpetual service life

II. Reduce cost, energy, and use of natural resources by increase use of:
   - Recycled Asphalt Pavement (RAP)
   - Warm mixture additives
   - Emulsions for Cold Mixtures Asphalt (CMA)

What Is Needed to Improve the Process of Engineered Paving Materials?

The engineering of pavement surface materials requires the use of analytical computer models that are both fast and accurate while requiring input data that are generated by simple, rapid, and accurate test methods. The approach that is most amenable to these requirements makes use of the measured response of the input materials and models the behavior using the disciplines of mechanics. The demand for accuracy in the input and the predictions is not academic; instead it is imposed by the need for high degrees of reliability in the predicted service life of the pavement material. The accuracy is determined by proper sampling and monitoring of delivered properties at the time of construction. Thus development of simple, rapid, and accurate methods to measure as constructed materials inputs is essential for improved engineering of pavement materials. Accurate predictions and high reliability are requirements of performance-based specifications and the use of warranties, as well as for the subsequent management of the maintenance, rehabilitation, and re-construction operations to be conducted by the operating agency. Engineering of materials should include models that can define the end result of this engineering process, which is reliable prediction of materials performance. It is a simple truth that reliability can be assured by almost any method; however, by reducing the variance of the predictions, the risk of spiraling life-cycle costs to the operating agency is reduced, as are the time-delay costs to the traveling public. Reducing the variance requires methods of measuring materials properties that have low coefficients of variation. The goal should be to have methods with measured coefficients of variation of approximately 5-10 percent rather than 35-40 percent. With this level of accuracy, it will be possible to reliably engineer materials for pavement surfaces that will meet all of the site-specific demands for performance.

Required Material Inputs–Components and Scaling

The material properties to be determined must take into account all of the physical, chemical, and thermodynamic processes that are known to have a significant effect on the performance of pavements. The deterioration processes include fracture and plastic deformation, both of which are scale-dependent phenomenon. Therefore, the materials properties that are measured and modeled must be consistent with the scale of the deterioration process. For example, the cracks and plastic zones that eventually coalesce into macroscale distress begin as micro-cracks and micro-plastic zones.

Asphalt concrete is a composite material that begins with the binder that may be altered by a modifier and/or a filler, and further altered by the addition of fine aggregate particles as well as coarse aggregate particles. Each alteration changes the material properties of the composite and the final composite properties are the result of the accumulation and interactions of all of the materials at smaller scales. The disciplines of micromechanics have developed energy-based methods of combining the properties of the constituent materials to produce composite properties that partition, store, release, and dissipate energy in the same manner as the actual composite material.

Research Needed to Better Engineer Paving Materials

While the list of properties needed for ideal mechanics based modeling seems to be impossibly long, this project will focus on finding the importance of these properties and identifying those that play a prominent role in enhancing the reliability of the engineering process. Major progress has been made by the consortium partners and others in identifying the most critical properties that are needed for modeling of performance. Also progress has been made to reduce testing requirements. For example, it has been found in recent moisture damage work at Texas A&M that when dealing with material properties, it is possible to catalog these fundamental properties and eliminate the need to repeat the measurements. The tests to assure that the materials have not changed or to determine the degree to which they have changed are simple and rapid to perform. Recent efforts at UW-Madison and FHWA have also introduced simple tests that can more accurately model the damage accumulation in asphalt binders. The MSCR test and the fatigue surrogate tests are such examples.

Cataloguing material properties simplifies the task of engineering materials and is one of the major benefits of focusing on analytical methods to model material properties. It is then possible to make use of mechanics-related computer models of pavements and use these catalogued properties and materials models to optimize the materials selection process for a give set of site conditions based on expected performance and resistance to distress. The principle objective of the Engineered Materials work plan is to define tools that allow reliable and cost effective methods (tests and models) to select materials to meet required and specific functional performance.

Engineered Paving Materials (EPMs) are modified mixtures which are designed to deliver specific functions related to increased traffic or environmental demands, to re-use of pavement materials, and to allow less energy intensive and more practical construction methods. EPMs include mixtures with binders of specific modification, aggregates with special characteristics, and void distributions that provide a high level of resistance to damage caused by traffic or environment. Furthermore, they include mixtures with high levels of RAP that is well characterized and introduced by specific production methods. Finally, EPMs include warm mixtures, cold mixtures, or other types of mixtures that are produced and constructed to optimize performance, production, and construction. Such mixtures will be designed using fundamental understanding of mechanisms of interactions between asphalt, mineral surface, and air voids; using micromechanics of viscoelastic materials and granular materials; and the use of damage resistance characterization.

RESEARCH HYPOTHESES

The consortium working hypotheses for EPMs are:

1. All materials of which asphalt concrete is composed have mechanical and geometric properties which may be combined, using the energy principles of micromechanics, to obtain the net properties of the composite materials.
2. Using additives and or new production processes, modified asphalt binders and mixtures can be designed to deliver superior performance that can tolerate extreme traffic and climatic conditions.
3. Using fundamental engineering principles in design of mixtures superior performance can be achieved with using high concentration of recycled asphalt mixtures, emulsions, or warm mixture additives.
4. Practical and effective protocols for testing and modeling of such superior materials could be developed. Such protocols would provide guidance for selecting high performance materials with predictable (less risky) performance.

GENERAL RESEARCH OBJECTIVES

1. Develop analytical models of the properties of binders, mastic, and mixtures using the principles of mechanics.

2. Develop guidelines for producing and selecting engineered pavement materials focused on limiting risks of pavement failures.
3. Develop guidelines for high level use of recycled pavement mixtures, warm mixtures, and cold mixtures.
4. Use laboratory damage testing and coordinate with validation activities of the consortium to verify that these guidelines are useful and implementable.

EXPERIMENTAL DESIGN - WORK ELEMENTS PLANNED

Eight major work elements, organized in two categories are planned. Modeling is considered a basic tool to improve prediction of material performance and thus reduce risk of failures. Design guidelines are the tools to make the best use of modeling in practice. The work elements compose an integrated solution linking materials' mechanics to traffic, climate, and age conditions.

Category E1: Modeling

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

The FHWA Pavement Distress Manual recognizes 17 different types of distress in asphalt pavements. The materials properties that are realistically needed to predict the appearance of distress include the viscoelastic, viscoplastic, and fracture properties, thermal conductivity and heat capacity, thermal expansion and contraction, time-temperature, and time-aging shift properties, diffusivity of the material to air and water in liquid and vapor form and several electrical properties that are important to non-destructive testing such as conductivity and permittivity. While this seems to be an impossibly long list of properties, it has been found in recent moisture damage work at Texas A&M that when dealing with material properties, it is possible to catalog these fundamental properties and eliminate the need to repeat the measurements. The tests to assure that the materials have not changed or to determine the degree to which they have changed are simple and rapid to perform. Cataloguing material properties makes the task of engineering materials much simpler and is one of the major benefits of focusing on analytical materials models of materials properties. It is then possible to make use of mechanics-related computer models of pavements to use these catalogued properties and materials models to devise the best materials from available components for a given site based upon the expected performance and resistance to distress. This is the principle objective of Engineered Materials.

Hypothesis

The properties of full asphalt mixes can be developed by applying the same broad principles and approaches of micro-mechanics to combine the properties of the mastic with the mechanics and geometric properties of the coarse aggregate portion of the mix. These properties include the relaxation modulus of the mixture including isotropy and anisotropy and non-linearity in both the response and damage properties, time-temperature-aging shift, viscoplasticity, permeability to both air and water in liquid and vapor form, thermal conductivity, thermal expansion and contraction coefficients, thermal heat capacity, both adhesive and cohesive fracture and healing characteristics, as they are affected by moisture and aging, and dielectric permittivity.

It is these properties of the full mixture that are needed as input to a pavement performance prediction model to anticipate what the expected performance and resistance to the various forms of distress will be. These properties can be estimated using the mechanics principles noted above and the accuracy that can be achieved with these measurements will be verified by the planned testing in this project. The performance prediction must be capable of translating the variance of the input values into the variance of the predicted result and the resulting reliability.

Objectives

1. Develop analytical models of the properties of binders using the principles of mechanics. Relate the properties of the binder to the molecular composition, structure, and energy potentials.
2. Develop analytical models of the properties of mastics as binders are altered by the addition of modifiers, fillers, and fine aggregates using the principles of micromechanics.
3. Develop models for the mechanical behavior of asphalt mixtures.
4. Verify with laboratory tests the predicted materials properties of the models from Items 1, 2, or 3.
5. Implement the models into a mechanics-based pavement performance prediction model which is capable of taking into account the effect of the traffic, weather, drainage, and subgrade support on the candidate asphalt mixture using the estimated mechanics properties. The model should be capable of predicting fatigue cracking, moisture damage, aging, and permanent deformation.
6. Calibrate the pavement performance model to actual known pavements in the LTPP data base with sufficient materials data to permit the estimation of the mixture properties using the analytical models of Items 1, 2, or 3 and verify the predicted distress with pavements that were not used in the calibration process.
7. Incorporate into the model of Item 6 the ability to calculate the variance of the estimated life and the reliability of the designed pavement structure for each of the predicted types of distress.
8. Design and initiate materials properties catalogues including all of the materials properties which are needed for the models of Items 1, 2, or 3 and which do not change or have predictable changes.
9. Design and initiate a selection engine which will calculate the best combinations of available materials which will provide acceptable mixture properties or resistance to distress.

Attaining these objectives will make it possible to provide the pavement designer with a rapid method of considering all available component materials, and using the materials property catalogues to select the combinations that will provide the greatest likelihood of successful construction and performance. The engineer will also be able to evaluate the likely service lives, variances and reliabilities of each type of distress. With these efficient computerized tools available, it will be possible to engineer pavement surface material properties as part of the engineering design of an engineered pavement structure.

The properties of the materials to be modeled and used in the models of the binder, mastic, and full mixture will be those for which laboratory characterization protocols will be developed in this research project in coordination with the other team members of the Consortium and with the ongoing binder characterization work in the FHWA.

Experimental Design

The development of the material property models of the binder, mastic, and mixture will not require an experiment design but will require that the other tasks in this project conduct the necessary tests to provide an evaluation of the accuracy of the models that are developed. This will require coordination with every task within this project in which characterization work is being accomplished. To the extent that no other task in this project is focused on developing a needed property, such as the coefficient of thermal expansion or contraction, it will be necessary to design a limited experiment within this part of the project to provide the experimental data to verify the model that is developed. In these experiments, the design will be reviewed or developed by the project statistician, Dr. E. S. Park of the Department of Statistics at Texas A&M University.

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

This task will focus the development of the following micro-mechanical models that relate binder molecular composition and morphology to:

- Compliance
- Diffusivity
- Thermal Coefficient of Expansion and Contraction
- Time-Temperature Shift
- Time-Aging Shift
- Surface Energy Components

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

Micro-mechanical models of mastic will be developed to relate the mastic physical and chemical properties to:

- Stress-Pseudo-Strain Curve
- Mastic Compliance
- Non-linearity in Compliance

- Time-Temperature-Aging Shift
- Thermal Coefficient of Expansion and Contraction
- Viscoplastic Properties of Mastic
- Adhesive Bond Energy
- Cohesive Bond Energy
- Healing Rate and Healing Capacity
- Thermal Conductivity
- Dielectric Permittivity

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

The micromechanical models for the asphalt and the binder will be incorporated in micromechanical models for asphalt mixtures to predict the following properties and quantities:

- Mixture Relaxation Modulus
- Micro-structural Stress Tensor
- Viscoplasticity Properties
- Time-Temperature-Aging Shift
- Mixture Permeability and Diffusivity
- Mixture Thermal Expansion and Contraction Coefficient
- Mixture Fracture Properties
- Mixture Healing Properties
- Mixture Thermal Conductivity
- Mixture Dielectric Permittivity

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

This task will be coordinated with the modeling efforts discussed in the fatigue and moisture damage plans. As discussed in the fatigue plan, a multi-scale modeling approach will be followed in order to relate the fundamental material properties to the models' parameters. This will be achieved by developing subroutines that use the micro-mechanical models of binders, mastic, and mixture to determine the parameters of the continuum models that will be used for predicting mixture performance.

Year 1 Project Direction

Year 1 will focus on subtasks E1a-1 and E1a-2 of the work plan.

Schedule

Subtask	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**
E1a-1. Analytical Micro-mechanical Models of Binder Properties	**X**	**X**	**X**		
E1a-2. Analytical Micro-mechanical Models of Modified Mastic Systems	**X**	**X**	**X**		
E1a-3. Analytical Models of Mechanical Properties of Asphalt Mixtures		**X**	**X**	**X**	
E1a-4. Analytical Model of Asphalt Mixture Response and Damage			**X**	**X**	**X**

Budget

The estimated budget for this work element is $820,000 over five years and the work will be conducted by Texas A&M University.

Relationship to FHWA Focus Areas

This work element is related to the focus area of Optimize Pavement Performance by concentrating on materials characterization and mix design. It targets developing analytical micro-mechanical models to relate binder, mastic, and mixture properties to its performance characteristics.

Work element E1b: Binder Damage Resistance Characterization (DRC)

Subtask E1b-1: Rutting of Asphalt Binders

While linear viscoelastic rheology is considered a major step forward in binder performance modeling, DRC is found necessary for low risk selection of high performance materials. Modified binders can be best differentiated and effectively qualified for high performance by using damage resistance testing principles. Binder rutting tests have been performed generally using low stresses. However, it is not clear that testing at a low stress level is the best way to characterize the rutting resistance of an asphalt binder. The stresses and strains in the binder can be very high, much higher than the linear limit for the material. Estimates of the strain in the binder of a typical mixture can vary between 0 and 500 times the overall mixture strain. Due to this fact, when the asphalt mixture is subjected to loading, some of the binder performs in the linear viscoelastic region and some of the binder reaches the region of nonlinear behavior. Current research is being performed at FHWA and also at UW Madison on the topic. A limited amount of binders and mixtures are currently being used to find a relationship between the binder non linear behavior and the mixture permanent deformation. FHWA results reported at the Binder ETG meetings indicates that stress levels that mimic binder conditions in typical mixtures are not known and are difficult to estimate. The stress levels that are used in the current version of the MSCR test (AASHTO TP 76) are intended to measure stress sensitivity but are not clearly related to mixture behavior. Recent results collected at UW-Madison, as part of a study for the Airfield Asphalt Pavement Technology Program (Project 04-02), indicates that stresses much higher than 3200 Pa, which is recommended in the MSCR AASHTO standard could be too low and a much higher stress is needed to correlate binder and mixture rutting. The recent results also indicate that stress level is not the only important parameter in rutting testing but the accumulated loading time. It is found that asphalt binders reach a yield point similar to the tertiary flow in mixtures and thus loading time in a binder rutting test needs to be considered as an important parameter. The results of these recent works will be extended in this study to confirm the validity of the current MSCR procedure or to propose modification to it based on testing a wider number of asphalt binders and mixtures. This work will be coordinated with FHWA staff.

Hypothesis

The stress level at which the binder performs and the time of total loading are two parameters that highly influence the permanent deformation of mixtures. Binder needs to be characterized at different stresses and loading times in order to accurately predict the rutting performance of mixtures.

Objectives

The objective of this task is to quantify the relationship between binder creep and recovery testing results using the newly proposed procedures and the rutting performance of asphalt mixtures. The binder testing will be done at various stress levels and for various loading times to mimic stress conditions in typical pavements. Based on these relationships, recommendations for binder specification limits will be proposed.

Experimental Design

The objective of this subtask will be addressed as follows:

i. Literature Review. A detailed search of existing data and published papers on the subject will be compiled. The review will include world wide publications and will cover the binder rutting evaluation and also most recent development in mixture rutting evaluation. An attempt will be made to focus on studies in which relationship between binder and mixture behavior is documented. A critical review will be conducted and documented in a report and also a data base will be established for data available.

ii. Selection of Asphalt Binders and Aggregate Properties and Development of Work plan. Based on the findings of the literature review an experimental plan will be developed. The plan will include testing a set of binders and aggregates to represent the different modification types currently used in the United States. It will also include critical mixture variables.

- High temperature PG grades: PG58-XX, PG 64-XX, PG 70-XX, and PG76-XX
- Modification types: SBS, Elvaloy, SB, EVA, PPA, oxidized.
- Mixture Gradation: Fine , Coarse, and OGFC
- Aggregate shape: Angular and Rounded
- Asphalt Content: Design and Design+ 0.5 %

The plan will also list the testing methods that are needed. It will include the following binder and mixture tests

- The binder test should include creep and recovery testing using the Dynamic Shear Rheometer. Creep test can also be included as a complement.
- Two geometries should be considered: parallel plate and cone and plate. Parallel plate should be included because is the most widely used geometry for testing binders. Cone and plate should be used because it provides a homogeneous distribution of shear rates which are needed for non linear characterization. The stresses should consider from 100 Pa (linear range) up to 50000 Pa (maximum range for commercial DSR).
- The time of loading (or number of cycles) should be enough to reach the tertiary creep region.
- The temperature of testing should be the same used in the mixture testing.
- Mixture rutting test should be performed on samples prepared with the selected binders. Two temperatures would be recommendable: 46C and 58C.
- Mixture rutting test using the creep and recovery should be used. At least two stress levels should be considered: 22 psi (standard stress for Flow Number test) and 100 psi (representing high tire pressures)

iii. Conduct Testing of Binders and Mixtures. Testing of binders and mixtures will be carried out. The data will be organized in a database to allow for statistical correlations and for modeling of behavior using various models found in the literature.

iv. Analysis and Interpretation. The data collected will be analyzed to identify the relationship between binder rutting and mixture rutting as a function of stress level, aggregate properties, and mixture volumetric properties. The data will also be used to verify the analytical models developed in work element 1a for mechanical behavior of asphalt mixtures. The focus will be on defining the importance of testing variables including stress level (no-linearity), temperature, total time of loading, RTFO aging, and number of cycles used to allow prediction of traffic volume effects. The interpretation will be conducted using statistical correlations and fitting as well as mechanics based phenomenological models.

v. Standard testing Procedure and Recommendations for Specifications. The results of analysis will be used to evaluate the current MSCR standard protocol and suggest modification if needed. Also a recommendation for inclusion of the procedure and limits for acceptance in the PG binder specification will be develop. The limits will be based on the correlations to mixture response and on LTPP data of rutting performance.

Schedule

Activity	Year 1	Year 2	Year 3	Year 4	Year 5
i. Literature Review	**X**	**X**			
ii. Select Materials & Develop Work Plan	**X**	**X**			
iii. Conduct Testing		**X**	**X**	**X**	
iv. Analysis & Interpretation			**X**	**X**	
v. Std Testing Procedure and Recommendation for Specifications		**X**	**X**	**X**	

Budget

The estimated budget for this subtask is $350,000 over the four years. The work will be conducted by the University of Wisconsin-Madison.

Relationship to FHWA Focus Areas

This work element is related to the following focus areas:

- Optimum Pavement Performance- Introducing methods for better characterization of modified asphalts.
- Advanced quality systems: Further development of test methods that are more related to actual pavement performance.

References

Delgadillo R., D. W. Cho and H. U. Bahia. "Non Linearity of Repeated Creep and Recovery Binder Test and the Relationship with Mixture Permanent Deformation. In *Transportation Research Record: Journal of the Transportation Research Board*, No.1962, TRB, National Research Council, Washington, DC, 2006, pp. 3 – 11.

Hudson, S. W. and S. B. Seeds. Evaluation of Increased Pavement Loading and Tire Pressures. In *Transportation Research Record: Journal of the Transportation Research Board*, No1207, TRB, Washington DC, pp.197-206, 1988.

Kose, S. Development of a Virtual Test Procedure for Asphalt Concrete. PhD Thesis, UW Madison, 2001.

Lakes, R. Viscoelastic Solids. CRC Press, 1999.

Masad, E., N. Somevadan, H. U. Bahia and S. Kose. Modeling and Experimental Measurements of Strain Distribution in Asphalt Mixes. *Journal of Transportation Engineering*, Vol. 127, Nº6, Nov/Dec. 2001, pp. 477-485.

Subtask E1b-2: Feasibility of Determining rheological and fracture properties of thin films of asphalt binders and mastics using nano-indentation (Year 2 start)

The effort in this subtask will be closely coordinated with similar work at WRI in the "Fundamental Properties of Asphalts and Modified Asphalts III" contract with FHWA. If any research is identified here in year 2, it will be complimentary research.

The behavior of asphalt mixtures is highly affected by the rheological and fracture properties of the asphalt mastic, the glue that holds together the aggregate skeleton in the composite asphalt mixture. The current asphalt binder specifications are based on mechanical tests performed on specimens with dimensions that are not representative of the scale of asphalt films found in a typical asphalt mixture, which is in the range of 13.5μm to 600μm, with 30 to 50% in the range of 13.5 to 17μm. Presently, there are no documented research studies that address the determination of mechanical properties of thin films of asphalt in an asphalt mixture non-destructively. If such technology is developed it can revolutionize the methods of accepting pavement materials after construction is complete. It will greatly simplify the task of monitoring changes in materials due to aging or repeated loading in the field and eliminate the need for expensive and destructive methods used today; and, perhaps most importantly, allows for rapid and simple quality control for contractors. The purpose of this study is to evaluate the usefulness of nano-indentation devices to measure asphalt binder or mastic properties. The work will be conducted in collaboration with the University of MN and will focus on utilizing nano-indentation equipment available at the University of MN or other research establishments for exploratory measurements. These measurements will be compared to measurements collected with conventional methods used today in the PG grading such as the DSR, BBR and the Direct Tension.

Hypothesis

In-situ properties of asphalt binders in asphalt mixtures can be determined using nano-indentation equipment with or without minor modifications.

Objectives

The proposed study has the following objectives:

- Determine the rheological and fracture properties of asphalt binders and mastics using nano-indentation equipment.
- Compare the rheological and fracture properties of asphalt mastics determined with the current PG grading test methods to the similar properties determined using nano-indentation.

Experimental Design

The experimental work may include the following activities:

i. Literature Review and Identification of Equipment
ii. Exploratory Use of Nano-indentation devices

iii. Conducting of Exploratory Tests on Mixture Samples
iv. Testing Binders and Mastics Using PG Grading Test Methods
v. Analysis and Report

References

Lawn, B., *Fracture of Brittle Solids*. Cambridge University Press. Second Edition, 1993.

Lawn, B. R. (2004). Fracture and deformation in brittle solids: A perspective on the issue of scale. *J. Mater. Res.*, Vol. 19, no 1.

Oyen, M. L., and R. F. Cook (2003). Load-displacement behavior during sharp indentation of viscous-elastic-plastic materials. *J. Mater. Res.*, Vol. 18, no 1.

Sakai, M. (2002). Time-dependent viscoelastic relation between load and penetration for an axisymmetric indenter. *Philosophical Magazine A*, Vol. 82, no. 10, 1841-1849.

Shimizu, S., T. Yanagimoto, and M. Sakai (1999). Pyramidal indentation load-depth curve of viscoelastic materials. *J. Mater. Res.*, Vol. 14, no. 10.

Standard Test Method for Plane Strain Fracture Toughness for Metallic Materials (ASTM Method E399-90), *Annual book of ASTM Standards, Part 10*. American Society for Testing and Materials, Philadelphia, PA 506-515 (1992).

Syed Asif, S. A., and J. B. Pethica (1998). Nano-scale viscoelastic properties of polymer materials. Materials Research Society Symposium Proceedings, Vol. 505, p. 103.

Volinsky, A. A., N. R. Moody, and W. W. Gerberich (2002). Interfacial toughness measurements for thin films on substrates. *Acta Materiala*, 50, 441-466.

Volinsky, A. A., J. B. Vella, and W. W. Gerberich (2003). Fracture toughness, adhesion and mechanical properties of low-K dielectric thin films measured by nanoindentation. *Thin Solid Films* 429, 201-210.

Work element E1c: Warm and Cold Mixes

Subtask E1c-1: Warm Mixtures

This subtask will focus on evaluation of the impact of Warm Mix Asphalt (WMA) additives on Binder and Mixture Performance

Rising energy prices and more stringent environmental regulations have resulted in significant interest in warm mix asphalt additives. These additives are means to decrease the energy consumption and emissions associated with conventional hot mix asphalt production by allowing asphalt mixes to be produced at lower mixing and compaction temperatures, addressing the prominent environmental and economic factors currently faced by industry. Lower production temperatures reduce plant emissions and energy consumption. There is also great technical benefit to the use of warm mixes, namely extension of the construction season and reduced aging of the asphalt binder. The ability to achieve a suitable in-place density at lower temperatures allows for extension of the construction season. Reduction of the short term aging (oxidation and volatilization) of the asphalt binder during conventional construction would also lead to enhanced pavement performance through reduced thermal and fatigue cracking, thus improving the life cycle cost of the pavement.

The concept behind warm mix technologies is reduction in asphalt binder viscosity, allowing for the asphalt to attain suitable viscosity for coating of the aggregate and compaction of the mix at lower temperatures. Currently there are two commonly used types of warm mix additives in the market, wax- based additives that are added to the asphalt binder through low shear mixing, and hydrated mineral compounds that are added to the pugmill during normal batching operations. Both of these additives achieve reduced binder viscosity by different mechanisms.

One of the most widely used wax-based additives currently on the market is Sasobit®. This additive is a "long chain aliphatic hydrocarbon produced by Fischer-Tropsch synthesis of coal or natural gas." The wax has been engineered such that it is completely soluble at 115ºC, allowing for it to be incorporated into the asphalt binder homogenously. This wax based additive has been classified as an "asphalt flow improver" due to its ability to reduce viscosity above the previously defined temperature threshold. Below this temperature threshold the wax additive crystallizes, forming a lattice structure in the binder that leads to enhanced binder stiffness at high temperatures while minimizing low temperature performance.

The hydrated mineral compounds reduce asphalt binder viscosity by foaming of the asphalt at mixing and compaction temperatures. Currently there are aluminum-silica and phosphorous based mineral additives available. These additives contain 18% - 21% water by mass and it is expected that the entrapped water is released in the asphalt at temperatures between 85 - 180ºC. At these temperatures the water is released in the form of vapor, creating a volume expansion of the binder which results in foaming of the asphalt. The foamed asphalt enhances lubrication, allowing for workability and aggregate coating at lower temperatures. In theory, once the asphalt mixture is placed and cooled, the water vapor evaporates from the mix. Therefore, the performance of the mixture is not enhanced.

The implementation of warm mix technology as a viable option for paving operations is a promising concept. However further investigation of the effects of the aforementioned additives on the constituent materials of asphalt mixtures and pavement performance must be first investigated. Specifically, the effects of the additives on fundamental binder and mixture properties must be defined, the impact of the additives on mixture workability quantified, and the field performance of pavements placed using warm mix technologies evaluated and compared to conventional HMA mixes. Past research has defined rutting, moisture damage, and mix design as some key issues that have yet to be fully resolved. Recent work at UW-Madison has shown that Sasobit additives increases the S(60) and decreases m(60) and thus low temperature cracking could be affected negatively. It is imperative that the effects of these additives be fully understood and evaluated to facilitate development of specifications and construction guidance to allow for wide spread application of this technology.

Hypotheses

1. Detailed investigation of the effects of wax and mineral based warm mix asphalt additives on the performance of asphalt binders and mixtures will provide a basis for best practices of incorporating this technology into current practice.
2. Laboratory testing of materials during field trials and subsequent monitoring of pavement performance will verify laboratory findings, identify deficiencies in current procedures, and allow for development of best practices for mix design and construction of warm mix asphalt.

Objectives

The overall objective of this research effort is to gain an understanding of the effects of commercially available warm mix additives on the performance of the asphalt binder and mixture and mixture workability. This understanding will allow for optimization of mixture design and construction practices for application of warm mix technology to the field. Optimized practices will be applied in field trials and evaluated/refined through monitoring of pavement performance.

Experimental Design

The following activities will be completed in order to achieve the objectives of this research effort.

i. Evaluation of the Effects of Warm Mix Additives on the Rheological Properties of Asphalt Binders

   Understanding of how the warm mix additives affect binder properties is imperative for further comprehension of mixture and field performance. The current state of industry requires that both polymer modified and neat binders be investigated. Previous research results and the overall objective of this project necessitate that the following binder properties be investigated:

   - Viscosity (Brookfield RV): The reduction in viscosity due to the addition of warm mix additives must be quantified over a wide range of additive concentration and binder temperatures. Furthermore, the time effect associated with creation and evaporation of the water vapor produced with the mineral additives must be understood.
   - Cohesion (Tack Test developed by UW): The effects of the release of water vapor over time on cohesion must be investigated further. The wax additive must also be evaluated to understand the contribution of the wax lattice structure to binder cohesion.
   - Rutting ($G^*/\sin\delta$ and MSCR): Rutting resistance has been identified as a major issue in the literature review, the following parameters will be used to quantify effects of warm mix additive on binder rutting:

  - SuperPave Rutting Parameter: G*/sinδ
  - Accumulated Strain: Multiple Stress Creep and Recovery (MSCR)
- Fatigue (Dissipated Energy Ratio): Fatigue life will be measured to identify any effects caused by the wax lattice structure or entrapped water from the mineral additives.
- Low Temperature Properties (BBR): Effects of both additives on low temperature binder properties must be investigated. Both entrapped water from the mineral additives and increased stiffness from wax additives could have negatively affect performance.
- Aging (RTFO and PAV): The reduction in short term aging due to lower mixing and compaction temperatures and its effect on the previously mentioned binder properties must be understood in order to predict mixture and field performance.

ii. Evaluation of the Effects of Warm Mix Additive on Mixture Workability and Stability

The Gyratory Load Plate developed by UW Madison will be used to measure the resistance of the asphalt mixture to compactive effort. Previous research has used air voids to define increased workability due to reduction in viscosity caused by warm mix additives. The use of the gyratory load plate will provide a more fundamental measure of these effects. Previous work by Faheem has defined two indices, the Construction Energy Index (from 88%Gmm to 92%) to quantify mix workability and the Traffic Energy Index (92% - 98% Gmm) to evaluate the stability of the mixture [1]. All mixes will be compacted past Nmax to allow for measurement of both these parameters. A list of the specific factors that will be investigated is provided below:

- Compactive Effort: Two levels (600 kPa and 250 kPa).
- Temperature: Temperature will be varied to define mixture workability and stability as a function of temperature for the warm mix additives and unmodified mixtures. Variation of temperature will also identify the tender zone for warm mixes.
- Aggregate Type: Different aggregate types have different properties in terms of aggregate shape and strength, necessitating the investigation on how these properties affect the performance of the warm mix additives. Granite, limestone, and gravel aggregate types will be used.
- Nominal Aggregate Size: Previous research has established nominal aggregate size as a significant effect on the contribution of the warm mix additives to workability. Nominal aggregate sizes of 9.5 mm, 12.5 mm, and 19.5 mm will be investigated.
- Gradation: Fine and Coarse or S-Shaped aggregate blends will be used.
- Traffic Level: ESAL designation dictates the gradation limits of the blend. The investigation of E3, E10, E30, and E30X will be investigated.

- Binder Grade: If viscosity testing reveals an effect on unmodified and modified binders, both neat and polymer modified binders will be evaluated to establish a relationship between binder viscosity and mixture compaction.
- Asphalt Content: Investigate the effects of asphalt content. Literature review identified a need to investigate if the asphalt content for warm mixes should be defined through normal mix design procedures or volumetrics obtained from warm mix compaction [2,4].
- Additive Concentration: Define high and low levels of warm mix additive concentration.

Nine parameters at two – four levels have been defined above, making a full factorial experimental design infeasible. A partial factorial design will be used to design an experiment that will identify significant effects while reducing the number of mixtures required for testing.

iii. Mixture Performance Testing

Effects deemed to be significant through binder and compaction testing will be varied to evaluate the performance of asphalt mixtures.

- Moisture Damage: Previous research has found moisture damage to be a significant mode of distress in warm mixes [3]. The following tests will be used in conjunction with binder cohesion testing to investigate moisture damage in warm mixes and its causes.
    - Adhesion: PATTI Testing will be conducted between different aggregate surfaces and binders modified with warm mix additives.
    - Mastic: The fine materials (R30 and below) will be used to create torsion cylinders to quantify the effects of moisture on the mastic in aggregate blends tested.
    - Mixture testing: Moisture damage will be defined using TSR testing.
    - If moisture damage is found to be a problem, investigate the use of liquid anti-stripping additives and hydrated lime.
- Simple Performance Tests (E* and FN)
    - Dynamic Modulus (E*) and Flow Number tests will be used to characterize the stiffness and rutting resistance of mixtures using warm mix additives and to compare the results to conventional HMA mixes. Tests will be performed on short and long term aged mixtures.
- Resistance to Fatigue and Thermal Cracking (IDT):
    - Fracture Energy: Literature review has shown that the fracture energy parameter at different testing temperatures is able to predict resistance to fatigue and thermal cracking [5,6].

iv. Develop Revised Mix Design Procedures

Results of binder and compaction testing will be used to identify any necessary revisions to current SuperPave mix design procedures. Possible revisions include:

- Binder grade: Define appropriate binder grade adjustments to account for contribution of wax lattice structure or to compensate for reduced rutting resistance.
- Aggregate Moisture Content: The appropriate moisture content of the aggregate blend must be defined to provide consistency between laboratory tests and field application.
- Optimum Asphalt Content: Guidance on whether optimum asphalt content should be based on warm mix compactions or conventional HMA compaction.
- Additive Concentration: Define concentrations of additive that will provide optimum performance.
- Mixing and Compaction Temperatures: Define optimum and mixing and compaction temperatures based on warm mix additive concentration.
- Anti-stripping additives: Specify additives and concentrations to prevent moisture damage.

v. Field Evaluation of Mix Design Procedures and Performance Recommendations

The results of the binder and mixture testing previously discussed will be used to identify key variables for field investigation and define parameters for the design of test sections for field investigation. Furthermore, guidance developed in Task 4 will be used in the construction of warm mix test sections to evaluate the mix design procedures. The following parameters should be measured in the field during construction:

- Mixing temperature.
- Compaction temperature.
- In-place density (Nuclear Gauge)
- Number of Passes to Achieve Target density
- Thickness
- Thickness-NMAS ratio

Field mix will also be obtained from each site and evaluated using the test procedures defined in the previous tasks that indicated potential effects caused by using warm mixes.

Field performance will be monitored through pavement distress surveys and pavement coring and correlated to laboratory testing results. This field evaluation will lead to refined mixture design and construction guidance. (Work will be done with UW Platteville.)

Year 1 Project Direction

Year one will focus on Activities i and ii in the work plan.

Schedule

Activity	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**
i. Effects of Warm Mix additives on rheological properties	**X**	**X**			
ii. Effects of Warm Mix additives on mixture workability and stability	**X**	**X**			
iii. Mixture Performance Testing		**X**	**X**		
iv. Develop Revised Mix Design Procedures			**X**	**X**	**X**
v. Field Evaluation of Mix Design Procedures and Performance Recommendations		**X**	**X**	**X**	**X**

Budget

The estimated budget for this subtask is $375,000 over five years. The subtask will be conducted by the University of Wisconsin-Madison.

Relationship To FHWA Focus Areas

- Environmental Stewardship
- Will develop the use of the gyratory plate as an improved measure of mix workability.
- Clear definition of mix design and construction procedures will provide basis for modeling of energy savings associated with the use of warm mixes.
- Field investigation quantifies the risk of compromising performance at the expense of energy savings.

References

1. Kanitpong, K., S. Sonthong, K. Nam, W. Martono, and H. Bahia. "Laboratory Study on Warm Mix Asphalt Additives." Transportation Research Record, Journal of the Transportation Research Board. Transportation Research Board 2007. Taken from the Annual Meeting CD ROM.

2. Hurley, G., and B. Prowell. "Evaluation of Aspha-min Zeolite for use in Warm Mix Asphalt." National Center for Asphalt Technology, Auburn University, 277 Technology Parkway, Auburn AL. June 2005

3. Hurley, G., and B. Prowell. "Evaluation of Potential Processes for Warm Mix Asphalt." *Journal of the Association of Asphalt Paving Technologists*, Vol. 75. Association of Asphalt Paving Technologists, Savannah, GA 2006.

4. Hurley, G., and B. Prowell. "Evaluation of Sasobit for use in Warm Mix Asphalt." National Center for Asphalt Technology, Auburn University, 277 Technology Parkway, Auburn AL. June 2005

5. NCHRP Report 530, "Evaluation of Indirect Tensile Test (IDT) Procedures for Low Temperature Performance of Hot Mix Asphalt.", Transportation Research Board, National Research Council, Washington DC. 2004.

6. Wen, H., and R. Y. Kim. "Simple Performance Test for Fatigue Cracking and Validation with WesTrack Mixtures." Transportation Research Record 1789, Paper No. 02-2924. Transportation Research Board, 2002.

Subtask E1b-2: Development and Evaluation of a Volumetric Mix Design Process for Cold Mix Asphalt

Rising energy costs and increasing environmental awareness have led to an interest in the research and development of cold mix asphalt technologies as a replacement for conventional HMA pavement. Cold mix technologies allow for coating of aggregates and subsequent compaction of the asphalt mixture at ambient temperatures. As a result, energy requirements and emissions are significantly reduced relative to conventional HMA mixtures [5]. The economic and environmental implications of successful implementation of cold mixture technology in the construction of flexible pavements have the potential to provide a sustainable alternative to current practice. However, further research is needed to develop of a mixture design procedure and subsequent materials testing and characterization to ensure that the performance of pavements is not significantly compromised at the expense of environmental sensitivity. Incomplete understanding of the impacts of cold mix technology on pavement performance could lead to premature, drastic pavement failures resulting in increased agency costs and user delay.

In cold mixes, the workability of the material is derived from reduction of viscosity in the asphalt binder through emulsification or foaming. The reduced viscosity allows the coating of aggregates and compaction of the mix to occur at ambient temperatures. In the emulsification process an emulsifying agent is added to the asphalt resulting in the dispersion of asphalt cement in water [1]. In this mixture the water serves as the continuous phase with the asphalt suspended in discontinuous droplets throughout the medium. This phase dispersion allows for coating of the aggregates and compaction of the mixture at ambient temperatures. After a certain period of time the emulsion sets or "breaks" and evaporates, leaving behind an asphalt mixture. The cure time of an emulsion is based on the grade of emulsion used. In foamed asphalts the asphalt and water mixture is pressurized and sprayed to allow for coating of the aggregates and compaction of the mixture. Similar to emulsions, the mix becomes stable given a certain cure time for the water to evaporate from the mixture.

The implementation of cold mix technology, as a viable option for paving operations, is a promising concept. However a volumetric mixture design procedure consistent with current Superpave specifications is needed. Specifically, this mix design procedure must include guidance on mixing and compaction temperatures, quantify the rate of curing of the mixture, and evaluate test methods to assess the moisture susceptibility of cold mixes relative to that of conventional HMA. If it is expected that cold mixes will serve as pavement layers, they need to be held to the same standard as conventional HMA mixes. Furthermore, the mix design procedure must be verified through mixture testing to quantify the effect of water entrapped in the mixture. Development of a mixture design process will help define potential uses for cold mixes and facilitate development of specifications and construction guidance to allow for wide spread application of this technology.

Hypotheses

1. Further understanding of required cure time, the effects of moisture damage, and recommended mixing and compaction conditions (temperature and humidity) will allow for development of a reliable Cold Mix Asphalt (CMA) design procedure.
2. Mixture performance testing (such as E* and FN used in the MEPDG) will provide understanding of the effect residual water and emulsifiers on mechanical properties and the risks in terms of pavement performance that could result from incomplete water evaporation.

Objectives

The overall objective of this study is to identify and resolve the outstanding issues preventing the definition a mix design procedure for cold mixes. The mix design procedure will include definition of the cure (setting) times required for the CMA pavement to perform as expected. The effects of residual water and emulsifiers will be investigated through comparing mixture testing results of cold mixes to conventional HMA. Establishment of a mix design procedure and evaluation of the mechanical properties of cold mixtures is the first step in practical application of cold mix technologies.

Experimental Design

The following activities will be completed in order to achieve the objectives of this research effort.

i. Development of a Specification for the use of Emulsions in Cold Mixes

   The first step in development of a mix design procedure is defining a clear specification for the use of emulsions in cold mixes. Currently emulsions are classified by their chemical charge (anionic or cationic), cure rate (rapid, medium, or slow), and relative viscosity (1,2). For example a MS-2 emulsion is more viscous than an MS-1 emulsion [1]. It is clear that this methodology is inadequate in terms of specifying appropriate emulsions for paving applications based on performance grading. In order to better understand the differences in commercially available emulsions as specified by ASTM D2397 [2] the following properties of emulsions will be further investigated.

- Rate of Setting / Curing: Curing of an emulsion is controlled by the rate of change of viscosity in the emulsion/asphalt mixture. The current definition of rapid, medium, and slow curing times alone is inadequate. The change in viscosity and its dependence on emulsion concentration and temperature must be quantified.
    - Field Applications: Further understanding of factors affecting setting of emulsions in the field will aid in providing guidance for field applications (mixing and compaction) of emulsified asphalts. For example, given a certain ambient temperature, how can field temperatures and humidity be used to select the concentration and type of emulsion to ensure practical field application?
    - Opening to Traffic: Understanding of the setting rate will also provide initial indications of when the emulsified asphalt has an adequate viscosity to resist traffic loading without detriment to pavement performance.
- Modified Asphalt Emulsions: How does the rate of setting and its dependence on concentration change with the use of a polymer modified asphalt? How is emulsifier selection affected by modification?
- These questions will be answered using the following properties:
    - Viscosity: The Brookfield Viscometer will be used to investigate rate of setting as a function of concentration, polymer type, and temperature
    - Cohesion (Tack Test Developed by UW): Strength of the mixture is related to the cohesion developed in the asphalt as the emulsion breaks [5]. A range of curing times based on viscosity testing will be defined and tested using the tack test to determine when the asphalt has attained similar cohesive strengths to those found in normal binders. Comparison of cohesive strength will also provide insight into the effects of entrapped water on binder cohesion.

ii. Evaluation of Asphalt Emulsion Rheological Properties

In addition to the effect of curing times on viscosity as studied in Task 1, binder performance properties of emulsified asphalts will be measured and compared to conventional asphalts. This investigation will evaluate the assumption that given appropriate curing time, emulsified asphalts will have the same performance as conventional binders. It will also allow for understanding of the loss of binder performance due to entrapped water that was not able to evaporate from the binder. The following properties will be measured:

- Rutting ($G^*/\sin\delta$ and MSCR): The use of cold-mix technology prevents short term aging of the binder, the effects of the lack of aging on binder rutting must be quantified.

    - SuperPave Rutting Parameter: G*/sinδ
    - Accumulated Strain (Multiple Stress Creep and Recovery):
- Fatigue (Dissipated Energy Ratio and G* sinδ).
- Low Temperature Properties (BBR)
- Aging (RTFO and PAV): It is expected that the cold-mix process will result in minimal aging of the binder. Therefore, the effects of short term and long term aging of the binder will be investigated.

The time of setting before testing and temperature at which emulsion will be conditioned will be varied. The end result of this investigation will be recommended thresholds to quantify binder performance and a comparison of these thresholds to current binder specifications.

iii. Development of Volumetric Mix Design Procedures

The results of Tasks 1 and 2 will serve as the basis for development of mix design procedures. Specifically the following issues must be resolved.

- Emulsifier charge selection: The interaction between aggregate mineralogy and emulsifier charge will be investigated further. General guidance provided recommends the use of a cationic charge with siliceous aggregates and an anionic charge with calcareous aggregates [1,2]. These guidelines must be further refined to account for aggregate blends that may use a natural sand of different mineralogy.
- Optimum emulsified asphalt content: Optimum emulsified asphalt content is currently determined using the Centrifuge Kerosene Equivalent Test [1]. This test will be evaluated and refined for application to mix design guidelines. Optimum emulsified asphalt content is known to be a function of aggregate gradation, aggregate moisture content, and emulsifier type. The rate of curing and aggregate properties will be considered in the development of a method to estimate optimum emulsified content. This includes definition of parameters to evaluate the mixes. Initial review indicates that evaluation of aggregate coating, workability, and volumetrics are possible evaluation criteria.
- Mixing and compaction conditions (temperatures and humidity): The current recommendation of preparing cold mixes at ambient temperature is inadequate. The effects of mixture gradation, temperature, and humidity will be used in conjunction with the predicted binder rates of curing to clearly define recommendations for mixing and compaction temperatures. Test methods will be developed to quantify the change in workability of the mix over time and its dependency on temperature.
- Gradation: Rate of curing is dependent on aggregate gradation [1]. Dense graded aggregate blends or fine aggregate gradations will result in longer curing times and less efficient asphalt dispersion. These effects will be investigated using the

gyratory shear plate to examine changes in workability based on aggregate gradation.

- Moisture Damage: It is expected that cold mixes will be more moisture susceptible due to the use of aggregates at field moisture content and the water entrapped in the mix. Currently moisture damage is quantified for cold mixes using ASTM D7196 [4] which is a test to quantify raveling. This test will be evaluated for use in mixture design to predict moisture susceptibility. TSR testing per ASTM D4867 [3] will also be conducted. If moisture susceptibility is defined as a problem, anti-stripping agents in cold mixes will be evaluated.
- Use of RAP: Is it feasible to use RAP in cold mixes? From an environmental standpoint it would be of benefit to have the option of using recycled materials in the mix.
- Timing: Given the varying cure times, what is the appropriate timing of mixing, compaction, and sample preparation? The rate of curing of the mixture has to be understood to ensure the mix design process is providing practical information.
- Volumetrics: Can N_{ini}, N_{des}, and N_{max} thresholds for conventional mix designs be used for cold mixes?

iv. Mixture Performance Testing

The mixture design process will be evaluated using mixture performance testing.

- Mixture Workability and Stability: Mixes of varying aggregate type and gradation will be combined with the appropriate emulsified asphalt as defined in Task 1. Samples will be evaluated for workability immediately after mixing then allowed to cure. After appropriate curing times the stability of the mix will be evaluated through compaction past N_{max}. The sensitivity of curing time on the mixture stability will also be investigated.
- Moisture Damage: Intuitively the use of field moist aggregates presents the potential for increased moisture susceptibility. Guidelines for moisture susceptibility will be developed using the following tests:
  - Mixture testing: Moisture damage will be defined using TSR testing [3].
  - Stripping: The stripping of aggregates will be evaluated using the ASTM D7196 test for raveling currently in place for cold mixes [4].
  - If moisture damage is found to be a problem, the use of liquid anti-stripping additives and hydrated lime will be investigated.
- Simple Performance Tests (E* and FN)
  - Dynamic Modulus (E*) and Flow Number tests will be used to characterize the stiffness and rutting resistance of cold mixtures and to compare the results to conventional HMA mixes. Tests will be performed on short and long term aged mixtures. Preliminary investigations into mix

stability using the gyratory load plate developed by UW will provide recommended cure times.

v. Develop Revised Mix Design Procedures and Recommendations for Applications

Results of mixture performance testing will be used to define any deficiencies in the previously established mixture design procedures. Areas of improvement will be corrected and re-evaluated using focused testing. Specific guidelines will be provided for the following, this list is not comprehensive:

- Emulsifier Selection based on PG grading
- Optimum Emulsified Asphalt Content
- Mixing and Compaction Temperature
- Timing of mixing and compaction to prepare samples for mix performance evaluation.

The results of this task will also use the mixture design and performance testing results to provide a preliminary evaluation of the feasibility of incorporating cold mixtures into the pavement construction process. Recommendations will include identification of constructability issues (i.e. weather, lift thickness, etc.) that must be addressed before widespread application of this technology. Mixture performance test results will also allow for verification that cold mixes are viable material alternatives in both the binder and surface layers.

Year 1 Project Direction

Year one will focus on Activities i and ii in the work plan.

Schedule

Activity	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**
i. Development of a Specification for the use of Emulsions in Cold Mix	**X**	**X**			
ii. Evaluation of Asphalt Emulsion Rheological Properties	**X**	**X**			
iii. Development of Volumetric Mix Design Procedures		**X**	**X**	**X**	
iv. Mixture Performance Testing				**X**	**X**
v. Develop Revised Mix Design Procedures and Recommendations		**X**	**X**	**X**	**X**

Budget

The estimated budget for this subtask is $630,000 over the five year time frame and will be conducted by the University of Wisconsin-Madison and the University of Nevada.

Relationship to FHWA Focus Areas

- Environmental Stewardship
- This subtask will develop the use of the gyratory plate as an improved measure of mix workability.
- A clear definition of mix design and construction procedures will provide basis for modeling of energy savings associated with the use of cold mixes.
- Mixture performance testing will provide insight into the risk of compromising performance at the expense of energy savings.

References

1. Asphalt Institute: "Asphalt Cold Mix Manual" Asphalt Institute, Lexington, KY, 1989.
2. ASTM D3628. "Selection and Use of Emulsified Asphalts." Annual Book of ASTM Standards, 2006, American Society for Testing and Materials, Philadelphia, PA.
3. ASTM D4867. "Standard Test Method for Effect of Moisture on Asphalt Concrete Paving Mixtures." Annual Book of ASTM Standards, Vol. 04.03, American Society for Testing and Materials, Philadelphia, PA.
4. ASTM D7196. "Standard Test Method for Raveling of Col Mixed Bituminous Emulsion Samples." Annual Book of ASTM Standards, 2006, American Society for Testing and Materials, Philadelphia, PA.
5. Jenkins K. J., Molenaar, A, de Groot, Van de Ven. "Foamed Asphalt Produced Using Warmed Aggregates." Association of Asphalt Paving Technologists, Colorado Springs, CO 2002.

Category E2: Design Guidance

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

It is well known that cost vary significantly among common asphalt modification techniques. Although modeling can be blind, materials' selection can be significantly improved if knowledge of trends in effects of modification types can be plotted or mapped. This work element will start in the second year and will be based on data collected in other work elements conducted by the consortium.

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

Reclaimed asphalt pavement (RAP) is produced either by cold planning (CP) or by heating/softening and removal of the existing aged asphalt pavement. Recycling of the aged pavement has become more popular since the late 1970's although it had been practiced as early as 1915. The escalation of crude oil prices as well as cost of energy in general are expected to result in increased prices of asphalts which in turn raises the interest in the use of RAP in pavements. Furthermore, several studies showed that asphalt mixtures containing RAP can have equivalent performance to virgin mixtures. Hence, many agencies and contractors have made extensive use of RAP in constructing highway.

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.

One of the main concerns in RAP HMA mixtures is the effect of the RAP material on the mixture durability. Moisture susceptibility is regarded as the main cause of poor mixture durability. Moisture susceptibility can be evaluated by performing laboratory tests on unconditioned and moisture conditioned specimens. However, two recent research studies did not support the concerns over the durability of RAP containing HMA mixtures. Stroup-Gardner et al. (1999) showed that the inclusion of coarse RAP decreased the moisture susceptibility of HMA mixtures. In 2000, Sondag used the tensile strength ratio to evaluate the moisture sensitivity of 18 different mix designs incorporating three different asphalt binders, two sources of RAP and varying amounts of RAP. Sondag concluded that the addition of RAP to a mixture had no positive or negative influence on the mixture moisture susceptibility. In 2007, Hajj et al. concluded that if the appropriate virgin binder grade and anti-strip additive are used, the moisture sensitivity of the RAP containing HMA mixtures can be greatly reduced.

The properties of RAP are largely dependent on the properties of the constituent materials (i.e. aggregate type, quality and size, extracted binder grade, etc.). The RAP composition is also affected by the previous maintenance and preservation activities that were applied to the existing pavement. Additionally, sometimes RAPs from several projects are mixed in a single stockpile where deleterious materials or lower quality materials are also present. Consequently, a high variability is introduced in the RAP materials affecting the RAP properties and most likely resulting in a variable HMA mixture. Using low quality and/or highly variable RAP materials will definitely lead to premature failure of the HMA pavement.

The RAP percentage in the mixture significantly affects the properties of the HMA mixture. Several highway agencies have their own specifications on RAP usage in HMA mixtures. Currently, a total of 35 highway agencies allow the use of RAP with the majority allowing in excess of 30% RAP in HMA mixes (Sebaaly & Shrestha 2004). Some highway agencies do not specify a maximum limit on the percentage of RAP but leave it up to the mix design process to identify the maximum allowable percentage of RAP. Several highway agencies restrict the use of RAP to the layer underneath the wearing course.

Hypothesis

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.

Objectives

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 RAP materials. 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.

Experimental Design

The following tasks will be completed in order to achieve the objectives of this research effort. The following Consortium members will participate in this effort: University of Nevada, Reno (UNR), University of Wisconsin, Madison (UWM), Western Research Institute (WRI), Advanced Asphalt Technologies, LLC (AAT), Granite Construction Company (Dr. Jon A. Epps). The following tasks are planned:

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

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.

In the case of the binder in the RAP, the two critical properties are: binder content and binder properties. The binder content of the RAP can be easily identified through the extraction process. However, measuring the properties of the binder is still a complex process. Extracting and recovering the asphalt binder from the RAP materials faces the fundamental issues of the impact of the extraction/recovery process on the properties of the recovered binder and the health/environmental impact of the chemicals used in the process. These issues become very difficult to resolve when polymer-modified or crumb rubber modified binders are present in the RAP materials.

This task will review the previous research work on the development of an effective system to test the properties of asphalt binders from RAP materials. The review will focus on considering one or more of the following alternatives:

1. If a binder extraction/recovery system that is feasible, environmentally safe, and practical exists, or could be developed, it will be developed and standardized.
2. If such a system does not exist and the potential of developing it is not likely, a separation technique of the mastic from the RAP, without using solvents, will be pursued. A method for estimating RAP binder properties from the mastic deploying the technology currently used in binder testing will be developed.
3. If mastic separation and testing is too complex and not likely to be successful, a RAP mixture testing system will be developed instead.

In the case of the aggregates in the RAP, the two critical properties are: gradation and specific gravity. The gradation of the aggregates in the RAP materials can be easily evaluated through the extraction process. Determining the specific gravity of the RAP aggregates represents a challenge. Several techniques have been used in the past but there is not an accepted standard procedure. This task will identify a standard method for measuring the specific gravity of RAP and aggregate and develop a standard procedure.

Subtask E2b-2: Compatibility of RAP and Virgin Binders

The compatibility between the RAP and virgin binders is a significant factor for the long-term performance and durability of the HMA mixture containing the RAP materials. There are chemical as well as rheological tests that can estimate the compatibility of binders. One of the possible simple compatibility tests is the measurement of viscosity of the blended binder. Also evaluation of G* and Phase angle could be used to measure compatibility. The expectation is that G* of blended binders should be in between the values of the virgin and the RAP binders. In most cases a linear relationship between log G* and % virgin binder is found for compatible binders. A significant deviation from the linear relationship could be an indication of incompatibility. These ideas and others could be used in this task to develop a simple and practical test for compatibility.

The compatibility of RAP binders and virgin binders can also be measured by using Automated Flocculation Titrimetry (AFT) and Atomic Force Microscopy (AFM). The AFT measurements can be made on various blends of RAP binder and virgin binder and basically evaluate the solubility characteristics of the materials. The AFT measurements will be coordinated and correlated with the rheological measurements. The AFM can be used to investigate the compatibility of the blended binders on a nanoscale. Recent developments in AFM research have revealed important aspects of asphalt behavior upon thermal cycling that can be applied to RAP and virgin blended binders.

The compatibility of RAP and virgin binders, both rheological and chemical, will consider the actual blending of the binders that takes place in hot-mix plants by comparing laboratory blending samples with samples of RAP mix obtained from hot-mix plants. WRI will work on evaluation of a chemical-based test while UNR and UW will share responsibility of developing a rheology-based test for compatibility.

Subtask E2b-3: Develop a Mix Design Procedure

This task will concentrate on developing a mix design procedure for HMA mixtures containing RAP materials. The mix design procedure will follow the Superpave Volumetric Mix Design Method. It is anticipated that some changes will have to be made to the Superpave method to account for factors such as: mixing and compaction temperatures and the number of gyrations, etc. This task will obtain RAP materials from 10 different sources to cover a wide range of pavement age, environmental conditions, and material sources. These sources will be used to develop a standard mix design method that is applicable to HMA mixtures containing RAP materials at various levels of 15, 30 and 45 percent.

The mix design method will use the recommendations of Tasks 1 and 2 in terms of the appropriate methods to evaluate the binder and aggregates in the RAP materials and assessing the compatibility between the virgin and RAP binders. The final product of this task will be a complete mix design system for HMA mixtures containing RAP materials that includes the following components:

- A process to evaluate the properties of the RAP binder
- A process to measure the specific gravity of the RAP aggregate
- A process to identify the appropriate mixing and compaction temperatures
- Recommendations for the number of gyrations
- Mix design criteria

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

This task will evaluate the impact of RAP materials on the performance of the final mix in terms of fundamental properties and resistance to distresses. In order for HMA mixtures containing RAP materials to be widely accepted, the agencies should be able to evaluate their fundamental properties and their potential long-term performance. In other words the agencies need to be able to input the fundamental properties of the RAP mixtures into the AASHTO MEPDG and use the appropriate performance models to conduct the final structural design.

This task will conduct an experimental program to evaluate the fundamental properties and resistance to distresses of the RAP mixtures that were used and designed in Task 3 using the following technologies:

- Evaluate the dynamic modulus master curves of short-term and long-term aged mixtures
- Evaluate the resistance of the short-term and long-term aged mixtures using the tests recommended by the Consortium research on moisture damage
- Evaluate the resistance to rutting using the repeated load triaxial test on short-term aged mixtures
- Evaluate the resistance to fatigue using the flexural beam fatigue test on long-term aged mixtures and/or the tests recommended by the Consortium research on fatigue
- Evaluate the resistance to thermal cracking using the thermal stress restrained specimen test on long-term aged mixtures and/or the tests recommended by the Consortium research on thermal cracking

The final product of this task will be a database of the fundamental properties and performance characteristics of HMA mixtures containing RAP materials from 10 different sources at four levels of RAP contents of 0, 15, 30, and 45 percent.

Subtask E2b-5: Field Trials

This task will conduct field trials of the developed system. In cooperation with Granite Construction Inc. and state highway agencies, field test sections will be produced and constructed following the system developed in this research. During the construction of the field test sections, the plant produced HMA mixtures containing RAP materials will be evaluated in terms of their properties and performance characteristics (i.e. rutting, fatigue, and thermal cracking) following the systems developed in the previous tasks.

The long-term performance of the field test sections will be monitored in cooperation with the state highway agencies and the data will be used to validate the design and evaluation systems developed in this research.

During the construction of the field trials, data will also be collected to achieve two additional goals: RAP source acceptance and RAP source variability. It will be unrealistic to expect the agencies to conduct rutting, fatigue, and thermal cracking tests on each RAP source. This task will attempt to develop an acceptance guideline based on simple tests either on the entire RAP mix or on RAP components. This task will also identify the tests to be used to assess the variability of the RAP stockpiles. The potential tests for measuring the variability of the RAP stockpiles will have to practical and reliable.

Year 1 Project Direction

It is anticipated that Subtasks E2b-1 and E2b-2 will start in Year 1.

Schedule

Subtask	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**
E2b-1. Develop a System to Evaluate the Properties of RAP Materials	**X**	**X**			
E2b-2. Compatibility of RAP and Virgin Binders	**X**	**X**			
E2b-3. Develop a Mix Design Procedure		**X**	**X**		
E2b-4. Impact of RAP Materials on Performance of Mixtures			**X**	**X**	**X**
E2b-5. Field Trials				**X**	**X**

Relationship to FHWA Focus Area

This research effort supports the FHWA Focus Areas of Optimize Pavement Performance and Environmental Stewardship.

Budget

The anticipated budget of the research partners are listed in the Table below. The participation of Granite Construction Co. will be used as a cost share component.

ARC Member	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**
UNR ($)	75,000	250,000	325,000	300,000	300,000
UWM	45,000	45,000	75,000	45,000	45,000
WRI	20,000	40,000	10,000	10,000	20,000
AAT	12,500	33,500	34,000	28,000	17,000

References

Hajj, E. Y., P. E. Sebaaly, and R. Shrestha, “A Laboratory Evaluation on the Use of Recycled Asphalt Pavements in HMA Mixtures,” Western Regional Superpave Center, University of Nevada, Reno, Final Report, 2007.

Sebaaly, P. E. and R. Shrestha, “A Literature Review on the Use of Recycled Asphalt Pavements in HMA Mixtures,” Western Regional Superpave Center, University of Nevada, Reno, Final Report, 2004.

Stroup-Gardiner, M., and C. Wagner, 1999, Use of RAP in Superpave HMA Applications. Transportation Research Record 1681, pp. 1-9.

Sondag, M. S., 2000, Investigation of Recycled Asphalt Pavement Mixtures. University of Minnesota, Final Report.

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

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. Therefore, it is recommended that the critical temperature and critical loading rate be identified for every HMA mixture. Once these two critical conditions are identified, they must be checked against the expected field conditions where the HMA mix will be placed. An HMA mix should not be placed at locations where its critical conditions are expected to be violated.

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.

Hypothesis

The strength and performance of HMA mixtures can be optimized by loading them below their critical conditions as depicted by the combination of temperature and loading rate.

Objectives

The objective of this research effort is to establish a practical test method to identify the critical temperature and critical loading rate of HMA mixtures. The test will be based on fundamental properties of the HMA mixture and consistent with the Superpave mix design method. The developed test method should be simple enough to be implemented as part of the mix design process.

Experimental design

The following subtasks will be completed in order to achieve the objective of this research effort.

Subtask E2c-1: Identify the Critical Conditions

As the HMA mix is placed at a given project location, it will immediately be subjected to the local environmental conditions and traffic loading. Due to the viscoelastic nature of the HMA mix, its behavior is highly dependent on both temperature and rate of loading. The pavement temperature is related to the air temperature through a relationship that has been established and verified based on the data from the Long Term Pavement Performance (LTPP) studies. This relationship has been accepted in the Superpave system. The loading rate of the HMA mix depends on the speed of the traffic using the facility. The loading rate varies from short under freeway traffic to long under urban traffic.

Low temperature coupled with a short loading rate is the best condition for an HMA mixture while high temperature coupled with a long loading rate represents the worst condition. In reality the combination of temperature and loading rate varies over a wide range. Identifying the temperature of the HMA mix is relatively simple since it only depends on the location of the pavement and the air temperature. However, identifying a loading rate represents a more difficult challenge since the mixed nature of traffic loading has to be included. This task will use dynamic mechanistic analysis of flexible pavements subjected to various traffic speeds to identify the loading rates that are applicable to the various road facilities (i.e., freeways, urban streets, intersections, and off ramps).

Subtask E2c-2: Conduct Mixture Evaluations

The objective of this task is to determine the critical combination of temperature and loading rate for HMA mixtures. The critical combination is defined as the one that creates an unstable HMA mix exhibiting excessive permanent deformation. Figure 1 shows the development of permanent strain in an HMA sample tested under the repeated load triaxial (RLT) test. It can be seen that the permanent deformation goes through three phases: initial phase with a high rate of permanent deformation but short duration, a secondary phase where the permanent deformation is linear with a long duration, and tertiary phase where the permanent strain is increased exponentially. It is believed that the formation of the tertiary phase is an indication of an unstable HMA mix.

The repeated load triaxial test is the most representative test of actual field conditions. The deviator and confining stresses can be varied to simulate the actual state of stresses within the HMA layer while simultaneously changing the temperature and the rate of loading. It is proposed that the RLT test be used to evaluate a variety of HMA mixtures ranging from weak to strong mixtures to identify their critical temperatures and rates of loading. It is anticipated that a total of 50 HMA mixtures will be evaluated. The permanent deformation curves similar to the one shown in Figure 1 will be developed for each mixture under the various combinations of temperature and rate of loading as determined in Task 1.

Subtask E2c-3: Develop a Simple Test

One disadvantage of the RLT test is its complexity since it requires accurate control of the deviator and confining stresses for the duration of the test, which makes it an impractical test for routine applications.

This task will use the evaluation data from the RLT tests conducted in Task 2 to investigate the possibility of developing a simpler version of the test. At this point, the researchers believe that a test that can be conducted in the Simple Performance Tester (SPT) may be feasible with some adjustments. This will have the advantage of conducting the critical conditions test in the same equipment used for the dynamic modulus test which will make it easier to implement as part of the mix design process. If the SPT proved unfeasible, then other tests will be investigated.

Subtask E2c-4: Develop a Standard Test Procedure

The objective of this task will be to develop a standard test procedure to be used for the identification of the critical conditions of HMA mixtures. The standard procedure will be developed in AASHTO format and submitted to AASHTO for approval.

Subtask E2c-5: Evaluate the Impact of Mix Characteristics

The objective of this task is to identify the mix characteristics that impact the critical temperature and loading rate of HMA mixtures. This task will use the test procedure developed in Task 4 to assess the impact of the various mix properties on the critical conditions.

It is anticipated that mix properties such as binder grade and content and aggregate properties and gradation may play a major role on the critical temperature and loading rate of HMA mixtures. The work conducted under this task will identify the various mix properties and their corresponding levels that have significant impact on the critical conditions of the HMA mix. Through this effort, it will be feasible to recommend changes in the mix properties that will improve their critical behaviors.

For example if an HMA mix is performing well under mainline traffic, but it is experiencing severe rutting at the intersection, then it is possible that it is reaching its critical loading rate under slow-stop traffic for the given location (i.e. temperature). The data generated in this task will help identify the necessary changes in mix properties that will improve its resistance to rutting at the intersection.

It is anticipated that this research effort will identify some mix properties that can be easily modified during production and that will lead to significant improvement in the response of the HMA mix under critical conditions. The research under this task will also cover other failure modes of the HMA mix in order to avoid improving the resistance of the mix to one mode of failure while at the same time jeopardizing its resistance to the other failure modes.

Year 1 Project Direction

It is anticipated that Subtasks E2c-1 and part of Subtask E2c-2 will be completed in the first year.

Schedule

Subtask	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**
E2c-1. Identify the Critical Conditions	**X**				
E2c-2. Conduct Mixture Evaluations	**X**	**X**			
E2c-3. Develop a Simple Test			**X**	**X**	
E2c-4. Develop Standard Test Procedure				**X**	
E2c-5. Evaluate the Impact of Mix Characteristics				**X**	**X**

Relationship To FHWA Focus Area

This research effort supports the FHWA Focus Areas of Optimize Pavement Performance and Advanced Quality Systems.

Budget

The estimated budget of this work element is $600,000.

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

Thermal cracking of HMA mixtures is caused by the non-polar oily or neutral fractions of the binder becoming a rigid solid at low temperature. Glass is a common example of such an amorphous super-cooled liquid and thus the analogy to glass is responsible for the term "glass transition temperature" of asphalts which is the temperature at which the liquid component of the asphalt freezes to a solid. Any attempt to deform the frozen structure results in fracture.

Oxidation raises the glass transition temperature of the binder, and therefore, decreases its resistance to thermal cracking. The impact of oxidation is two fold: the introduction of polar groups and the decrease in the amount of oily fractions. However, there is a big question whether oxidation only occurs within the top one inch of the pavement surface or it actually progresses throughout the depth of the HMA layer. The two common sources of information on this issue provide contradicting recommendations. The work by Coons and Wright in 1968 concluded that binder oxidation occurs only in the top inch of the pavement and that below the top inch, the binder is left virtually unaffected by years of use and years of environmental exposure. On the other hand, recent work by Glover et al (2005) indicated strongly that in fact binders can age in pavements well below the surface and that the hardening of binder in the pavement is virtually unabated over time. Recent studies on glass transition behavior during the SHRP program on binders, and subsequently at the University of Wisconsin, Madison (UWM) on binders and mixtures, has shown that sources of asphalt binders, modification, aging, and aggregate properties can alter the glass transition behavior significantly. In addition, recent studies at UWM, as part of a pooled fund study TPF-05 lead by MnDOT, showed that thermal cycling has an important effect. Results show that the coefficient of contraction for mixtures could be significantly different from coefficients of expansion and thus thermal cycling needs to be modeled carefully for more accurate prediction of thermal stresses and cracking.

These recent results on aging and glass transition behavior merit a fresh look at the prediction of thermal cracking models. In addition the increasing use of modified binders, particularly polymer and acid modified binders require a more in depth evaluation of these factors for better cracking prediction.

Hypothesis

Field performance data indicate that HMA mixtures in the intermountain region of the U.S. experience severe thermal cracking distresses that are not well covered by the current technology. The intermountain region experiences significant hardening of the asphalt binder coupled with extreme thermal cycling, and highly absorptive aggregate leading to thermal cracks that are six inches wide.

Objectives

The objective of this research effort is to develop a binder/mix evaluation and testing system that can effectively simulate the long term properties of HMA mixtures in the intermountain region and to assess the impact of such properties on the resistance of HMA mixtures to thermal cracking.

Experimental Design

In order to achieve the objectives of this research effort, the following subtasks will be completed. The following Consortium members will participate in this effort:

- University of Nevada, Reno (UNR)
    - Dr. Claine Petersen (Consultant)
    - Dr. Charles Glover (Consultant)
- University of Wisconsin, Madison (UWM)

Subask E2d-1: Identify Field Sections

This task will identify the extent of thermal cracking in HMA pavements located within the intermountain region of the U.S. Several HMA pavements will be identified at various locations within the intermountain region and their performance for the past 10-15 years will be collected and analyzed. A concerted effort will be made to select pavement sections that coincide with the LTPP SPS sections in the intermountain region. The research team will consult with FHWA and Nichols Consulting Engineers to select the appropriate LTPP SPS sites in the intermountain region. The performance of the selected pavement sections will be collected from the pavement management systems (PMS) of the corresponding owner agencies and the LTPP databases. The selected pavements will cover a wide range of pavement age, environmental conditions, and traffic loadings. Since thermal cracking develops in the form of transverse cracks which highly resembles reflective cracking, special efforts will be made to separate the two modes of distress.

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

This task will obtain samples from the various pavement sites that are experiencing thermal cracking and conduct laboratory testing to identify the causes of the thermal cracking failure. The following tests will be conducted on the samples obtained from the various sites.

- Compare the environmental conditions at the site with the critical temperatures of the binder used during construction as specified by the Superpave PG system.
- Measure the temperature profile throughout the depth of the HMA.
- Measure the volumetric properties of the samples from the various sites.
- Measure the fracture temperature of the mix using the thermal stress restrained specimen test (TSRST) conducted on field samples.
- Extract and recover the binder from the samples at 1.0” depth increments and measure their rheological properties following the Superpave PG system and the master curves of G’, G”, and G*.
- Test the recovered binders for oxidation, solvent removal, and low shear rate limiting viscosity.
- Evaluate the extent of binder oxidation as a function of depth of the HMA layer.
- Measure the glass transition behavior of extracted binders and of mixtures at cooling and heating rates that resemble the conditions of the pavement sections that are sampled.

The activities of this task will be closely coordinated with the activities of other Consortium partners on aging of HMA mixtures that will be conducted under the fatigue and moisture damage areas.

Subtask E2d-3: Identify an Evaluation and Testing System

The objective of this task is to identify a system to evaluate and test HMA mixture’s resistance to thermal cracking in the intermountain region. It is anticipated that HMA pavements in the intermountain region are subjected to significant hardening of the asphalt binder coupled with extreme thermal cycling, and highly absorptive aggregate leading to thermal cracks.

Based on the data generated from Subtasks 1 and 2, the researchers will work on developing an evaluation and testing system to simulate the actual conditions in the intermountain region. At this point the researchers anticipate that the work under this task will cover the following parameters:

- A binder aging system that simulates the field aging process of HMA mixtures in the intermountain region.
- The impact of fillers on the aging characteristics of the HMA mix.

- The impact of air voids on the aging characteristics of the HMA mix.
- The impact of highly absorptive aggregates on the aging characteristics of the HMA mix.
- A thermal cracking test that simulates the actual tensile mode of loading that is experienced by the HMA layer.

The activities of this task will be closely coordinated with the activities of other Consortium partners on aging of HMA mixtures that will be conducted under the fatigue and moisture damage areas.

Subtask E2d-4: Modeling and Validation of the Developed System

This task will develop a software program for prediction of critical cracking temperatures using the input variables measured in Subtask 3. The software will include variables that are found to be important in Subtask 3 and that have shown clear role in predicting the performance observed in the field.

The task will also include validation of the testing and modeling system. The validation process will be conducted in the laboratory based on the use of the TSRST. Although the SHRP research concluded that the TSRST is too complex to become a production test, it is clear that the test can be used effectively to evaluate stress build up and cracking under well controlled variables.

In addition, this task will make a concentrated effort to validate the developed system on a national basis. Some national pavement sites will be identified and used for this validation effort.

Subtask E2d-5: Develop a Standard

This task will develop a standard testing procedure for the system developed in Subtask 3 and validated in Subtask 4. The standard will be prepared in AASHTO format.

Year 1 Project Direction

It is anticipated that Subtask E2d-1 will be started in Year 1.

Schedule

Subtask	Year 1	Year 2	Year 3	Year 4	Year 5
E2d-1. Identify Field Sections	**X**	**X**			
E2d-2. Identify the Causes of the Thermal Cracking		**X**	**X**		
E2d-3. Identify an Evaluation and Testing System		**X**	**X**	**X**	
E2d-4. Modeling and Validation of the Developed System				**X**	**X**
E2d-5. Develop a Standard				**X**	**X**

Relationship to FHWA Focus Area

This research effort supports the FHWA Focus Areas of Optimize Pavement Performance and Advanced Quality Systems.

Budget

The estimated budget of this work element is $930,000 and will be conducted by the University of Nevada and the University of Wisconsin-Madison.

References

Coons, R. F., and P. H. Wright (1968). An Investigation of the Hardening of Asphalt Recovered from Pavements of Various Ages. AAPT, 37, 510.

Glover, C. J., R. R. Davison, C. H. Domke, Y. Ruan, P. Juristyarini, D. B. Knorr, and S. H. Jung (2005). Development of a New Method for Assessing Asphalt Binder Durability with Field Validation. Report FHWA/TX-03/1872-2, Texas Transportation Institute, College Station, TX.

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

There is an urgent need to provide additional guidance to engineers concerning the design of fatigue and rut resistant mixtures. Excellent progress in understanding the relationship between mixture volumetric factors and pavement performance was made in National Cooperative Highway Research Program (NCRHP) Projects 9-25 and 9-31. In these projects, models based on volumetric composition and binder properties were developed for:

- Dynamic modulus

- Rutting resistance
- Fatigue cracking resistance
- Permeability

These models have been used to establish the general design criteria that are incorporated in the new Mix Design Manual for HMA that is being produced in NCHRP Project 9-33.
Further improvement of some of these models is needed to address specific shortcomings that were identified in subsequent validation efforts, and to expand the range of mixtures (nominal maximum aggregate size, compaction level, aggregate type, binder grade, modifier type etc.) used in the model development.

Hypothesis

Models relating mixture composition and binder properties to performance can be used to design and evaluate HMA mixtures for high traffic levels.

Objective

The objective of this research is to develop a document containing supplemental design guidance for HMA mixtures for high traffic levels a high resistance to rutting and fatigue cracking is needed. This document would supplement the general design guidance included in AASHTO M323 and the new Mix Design Manual for HMA being prepared in NCHRP 9-33. The design guidance will be based on improved models relating mixture composition and binder properties to pavement performance.

Experimental Design

The following subtasks will be completed in order to achieve the objective of this research effort.

Subtask E2e-1: Identify Model Improvements

The models that were developed in NCHRP Projects 9-25 and 9-31 were validated by AAT in NCHRP Project 9-33 using available data test roads and accelerated loading facilities including: the FHWA ALF, MinnRoad, NCAT, and Westrack. Additionally some of the models have been independently evaluated by other researchers (1). In this task, the results from these validation and evaluation efforts will be reviewed to identify a prioritized list of model improvements that should be considered in this project.

Subtask E2e-2: Design and Execute Laboratory Testing Program

Based on the results of Task 1 and the available budget, specific laboratory experiments will be designed to improve the existing model. These experiments will consider a range binders, modifiers, aggregates, mixture gradations, etc so that the resulting data can be used to develop robust models. Sufficient replication will be included to allow estimates of the precision of the resulting models to be made.

Materials for each experiment will be procured. The necessary laboratory testing will be performed and the results of the testing will be assembled into databases for subsequent statistical analysis.

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

In this task engineering and statistical analyses will be performed to refine the models developed in NCHRP Projects 9-25 and 9-31. The primary analysis technique will be regression with the model parameters selected based on engineering principles so that the parameters have specific physical significance and are factors that can be controlled in HMA mixture design.

Subtask E2e-4. Validate Refined Models

The refined models will be validated using laboratory data from other sources and pavement performance data from various accelerated loading facilities, test roads, and the LTPP program.

Subtask E2e-5. Prepare Design Guidance

In this task a report providing guidance for the design of mixtures for high traffic applications will be developed. This report will be prepared as a supplement to the Mix Design Manual for HMA that is being developed in NCHRP 9-33. If appropriate, a Standard Recommended Practice for Design of Mixtures for High Traffic Levels will be prepared based on the report and submitted to the Mixtures and Construction Expert Task Group for consideration as an AASHTO Recommended Practice.

Year 1 Project Direction

It is anticipated that Subtasks E2e-1 and part of Subtask E2e-2 will be completed in Year 1.

Schedule

Subtask	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**
E2e-1. Identify Model Improvements	**X**				
E2e-2. Design and Execute Laboratory Testing Program	**X**	**X**	**X**		
E2e-3. Perform Engineering and Statistical Analysis to Refine Models			**X**	**X**	
E2e-4. Validate Refined Models				**X**	
E2e-5. Prepare Design Guidance					**X**

Relationship to FHWA Focus Area

This research effort supports the FHWA Focus Area of Optimize Pavement Performance.

Budget

The estimated budget for this work element is $371,500 and will be conducted by Advanced Asphalt Technologies.

References

Dongre, R., L. Myers, J. D'Angelo, C. Paugh, and J. Gudimettla (2005). Field Evaluation of Witczak and Hirsch Models for Predicting Dynamic Modulus of Hot-Mix Asphalt. *Journal of the Association of Asphalt Paving Technologists*, Vol. 74.