Mn/DOT Contract No. 81655
Work Order No. 128
CFMS Contract No. A65644

WORK PLAN

Task 1: Literature review

The University will conduct a comprehensive literature review of previous and current research efforts in the area of low temperature performance of asphalt pavements at the beginning of the project. The University's review will include research performed in asphalt materials characterization, experimental results analysis and modeling, pavement system analysis and modeling and pavement performance related to low temperature behavior of asphalt pavements.

Deliverable(s): Literature Review – Summary Report

Duration: 4 Months

Task 2: Identify pavement sites and laboratory materials

The University will investigate two sets of materials in this study. The first set consists of materials that have been used in already built pavements for which performance information is well documented and readily available. The second set consists of laboratory prepared specimens following a statistically designed test matrix.

Field samples

The project research team would prefer that field samples as well as the original materials (loose mix and original binder) be available for these pavements as environmental factors can have a significant impact on thermal cracking. Table 1 outlines the matrix for selecting the field sites.

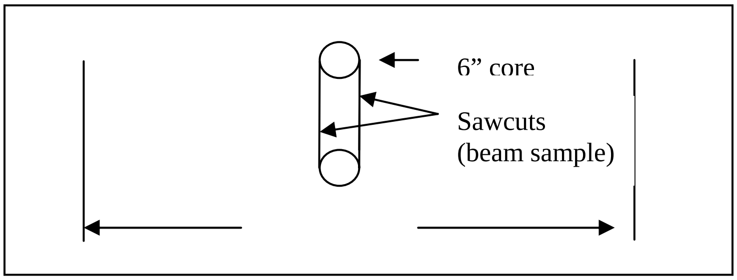
Table 1. Experimental Layout Linking Field Performance to Laboratory Performance

Pavement Performance	Field Sites (Field Samples)	Field Sites (Laboratory Samples)
Good	A, B	A, B
Poor	C, D	C, D

Each alphabetical letter represents a different pavement and it is desirable to select both newer and older pavements in each of the two categories, for example A is a newer good performer (less than 3 years) while B is an older (more than 7 years) good performer. The temperature history will be part of the selection process to avoid good performers associated with higher than normal field temperatures. The research team's initial thinking is that Long Term Pavement Performance (LTPP) sites with the range of performance described could be used. The corresponding materials would be obtained from the American Association of State and Highway Transportation Officials (AASHTO) Materials Reference Library (AMRL) in Reno, Nevada. The research team would match corresponding sites with sufficient materials in the AMRL. However, the main thrust will be to obtain field samples from selected sections identified as appropriate by the participating states. This includes test sections at MnRoad. Additional information, such as construction information, pavement layers information including base and subbase, crack spacing (and crack width if available) and historical temperature data should be readily available for the selected sites. Asphalt overlays will not be considered in this study to eliminate the effect of reflective cracking.

For the field samples both cores and beams should be obtained, wherever possible. It is suggested that sampling should be performed between the wheel paths as shown in Figure 1. This method has the advantage of allowing beam samples to be taken such that the axis and direction of fracture in the lab, using the single edge notched beam (SENB) geometry, matches the field (assuming a top-down crack). Part of the cylindrical cores will be used to cut semicircular bend (SCB) test specimens at various depths from the surface that would allow performing a limited analysis of aging effect with pavement depth. This will be combined with a comprehensive extraction and recovery process on multiple, thin slices of pavement at various depths to evaluate binder aging effects with pavement depth.

Figure 1. Field sampling between the wheel path



Mn/DOT, with help from the participating states and the core project research team, will be responsible for this subtask. The coring, shipping and delivery of the pavement information will be the responsibility of the participant state where the pavement site is located.

Laboratory specimens

The second set of materials consists of laboratory prepared specimens that follow a statistically designed matrix. Field samples provide the critical link between lab experiments and field performance; however, the number of factors that can be evaluated is often limited, unless the field sites were built according to a statistical design. Laboratory conditions provide a better control of the factors that affect material properties and offer the advantage of a statistical design that can identify the significant factors of interest.

Table 2 summarizes the test matrix for the laboratory prepared specimens. The matrix contains a combination of binder and mixture factors. The low temperature performance of asphalt materials is dictated by a multitude of factors. The main focus of this task is to quantify the effects of the factors considered to be the most significant based on empirical evidence accumulated over the years: binder type, film thickness, air voids and differential contraction between the aggregate particles and the binder.

Ten different asphalt binders, both plain and modified, that cover five different performance grades were selected for this study. Two more Performance Grade (PG) grades, a 64-22 and a 70-22 will be included in the test matrix if additional funding becomes available (marked with Z in the table). One 12.5-mm Superpave mix design will be used to prepare the specimens. Two levels of air voids will be used: the design value of 4% and 7% representing typical as-constructed values. Although previous work indicated that higher air voids translates into lower fracture resistance, it is important to quantify this difference for further improvements in construction practice and performance prediction modeling. Two levels of asphalt content will be used, the design value and the value resulting from a recently proposed film thickness approach (Iowa, Minnesota, French richness coefficient). Although it is expected that a richer mixture will most likely be more crack resistant, no well-documented data to support this statement is currently available. The mixtures will be prepared using two different types of aggregates such as limestone (coefficient of thermal expansion contraction of approximately 3.8×10^{-6}) and sandstone (coefficient of thermal expansion contraction of approximately 6.5×10^{-6}) to investigate the effect of the differential contraction between the asphalt binder and the aggregate. In addition, other relevant information about the two aggregates used, such as porosity and surface area, will be acquired and stored for a more in-depth analysis of the asphalt aggregate interaction if additional funding will allow this type of analysis to be performed in the future.

Table 2. Laboratory Experimental Layout with Mixture/Binder Test Variables

Air Voids		Design (4%)				As constructed (7%)			
Aggregate Type		Aggregate 1		Aggregate 2		Aggregate 1		Aggregate 2	
Binder Content[1]		Design	Film thickness	Design	Film thickness	Design	Film thickness	Design	Film thickness
Binder Type (modification)	PG58-40 modifier 1	X	X	X	Z				
	PG58-40 modifier 2	X		X					
	PG58-34 modifier 1	X	X	X	Z				
	PG58-34 modifier 2	X		X					
	PG58-28 plain 1	X	X	X	X	X	X	X	X
	PG58-28 plain 2	X		X					
	PG64-34 modifier 1	X	Z	X	Z	Z	Z	Z	Z
	PG64-34 modifier 2	X		X					
	PG64-28 plain 1	X	Z	X	Z				
	PG64-28 modifier 1	X	Z	X	Z				
	PG64-22 plain	Z	Z	Z					
	PG70-22 modified	Z	Z	Z					

[1] The variation of binder content from the design optimum could be optimum "0.5%.

An X in Table 2 represents the proposed experimental plan with the current funds available, which includes 28 different mixtures to be tested. If more funds become available and dependent upon the initial research findings, the research team's initial thinking is to expand the proposed experimental plan as indicated with Z's (included as task 3b in the budget). This will add 18 more mixtures to the initial set of 28 mixtures bringing the total to 46 laboratory prepared mixtures. It should be noted that each experimental cell would consist of triplicate tests for an appropriate set of statistical analyses.

The project research team acknowledges that the aggregate gradation plays an important role in the fracture properties of asphalt mixtures. However, taking into consideration that changing the aggregate gradation changes some of the factors used in the statistical design, such as air voids and film thickness, it was decided to keep this important factor constant. If additional funds become available the test matrix will be extended to include different aggregate gradations for two of the most promising binders selected based on the present analysis. This additional work is included as task 3c in the final budget. The dollar amount requested for this additional task also includes testing and data analysis for two "specialty" mixtures such as Stone Matrix Asphalt (SMA) and Open Graded Friction Course (OGFC).

Deliverable(s): Description of Field Sites, Field Specimens and Laboratory Materials Used in the Analysis – Summary Report

Duration: 4 Months

Task 3: Laboratory specimen preparation and experimental testing

The University will perform both current-testing protocols (such as creep and strength for both asphalt binders and mixtures and Dynamic Shear Rheometer (DSR) for asphalt binders and newly developed testing protocols, such as hollow cylinder test, SENB test, SCB test) on a common set of asphalt binders and mixtures. This approach will allow determining the best testing protocol and data analysis for selecting the most fracture resistant asphalt materials. It also allows bringing together the asphalt binder and asphalt mixture specifications.

In order to minimize the effect of specimen preparation on the test results, all gyratory compacted specimens will be prepared at the Michigan Technological University (MTU) facility. For the beam specimens, MTU will prepare the specimens required for the Thermal Stress Restrained Specimen Test (TSRST) and University of Illinois at Urban Champaign (UIUC) will prepare the specimens for the SENB test. MTU will also extract and recover the binders from the field mixture samples investigated. The University of Wisconsin will perform the aging of the 10 binders used in the test matrix shown in table 2. The polymer-modified binders will be Rolling Thin Film Oven Test (RTFOT) aged using a modified RTFOT procedure developed under NCHRP 9-10 project. The test methods used to evaluate mechanical and physical properties of the asphalt binders and mixtures are summarized in Table 3.

The laboratory tests will be conducted on the field collected samples and the specimens prepared in the lab as described in Tables 1 and 2. It is suggested that for the fracture, creep, and strength the PG –40 and –34 binders and mixtures tests will be performed at –36, -30, and -24ºC and for the PG –28 and -22 binders and mixtures at –30, -24, and -18ºC. For the TSRST different cooling rates that simulate real field thermal conditions will be used. The fracture tests and TSRST on asphalt mixtures performed at the University of Minnesota will be monitored using acoustic emission (AE) techniques to investigate the crack propagation mechanism at micro structural level. University of Wisconsin will be responsible with determining, using dilatometric methods, the coefficient of thermal expansion /contraction for the asphalt mixtures and binders investigated that represents a critical parameter in the development of thermal stresses in asphalt materials.

Table 3. Experimental Layout for Laboratory Tests with Linkage to Field Performance

		MTU	UIUC	UMN	WISC
Laboratory Test	Mixture Indirect Tension Creep and Strength	X			
	Mixture Hollow Cylinder Creep and Strength		X		
	Mixture Fracture Test SENB		X		
	Mixture Fracture Test SCB			X	
	Mixture Thermal Stress Test TSRST	X		X*	
	Binder Low Temperature DSR, BBR and DTT			X	X
	Binder Fracture Test SENB			X	
	Mixture and Binder Dilatometric Measurements				X

* instrumented with acoustic emission

Over one thousand mixture tests will be performed part of this task taking into consideration that tests are performed at multiple temperatures and in replicate specimens. Over five hundred asphalt binder tests will be also performed as part of this task.

Deliverable(s): Description of the Laboratory Procedures Used in the Experimental Investigation and of the Raw Data – Summary Report (Includes Test Results Data Base) – Task Summary Report

Duration: 14 Months

Task 4: Analysis of experimental results

All experimental results from testing field samples and laboratory specimens will be incorporated into an Access database that will be delivered at the end of the project as part of the final report. The database will also include any relevant information about the material tested, such as construction information, pavement system information (layer thickness, granular materials and soil information, etc) and environmental information for the field samples, as well as volumetric, sample preparation and aging and any other relevant information for the laboratory prepared specimens. The University and MTU will be primarily responsible for developing the database.

The analysis of the test results will involve all four universities. The analysis will focus on finding the most promising experimental parameters for selecting the most crack resistant materials and for correctly analyzing the crack propagation mechanism in the pavement system and predicting performance. The comprehensive test matrix detailed in Table 2 will allow investigating the effect of the test method on material parameters, such as the fracture toughness obtained in the SENB and SCB configurations. It will also allow developing useful correlations between the different material parameters obtained from the different test methods include in the test matrix. For example correlations between the rheological and the fracture properties of asphalt materials will be investigated. Particular emphasis will be placed on the role of temperature on the mechanical properties of asphalt materials. An important priority will be given to investigating the contribution of each of the asphalt mixture components and their interactions to the fracture resistance of the mixture, with emphasis on the role played by the asphalt binder and the binder-aggregate interaction.

A series of statistical analyses will be done consistent with the developed experimental plan. The analyses will include means tests, such as Student-Newman Keuls and Duncan's Multiple Range Test, to examine the effects of the independent experimental variables on thermal cracking for the various performance tests. The analyses will also provide a relative ranking of importance of the independent variables on thermal cracking potential. Additional statistical methods such as Ridge Regression will also be considered as appropriate.

It is expected that this task will result in testing protocols that will improve the current selection process of asphalt binders and mixtures with enhanced low temperature cracking resistance. They will also provide better temperature dependent material parameters that will be incorporated in the analysis tools developed in Task 5 to reasonably predict the field performance of asphalt pavements exposed to low temperatures.

Deliverable(s): Analysis of Test Results – Summary Report

Duration: 14 Months

Task 5: Modeling

In developing a rigorous understanding of thermal cracking mechanisms, an integrated study involving bench-scale laboratory fracture testing and full-scale experiments and field sections is essential. Fracture modeling is a critical element to this approach, as it provides two critical "links," namely: 1) the ability to properly interpret bench-scale laboratory test results (to obtain fundamental material properties/minimize size effects), and; 2) the ability to accurately extend fracture models to full scale, in order to develop an accurate and complete description of thermal cracking mechanisms.

A key component of this study will involve the reexamination of the mechanisms of thermal cracking by applying modern computational fracture mechanics models. As a short summary, discrete fracture and damage tools will be utilized to model crack initiation and propagation in pavement systems using the finite element method code I-FRANC2D (Illinois Fracture Analysis Code in Two Dimensions). The project research team will also utilize cohesive fracture models and damage models in specially designed subroutines developed for the commercially available finite element code ABAQUS. These models can predict crack nucleation, initiation and propagation in 2D or 3D and have been applied recently to examine mixed-mode crack propagation (tension and shear), which would obviously be present if traffic loads were to combine with thermal loads to create a critical condition. This work will also include refining a simple model recently developed at the University to predict the crack spacing and the lateral movement of the crack using 2D (or 3D if necessary) viscoelastic analysis based on the cohesive-frictional characteristics of the subgrade, the constitutive properties of the asphalt mixture and the thermal history of pavement system.

Once the mechanisms of thermal cracking are better understood, the researchers will be in a much better position to determine the best approach for recalibration and/or modifying the existing TCMODEL program in the 2002 Design Guide and to recommend appropriate testing protocols to support this approach.

One area where considerable emphasis will be placed is in the evaluation of the current crack propagation model in TCMODEL. While thermal fatigue cracking might be a contributor to pavement deterioration in some areas, the control of single event thermal cracking must remain a top priority due to its devastating effect on pavements in cold climates. Furthermore, the control of single-event thermal cracking in many cases should provide an inherent factor of safety against thermal fatigue cracking.

It is anticipated that the new analysis tools proposed herein will allow researchers to:
- Apply a true fracture propagation model in the study of thermal cracking mechanisms
- Improve response modeling to include 3-D effects (current model is 1D)
- Utilize data from low-temperature fracture tests
- Allow consideration of multiple AC layers, and material property gradients within layers (both temperature and aging related should be considered)
- Combine thermal and mechanical loads (thermo-mechanical analysis)
- Integrate testing and modeling program

Deliverable(s): Modeling – Summary Report

Duration: 18 Months

Task 6: Draft Final Report

The University will deliver a draft final report detailing the work performed in the previous five tasks at the end of this task. The University will prepare the draft final report following the Mn/DOT publication guidelines documenting the project activities, findings and recommendations. The University will submit the draft final report through the publication process for technical and editorial review. 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).

Deliverable(s): Draft Final Report

Duration: 4 Months

Task 7: Final Report Completion

The University will incorporate the technical and editorial comments from the review process into the final report as appropriate. The University will consult the reviewers for clarification or discussion of comments. The University will prepare and submit the revised, final, report for publication.

Deliverable(s): Final Report

Duration: 4 Months

PROJECT SCHEDULE

MONTHS

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Task 1	X	X	X	X										
Task 2	X	X	X	X										
Task 3			X	X	X	X	X	X	X	X	X	X	X	X
Task 4					X	X	X	X	X	X	X	X	X	X
Task 5					X	X	X	X	X	X	X	X	X	X
Task 6														
Task 7														

	15	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**
Task 1														
Task 2														
Task 3	X	X												
Task 4	X	X	X	X										
Task 5	X	X	X	X	X	X	X	X						
Task 6							X	X	X	X				
Task 7											X	X	X	X

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