Investigation of Low Temperature Cracking in Asphalt Pavements
National Pooled Fund Study
Phase II

Introduction

In phase I, a comprehensive research effort in which both traditional and new experimental protocols and analyses were applied to a statistically designed set of laboratory prepared specimens and to field samples from pavements with well documented performance to determine the best combination of experimental work and analyses to improve the low temperature fracture resistance of asphalt pavements

The two sets of materials were evaluated using current testing protocols, such as creep and strength for asphalt binders and mixtures as well as newly developed testing protocols, such as the disk compact tension test, single edge notched beam test, and semi circular bend test. Dilatometric measurements were performed on both asphalt binders and mixtures to determine the coefficient of thermal contraction.

Discrete fracture and damage tools were utilized to model crack initiation and propagation in pavement systems using the finite element method and TCMODEL was used with the experimental data from the field samples to predict performance and compare it to the field performance data.

Phase I has resulted in a number of important findings and recommendations. They can be summarized as follows:

1. Field performance correlates best with fracture parameters for both asphalt mixtures and binders. These results clearly indicated that, while the current properties such as creep and strength are needed for stress calculations and pavement design, the selection of fracture resistant binders and mixtures should be based on simple fracture tests.
2. The PG specification for binders provides a good start; however, other factors such as aggregate type and air voids affect fracture resistance. Therefore, asphalt mixture specification criteria similar to the current PG system for binders need to be developed
3. At low temperature, asphalt mixtures are complex viscoelastic composite materials that are significantly temperature and loading rate dependent. Any new specification should be based on test results at multiple temperatures and loading rates similar to the rates experienced by real pavements.
4. While the selection of materials with good fracture properties will significantly improve pavement performance, it is critical to understand the role of all components of the pavement system. Therefore, the pavement mechanics models developed in phase I need to be further refined.

Tasks

The work proposed for phase II builds upon the findings and recommendations of phase I. Each of the four main recommendations will be addressed in this phase; however, the main thrust will be the development of test methods and specification criteria that will allow the selection of fracture resistant asphalt mixtures and binders at low temperatures. In order to accomplish these goals, the following major tasks are proposed for phase II.

Task 1 – Update on low temperature cracking research

In this task, a brief literature review will be performed to document any new research in the area of low temperature cracking, including the work performed by the Asphalt Research Consortium research team. Details of the MnROAD test cells constructed in 2007 and 2008 in relation to low temperature cracking will be provided. In addition, test specifications from Canada & Europe that may be similar to the current DCT and SCB tests will be documented, as well as any modifications to the SCB and DCT tests that have been done since the end of Phase I.

Task 2 – Expand Phase I test matrix with additional field samples

In task-2, nine new asphalt mixtures used in field studies will be tested and analyzed with respect to their low temperature cracking resistance. The research team is proposing the following seven mixtures plus two additional mixtures from Wisconsin and New York. The tests will consists of IDT creep and strength tests as well as SCB and DCT fracture tests. These include warm mixtures, mixtures with RAP, and acid modified and mixtures prepared with similar PG binders but different sources:

Location	Construction Date	Description
MnROAD 33	September 2007	58-34 Acid only no RAP
MnROAD 34		58-34 SBS + Acid no RAP
MnROAD 35		58-34 SBS only no RAP
MnROAD 77		58-34 Elvaloy + Acid no RAP
MnROAD 20	August 2008	58-28, 30% non-fractionated RAP, level 4 SP, wear & non-wear
MnROAD 21		58-28, 30% fractionated RAP, level 4 SP, wear & non-wear
MnROAD 22		58-34, 30% fractionated RAP, level 4 SP, wear & non-wear
Wisconsin 9.5 mm SMA	2008	Wisconsin will provide materials
New York "Typical Mix"	2008	New York with PG 64-22 binder and an aggregate other than limestone and granite.

The experimental variables that are important in differentiating low temperature cracking mix performance are test temperature, long-term aging or mix conditioning, and mix air voids. The proposed experimental plan for establishing the proposed low temperature cracking criteria is shown in the table below.

Test Device	Temp	Mix Conditioning	MN/Road Test Section				SMA WI		Mixture NYS	
			33, 34, 35, 37		20, 21, 22					
			Air Voids, %							
			4	7	4	7	4	7	4	7
SCB	PG	4Hours@135ºC	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx
	PG+10ºC	4Hours@135ºC	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx
	PG	None	xxx		xxx		xxx		xxx	
	PG+10ºC	None	xxx		xxx		xxx		xxx	
DC(T)	PG	4Hours@135ºC	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx
	PG+10ºC	4Hours@135ºC	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx
	PG	None	xxx		xxx		xxx		xxx	
	PG+10ºC	None	xxx		xxx		xxx		xxx	
IDT	PG	4Hours@135ºC	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx
	PG+10ºC	4Hours@135ºC	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx
	PG	None	xxx		xxx		xxx		xxx	
	PG+10ºC	None	xxx		xxx		xxx		xxx	

The initial validation plan detailed in the table above consists of performing 54 tests per mixture for a total of 486 tests. All nine mixtures will be DCT tested at UIUC laboratory, and SCB and IDT tested at UMN laboratory, respectively. For three of the nine mixtures, DCT tests will be also performed at UMN and SCB test will be also performed at UIUC; Iowa State will perform a limited number of tests (SCB and/or DCT), if equipment becomes available. All laboratories will provide a detailed QA plan to ensure the accuracy of the test results. The progress of this work will be presented periodically at the Expert Task Group meetings, and it is expected that, at the end of Task 2 or subtask II of Task 3, a round robin will be initiated through ETG mechanisms, at no cost to the current project, to obtain precision and bias information on the fracture test methods.

The laboratory test results will be correlated to the low temperature cracking field performance of the MN/Road mixes. This plan will determine which device is best and the best temperature, mix conditioning, and air void level for establishing the low temperature specification criteria. The research team envisions that there will be two levels of specification consisting of simply a mix criteria and a more advanced one using models. The more advanced specification will consist of additional mix testing beyond that of the mix design criteria for use in the developed advanced models.

Subtask on Physical Hardening

This task will also contain a subtask in which the effect of PPA, Warm Mix Additives and Polymers on Physical Hardening of Asphalt Binders will be evaluated. In Phase I it was shown that isothermal physical hardening could have serious effects on stiffness and "m" values of binders. It has been indicated in previous studies that modifiers used could change the physical hardening due to effects on morphology of binders. Physical hardening measurements require a long time and could complicate specification testing. However, studies during SHRP program as well as more recent studies have shown that physical hardening trends can be predicted from relatively short time tests. The success of including physical hardening in routine testing depends on simplification of test procedure and understanding effect of various additives used for modification today. The objectives of this subtask are:

1. Develop a protocol to simplify the measurements of physical hardening and include a numerical approach to adjust S and m values based on such protocol and based on climatic condition.

2. Collect physical hardening for a variety of asphalt binders and verify the model that will be developed in task 5.

3. Use the glass transition measuring technique to quantify effect of isothermal storage on dimensional stability of asphalt mixtures.

Task 3 – Develop low temperature specification for asphalt mixtures

The main objective of this work is the development of low temperature performance specification for asphalt mixtures. Currently, the simple performance test provides the parameters needed to predict the intermediate and high service temperature performance. There is a need for a similar test to fill the gap in the low temperature range. In order to accomplish this goal the following subtasks will be performed:

Subtask 1 – develop test method

- Refine and possibly simplify the SCB and DCT fracture tests used in phase I.
- Propose a standard fracture test method based on SCB configuration for asphalt mixtures. Note that the DCT has been already approved as an ASTM standard.
- Develop standard fracture method. At the end of this task the research team will recommend only one fracture test but provide correlations between the results from the two methods.

Subtask 2 – develop specification

- Revisit the supporting field and experimental data that was used to develop the current PG system used to select asphalt binders. A similar approach, based on criteria providing limiting temperature values, will be used for the mixture specification
- Based on the experimental work performed in phase I and the work performed in task 2 and data available in previous research projects, develop limiting criteria for selecting asphalt mixtures resistant to low temperature cracking. The criteria will be based on fracture tests performed on specimens prepared from original loose mix.

Subtask 3 – propose simplified method to obtain mixture creep compliance

- Since the IDT creep and strength data represent critical inputs in the MEPDG software it becomes important to revisit the IDT strength and creep test methods and analyses to find out if similar information can be obtained from other simpler tests.
    - Investigate if creep compliance can be obtained directly from tests performed in the SCB and DCT configuration
    - Investigate if BBR testing of thin asphalt mixture beams. This will be based on work in progress performed at University of Minnesota as part of recent NCHRP Idea project
    - Revisit work performed under previous MnDOT project to evaluate the feasibility of using Hirsch model
    - Investigate if strength can be obtained from BBR testing of thin asphalt mixture beams to failure; this work will be performed in conjunction with ARC work performed by University of Wisconsin

The primary outcome of task will be the development of a simple mixture design specification, based upon mixture fracture testing and Superpave low-temperature binder test data, to control thermal cracking. It is not anticipated that the specification will involve the use of a computer program as part of routine design. However, the improved TCMODEL program to be developed under Task 4 will be used to choose specification parameters and to set specification thresholds. An optional, more rigorous specification, which will require running the TCMODEL program, will be developed under Task 4.

Task 4 - Develop Improved TCMODEL

TCMODEL is a computer program developed under SHRP and later revised and adopted for the M-E PDG that predicts transverse cracking versus time based upon hourly air temperatures, HMA creep compliance and tensile strength from the IDT (AASHTO T-332), HMA thermal coefficient, and other pavement layering information. Phase I of the study demonstrated the benefits of the mixture fracture energy measurement as compared to mixture tensile strength, particularly for polymer-modified mixtures.

TCMODEL will be enhanced in Phase II ("NewTCMODEL") to better capture the true fracture properties of hot-mix asphalt. The resulting program will be used to guide the specification design team in the development of a simple specification for the control of thermal cracking based upon a mixture fracture test and standard Superpave binder test results. The program will also be delivered as part of an optional rigorous thermal cracking design specification, where the running of NewTCMODEL is part of the design specification. This system will bear similarity to the M-E PDG, although it will use mixture fracture tests instead of tensile strength and will have an improved fracture model (cohesive zone fracture model instead of the Paris law model). Climatic files for participating states (3 climatic zones per state) will be developed and included in the software for a range of asphalt layer thicknesses. The TCMODEL program will be made available as a freeware program, to be posted on University, FHWA, and State DOT websites. The program and an accompanying user's manual will be bundled with the final report.

In addition, UIUC researchers will work with other university team members to conduct a preliminary calibration and validation of the new model at the end of the second year of the study. Data from phase I project, along with new data generated from the Mn/ROAD project will be used to calibrate and validate the accuracy of the new model. Direct comparisons to the existing TCMODEL code will also be made.

The subtasks below will be performed if additional funding becomes available:

- Allow multiple (e.g. up to three) HMA layers.
- Develop interface with environmental integrated climatic model.
- Development and implementation of a library of cohesive zone models in NewTCMODEL; tailored for pavement fracture behavior.
- Implementation of temperature-dependent material properties in NewTCMODEL, i.e., consideration of distinct thermal coefficient variation upon heating and cooling. The numerical model will follow a non-linear implementation that accounts properly for the temperature dependency on material properties.
- Implementation of aging gradients in the viscoelastic bulk material in NewTCMODEL, i.e., the space-time properties of the HMA will be based upon a functionally graded material concept.
- Development of a professional user interface, online help files, examples, and a troubleshooting guide for the NewTCMODEL program.

Task 5 - Modeling of Asphalt Mixtures Contraction and Expansion Due to Thermal Cycling

One of the main findings of Phase I of the project was that asphalt mixture contraction and expansion follows different trends. The existing models for thermal cracking predictions over- simplify thermo-volumetric properties of asphalt mixtures. All published models, including those use in the MEPDG, considers a linear contraction and expansion behavior and a single coefficient value is used. In fact many models use a default value or uses a formula to estimate it form volumetric properties. The formula was introduced in the 1960s and is derived empirically based on testing a relatively small collection of mixtures. The only justification for this over-simplification is the difficulty in measuring the coefficient of contraction and expansion and the lack of sufficient knowledge about effects of various mixture variables on these coefficients. In this phase of the project a model for representing the contraction and expansion will be developed. The data collected in Phase I, as well as new data for mixtures to be tested in Phase II, will be used to simplify model and give average default values that can be used in predicting cracking. The data will first be used to study which material properties are statistically important for contraction and expansion. An estimation procedure for the following parameters will be developed to use materials properties used in mixture design such as binder grade or stiffness, aggregate gradation and angularity, and air voids.

- Coefficients of *contraction* above and below Tg. (α_{cl}, α_{cg}),
- Coefficients of *expansion a*bove and below Tg. (α_{el}, α_{eg}), and
- Glass transition temperatures during contraction (TGc) and during expansion (Tge)

It is not clear if all these estimated parameters are needed. The TCMODEL will be used to conduct a sensitivity analysis to determine which are statistically important in terms of effect on cracking of pavements.

The main objectives of this task are:

1. Expand the data base for thermo-volumetric properties of asphalt binders and mixtures to a wider range of modified asphalts and types of mixtures to fully quantify the effects of binders and aggregates in the asymmetrical thermo-volumetric behavior (glass transitions and coefficients).

2. Develop a micromechanics numerical model that can be used to estimate the glass transition temperatures and coefficients from mixture variables commonly measured for binder grading and for mixture design.

3. Conduct thermal cracking sensitivity analysis to determine which of the glass transition parameters (6 parameters) are statistically important for cracking, which ones need to be measured, and what is the effect of used estimated values rather than measured values.

This task will be coordinated with the WRI Asphalt Research Consortium (ARC) project. The ARC is currently involved in modifying the TG instrument to make it more user friendly. The ARC project is also looking at the effect of aging and effect of cooling rates. Although different mixtures are used, the concepts remain the same and the effect of aging and cooling/heating rates will be used to define what the critical factors for thermal cracking are and which material properties need to be used in modeling and in specification.

Task 6 – Validation of new specification

Based upon the outcomes of the testing of the preliminary validation experimental plan, the best test device and method of conditioning mixes for long-term aging will be selected for the final validation. The final validation will be based upon testing of the 11 Olmstead County, Minnesota mixes placed in the 2006 construction season. The testing will be at the low performance grade temperature as well as at

10ºC above the low temperature performance grade. The mixes will also be tested in triplicate at both 4 and 7 percent air voids. Based upon the outlined test parameters and the two air void contents for the 11 mixes, a total of 132 samples will be tested in the final validation component of this study.

The other test sections that will be used as part of the validation process in year 3 of the project are listed below. **The IDT will be performed only in this task** and IDT creep compliance data will be used to develop and validate new method to predict mixture creep compliance from Bending Beam Rheometer (BBR) binder creep compliance, as described in task 3.

Location	Construction Date	Description
Olmsted Co Rd 104	Jul-07	Reinke's Warm Mix (58-28 w/ RAP & antistrip)
Olmsted Co Rd 112	Aug-06	WRI-Mathy Study (Citgo, 58-28, 12.5 mm)
Olmsted Co Rd 112	Aug-06	WRI-Mathy Study (Citgo, 58-28, 19mm)
Olmsted Co Rd 112	Aug-06	WRI-Mathy Study (Marathon, 58-28, 12.5 mm)
Olmsted Co Rd 112	Aug-06	WRI-Mathy Study (Marathon, 58-28, 19mm)
Olmsted Co Rd 112	Aug-06	WRI-Mathy Study (MIF, 58-34 RAP, 12.5 mm)
Olmsted Co Rd 112	Aug-06	WRI-Mathy Study (MIF, 58-34 Virgin, 12.5 mm)
Olmsted Co Rd 112	Aug-06	WRI-Mathy Study (MIF, 58-34, 19mm RAP)
Olmsted Co Rd 112	Aug-06	WRI-Mathy Study (MIF, 58-34, 19mm virgin)
Olmsted Co Rd 112	Aug-06	WRI-Mathy Study (Valero, 58-28, 12.5 mm)
Olmsted Co Rd 112	Aug-06	WRI-Mathy Study (Valero, 58-28, 19mm)

Task 7 - Development of draft AASHTO standards and Final Report

A final report containing the updated reports from task 1 to 5 will be delivered at the end of this task. The report will also contain the following:

- Access database containing all the experimental results as well as additional information on the field samples and laboratory prepared specimens
- Proposed test protocols (experimental set up and data analysis) for selecting asphalt binders and mixtures with enhanced fracture resistance to low temperature thermal cracking
- Software and documentation describing a new fracture mechanics-based thermal cracking program (improved TCMODEL). Stand alone program and user manual will be provided.

Budget by Task
The following funds will be required to complete the tasks of this research effort:

Task 1………...$ 16,785
Task 2………..$116,785
Task 3………..$123,286
Task 4………..$ 81,786
Task 5………..$ 48,804
Task 6………..$ 63,804
Task 7………..$ 23,750
Total…………$475,000

University of Minnesota, with Dr. Marasteanu as the PI, will be the lead university and will administer the project. A fee of 10% of the total cost of the project will be charged to cover the expenses associated with the contract administration. The remaining funds will be allocated to the four participating universities as follows:

• University of Minnesota	$265,000
• University of Wisconsin at Madison	$ 85,000
• University of Illinois at Urbana Champaign	$ 85,000
• Iowa State University	$ 40,000

The funds for University of Minnesota include salaries for project PI Dr. Marasteanu and co-PI's Dr. Labuz, Dr. Stolarsky, and Dr. Mogilevskaia, graduate student support for 36 months, support for laboratory scientist as well as laboratory supplies and travel.

University of Wisconsin funds will be used to cover Dr. Fratta (PI for UW Madison work), Dr. Daranga, and Dr. Bahia salaries as well as laboratory supplies.

UIUC funds will be used to cover salaries for co-PI's Dr. Bill Buttlar and Dr. Glaucio Paulino as well as graduate student support and miscellaneous expenses. Note that UIUC team is working with the new NextTrans University Transportation Center to procure matching funds for the LTC, phase II study.

ISU funds include salary for Dr. Chris Williams, graduate student, travel and miscellaneous expenses.

A detailed distribution of funds per task and university is shown in the next table.

University	Task 1	Task 2	Task 3	Task 4	Task 5	Task 6	Task 7	Total
UMN	$16,785	$66,785	$83,286	$26,786	$18,804	$43,804	$8,750	$265,000
WISC		$30,000	$15,000		$30,000	$5,000	$5,000	$85,000
UIUC		$10,000	$10,000	$55,000		$5,000	$5,000	$85,000
ISU		$10,000	$15,000			$10,000	$5,000	$40,000
Total:	**$16,785**	**$116,785**	**$123,286**	**$81,786**	**$48,804**	**$63,804**	**$23,750**	**$475,000**

Timeline
The proposed project schedule is shown below. It is anticipated that the work will begin in late spring 2008 and that all tasks, will be completed within 40 months of the start date, including 4 months for final report review.

	Month												
	3	**6**	**9**	**12**	**15**	**18**	**21**	**24**	**27**	**30**	**33**	**36**	**40**
Task 1. Literature review	■	■											
Task 2. Testing		■	■	■	■	■	■						
Task 3. Specification				■	■	■	■	■	■				
Task 4. TC model					■	■	■	■	■	■	■		
Task 5. Contraction						■	■	■	■	■	■		
Task 6. Validation									■	■	■		
Task 7. Final report												■	■

Deliverables
Quarterly reports documenting the work progress will be delivered periodically to Mn/DOT. Task reports documenting the work performed in each task will be completed and delivered to Mn/DOT at the end of each task. At the end of the 36 months of project time a draft final report will be delivered to Mn/DOT as indicated under task 7.