7. Low temperature cracking in HMA

Pavement Cracking – Al-Qadi, Scarpas & Loizos (eds)
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Integration of laboratory testing, field performance data and numerical simulations for the study of low-temperature cracking

E.V. Dave, A.F. Braham, W.G. Buttlar & G.H. Paulino
University of Illinois at Urbana-Champaign, USA

A. Zofka
University of Connecticut, Storrs, Connecticut, USA

ABSTRACT: Low temperature cracking remains one of the major pavement distresses in asphalt concrete pavements in cold regions. An integrated laboratory testing, field performance data, and numerical simulation approach was used to study thermal cracking as part of a US National Pooled Fund Study on Low-Temperature Cracking. This paper focuses on testing, analysis, and field data from five controlled test sections at the Minnesota Road Research Program facility (MnROAD).

Low temperature viscoelastic relaxation modulus master curves and tensile strength were obtained from indirect tension testing conducted at three temperatures. Fracture energy of field samples were obtained using the disc-shaped compact tension (DC[T]) test. Temperature-dependent thermal coefficient data was collected by one of the research partners (the University of Wisconsin) for each of the five field mixtures.

A bi-linear cohesive zone model was used in the simulation of thermal cracking in five MnROAD pavement sections. Four custom-designed user subroutines were employed in the commercial finite element program ABAQUS, including: a bi-linear cohesive zone fracture model, a temperature shift factor routine, a time- and depth-dependent temperature profile algorithm, and a bi-linear thermal coefficient routine. The temperature boundary conditions were generated using the Enhanced Integrated Climatic Model (EICM) available in the AASHTO Mechanistic-Empirical Pavement Design Guide (MEPDG) using air temperatures obtained from National Weather Service databases. Detailed field performance crack maps were used to compare actual field cracking against numerical simulation results. This paper describes how this comprehensive, integrated testing and modeling program provided new insights towards the mechanisms of thermal cracking in asphalt pavements.

1 INTRODUCTION

The low temperature cracking of asphalt concrete pavements is a major pavement distress mechanism in cold regions costing millions of dollars in rehabilitation costs to various agencies. The Strategic Highway Research Program (SHRP) conducted during mid-1990s led to development of thermal cracking prediction software TCModel (Roque et al. [1995]). In recent years sophisticated laboratory tests such as disk-shaped compact tension test (DC[T]) and single edge notch beam (SE[B]) developed by Wagoner et al. [2005a, 2005b] and semi-circular bend test (SC[B]) explored by Molenaar et al. [2002], Li et al. [2006], and Artamendi et al. [2007], have been developed with capability for rigorous fracture characterization of asphalt mixtures. Powerful fracture modeling tools, such as the cohesive zone fracture approach, have increased analysis capabilities through energy based formulations which accurately capture softening (damage) and fracture in quasi-brittle materials such as asphalt concrete. The present study illustrates the integration of recently developed laboratory techniques with computer simulation models utilizing cutting-edge fracture modeling capabilities for the prediction of thermal cracking in asphalt concrete pavements. This work was conducted as part of US National Pooled Fund Study on Low-Temperature Cracking.

2 INTEGRATED APPROACH

This paper describes a highly integrated laboratory testing and computer simulation approach that was employed in studying thermal cracking which developed at several pavement sections at the Minnesota Road Research facility (MnROAD). Laboratory bulk and fracture characterization of asphalt concrete specimens fabricated from field samples was performed, including:

- Creep compliance/relaxation modulus master-curve using the 1000 second Indirect Tension Test configuration (AASHTO T-332) and time-temperature superposition at three temperatures
- Fracture energy from the Single-Edge Notch Beam, the Semi-Circular Bend, and the Disk-Shaped Compact (ASTM D7313-06) fracture tests
- Tensile strength from indirect tension testing (AASHTO T-332)
- Coefficient of thermal expansion

Multiple properties are required in order to accurately simulate pavement responses and distress development, such as thermal cracking. At the same time, practical considerations of pavement sampling and laboratory testing expense and rigor must be considered in the development of a useful testing and modeling system. A detailed analysis of these tests is beyond the scope of this paper, but can be found in the final project report (Marasteanu et al. [2007]). This work will outline the overall conclusions and findings from the report.

Pavement simulation models were generated using properties obtained from these tests, along with published information on the thickness and mechanical properties of underlying granular and subgrade materials. The temperature boundary conditions for simulation models were generated using the enhanced integrated climatic model, which utilizes climatic information such as air temperature, percent sunshine, latitude, elevation, etc. Additional details concerning laboratory tests and simulation modeling performed are provided in a later section.

The Pooled Fund low temperature cracking study involved the investigation of twelve existing pavement sections, some from the sponsor state, Minnesota (featuring a number of MnROAD) sections, along with sections from other participating states. In this paper, five of the pavement sections from that study are presented to illustrate the integrated testing and simulation approach. Five MnROAD test cells are studied in this paper; namely sections 03, 19, 33, 34, and 35. The pavement layer types (asphalt binder grades, granular base types) and thicknesses for these sections are as illustrated in Figure 2.1.

In order to capture a wide range of properties, three testing temperatures were chosen to encompass the transition from brittle-ductile behavior to brittle behavior. The three temperatures were each 12°C apart, with the middle testing temperature 10°C higher than the low-temperature PG binder grade. This also ensured that asphalt binder and mixture properties were available at one common temperature. Table 2.1 shows the testing temperature used for each mixture. Figure 2.2 presents the creep compliance master curves obtained. There is little difference between Cells 03, 19, 34, and 35, especially at shorter times (also the lower temperatures). Cell 33 appears to have significantly higher compliance at longer loading times, suggesting a more relaxant mixture. This is rather unexpected as it does not have the softest binder (Cell 35 has the softest binder). However, the binder stiffness could be negated based on the testing temperatures relating to the asphalt binder grade.

In addition to creep compliance in the Indirect Tension Test setup, the tensile strength was measured for all five mixtures. Figure 2.3 shows the results of the tensile strength testing. For low temperature testing, it is not uncommon to observe a maximum tensile strength at the intermediate testing temperature selected. This is because although tensile strength in hot-mix asphalt generally increases as temperature is lowered, eventually a point is reached where the brittleness of the binder evidently reduces the tensile strength of the overall composite, possibly aided by the relatively fast testing rate used in the IDT (a loading head velocity of 12.5 mm/minute is used).

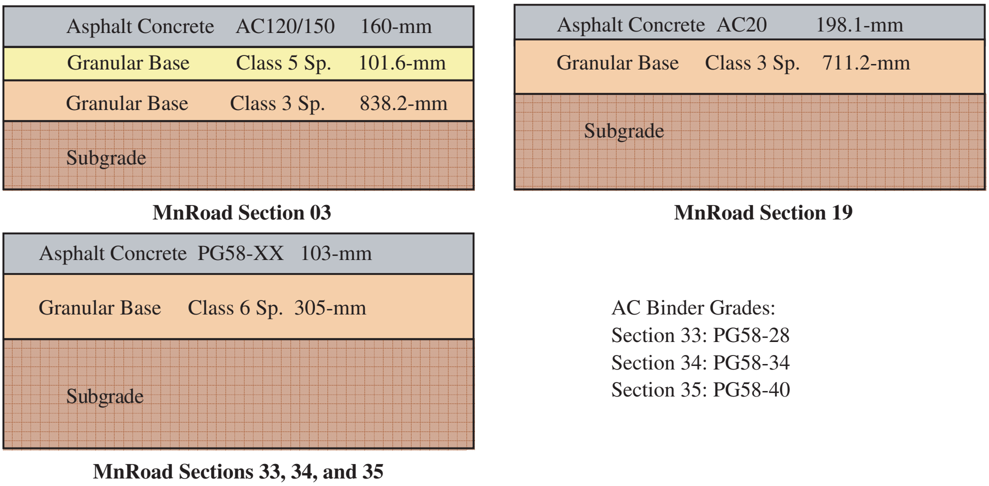


Figure 2.1. Pavement sections studied in this paper.

Table 2.1. Testing temperatures for five mixtures.

		Testing temperatures (°C)		
	PG binder grade	High	Mid	Low
MnROAD 03	PG58-28 (120/150)	−6	−18	−30
MnROAD 19	PG58-34 (AC-20)	−12	−24	−36
MnROAD 33	PG58-28	−6	−18	−30
MnROAD 34	PG58-34	−12	−24	−36
MnROAD 35	PG58-40	−18	−30	−42

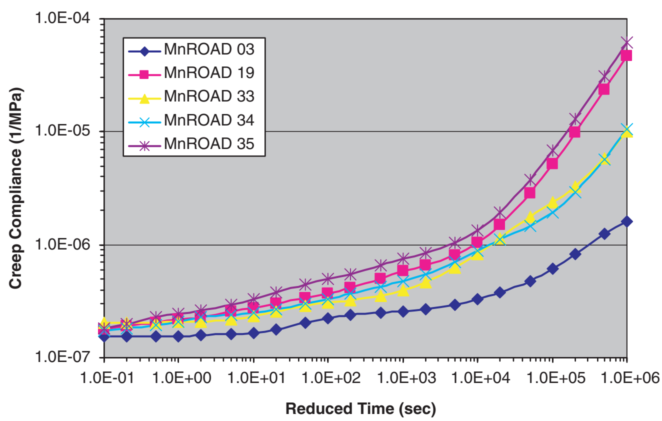


Figure 2.2. Creep compliance mastercurves at reference temperature of −30°C.

Finally, the fracture energy was measured for all five mixtures using the Semi-Circular Bend (SC[B]), the Disk-Shaped Compact Tension (DC[T]), and the Single-Edge Notch Beam (SE[B]). Figures 2.4 show the results at the three testing temperatures selected.

The tests are dissimilar, possess different configurations, and exhibit size effects, which are beyond the scope of this work. While the tests provided similar rankings between mixtures, there

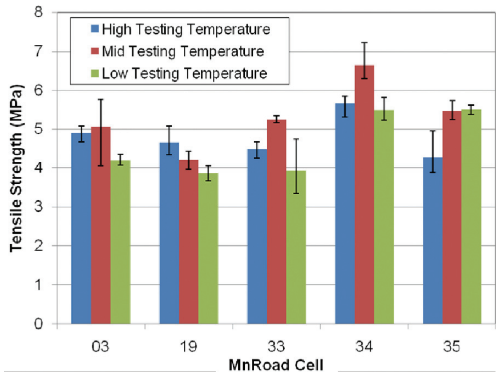
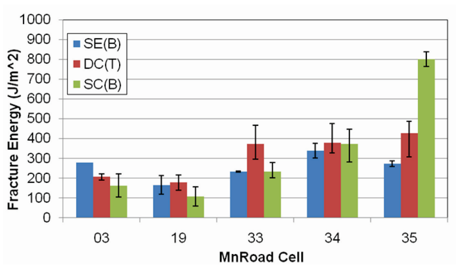
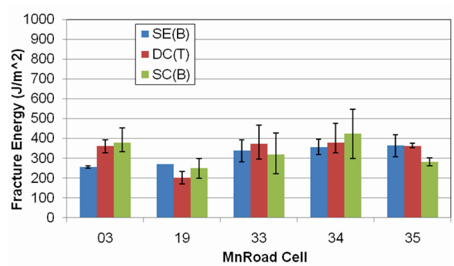


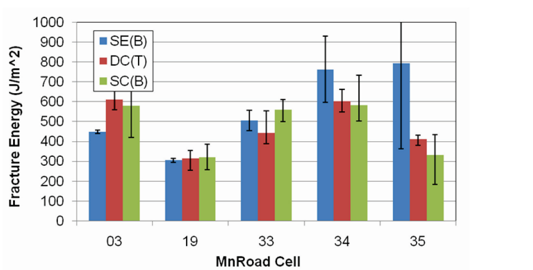
Figure 2.3. Tensile strength summary.



(a) Low Testing Temperatures



(b) Mid Testing Temperature



(c) High Testing Temperature

Figure 2.4. Fracture energy results.

were some differences in fracture energy values between the three tests. Given different test geometries used, the different modes of failure, and the different loading rates for each test, the differences were not unexpected. A detailed investigation of these differences can be found in Li et al., 2008. For the numerical simulations presented hereafter, the fracture energy from the DC[T] was used.

3 PAVEMENT SIMULATION MODEL

Numerical simulations were performed using the finite-element (FE) analysis technique with the aid of the commercially available software program ABAQUS. The program was customized by developing and implementing several user-subroutine codes to enable fracture tools to be employed in the simulation of low temperature pavement cracking. The following section is divided into subsections describing various aspects of the simulation model.

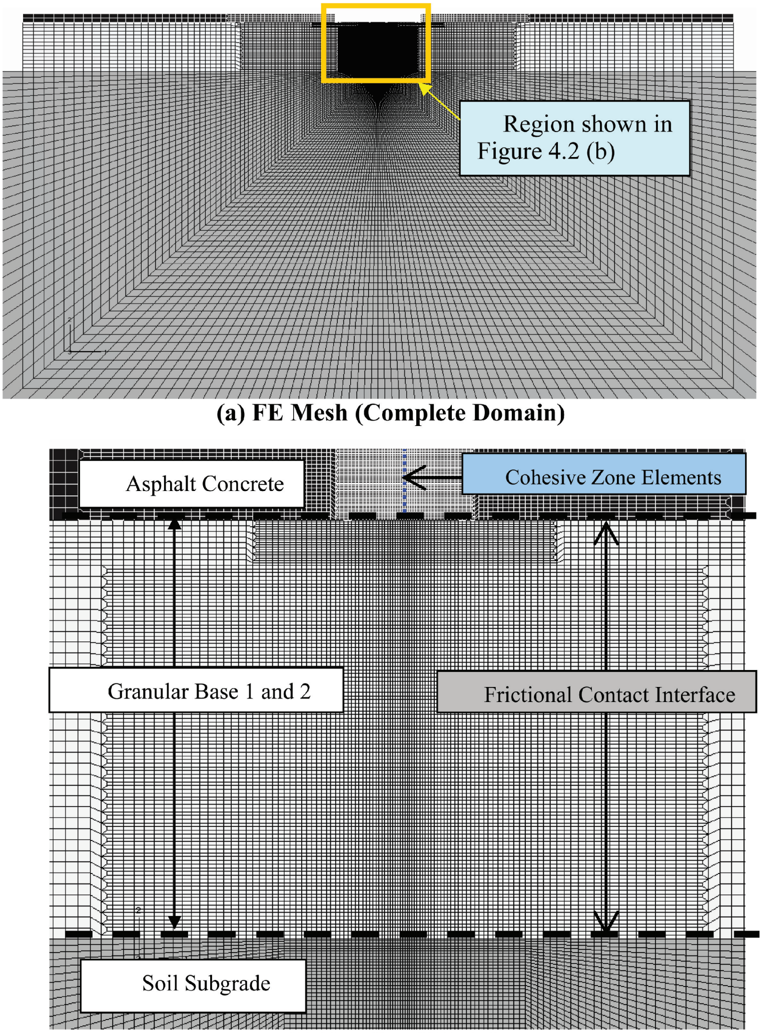


Figure 3.1. Finite element pavement model.

3.1 *Finite element model domain and boundaries*

The simulations in this study were performed by simplifying the pavement sections under investigation into two-dimensional FE models created along a slice taken in the longitudinal direction (direction of traffic movement). Model boundaries were selected on the basis of previous work by Dave et al. [2007], to ensure that sufficient domain extent was provided to avoid end effects. The FE model was generated using a domain length of 12192-mm (40-ft). The subgrade thickness was selected as 6096-mm (20-ft), beyond which the subgrade was modeled as a semi-infinite boundary by use of special infinite elements to create an infinite half space. Figure 3.1(a) shows a typical mesh used in this study. The FE models for low-temperature cracking simulations were constructed using graded meshes, which are used to significantly reduce the computational requirements. Graded meshes typically have a finer element size close to the areas of high stress variations and potential non-linearity, whereas in the regions of low stress gradients, larger elements are used.

Figure 3.1(b) shows an area in the vicinity of potential crack path. Details of the region where cohesive zone fracture elements are embedded into the mesh to allow for cracking are provided. The mesh in close vicinity to a potential thermal cracking region is constructed with smaller elements ($\sim$2 mm). Also notice that frictional interfaces between various pavement layers are provided, as indicated in this figure. Multiple, interacting cracks, although possible to simulate with this approach, are not presented herein for brevity. Due to two-dimensional simulation schemes, each crack represents a transverse crack through the width of pavement. The interface between asphalt concrete and granular base and granular base and soil subgrade is especially important because of the potential for relative movement between these layers. In the current project these interfaces were modeled using a small-sliding frictional interface model available in ABAQUS. This model allows for a frictional sliding of the asphalt concrete due to thermal expansion/contraction.

3.2 *Bulk material constitutive models*

An appropriate bulk material constitutive model is crucial to the accurate simulation of material behavior in the FE modeling technique. Asphalt concrete material is known to have time and temperature dependent behavior across most of the in-service temperature range. Creep tests on asphalt concrete materials have shown linear viscoelastic behavior at low and moderate temperatures. For the numerical simulations, asphalt concrete was modeled using the generalized Maxwell model. The model parameters were determined using the creep compliance data presented in the laboratory testing section. To capture temperature dependent asphalt concrete properties, a customized user-subroutine in ABAQUS was developed using the time-temperature superposition principle. The thermal coefficient of asphalt concrete material was modeled by means of a user subroutine in the form of a nonlinear relationship on the basis of experimental findings. More details on the experimental study of coefficient of thermal expansion are described in the final report of the LTC project [2007]. Granular bases and subgrade materials were modeled using a linear elastic material model. Typical values for elastic modulus and Poisson's ratio of granular base and subgrade were determined based on the information obtained from section profiles and details available through reports published by the Minnesota Road Research Program [2000]. In the case of field section simulations, the use of an elastic model for the granular base and subgrade was deemed adequate due to the relatively low stress levels in the base and subgrade layers, and the relative predominance of thermal stresses relative to traffic induced stresses for the thermal cracking problem.

3.3 *Intrinsic cohesive zone fracture model: bi-linear shape*

For simulation of crack initiation and propagation, a cohesive zone model was selected because of its accuracy and efficiency in accounting for material response ahead of the crack tip in the nonlinear fracture process zone (region of micro-cracking, crack pining, branching, material softening, etc.). Wagoner et al. [2006a, 2006b], Li et al. [2006] and other researchers conducting fracture tests of asphalt concrete at low temperatures recognized the influence of the fracture process zone. Among others, Soares et al. [2004], de Souza et al. [2004], Song et al. [2006], Baek and Al-Qadi [2006], and Dave et al. [2007] have applied the cohesive zone model to simulate cracking in asphalt concrete.

The cohesive zone approach readily utilizes experimentally determined fracture energy. In the cohesive fracture approach, the material begins to incur damage (softening) once the stresses exceed the limit stress of material, which in this case is assumed to be the tensile strength. Beyond this peak, the material undergoes a stage of softening (damage) whereby its capacity to transfer load across the potential crack continuously decreases. Once the material dissipates the energy equivalent to its fracture energy, a macro-crack is developed. The region between the point of damage initiation and point of complete failure is often called the fracture process zone. Figure 3.2(a) illustrates the process zone, modeled herein as the region between the cohesive crack tip (where the traction is at a maximum and equivalent to material's tensile strength, (σ_t) and the material crack tip (where the traction is zero). Figure 3.2(b) shows a schematic illustration of the fracture process zone or cohesive zone (hashed region) with traction forces along the potential crack faces illustrated by a series of arrows.

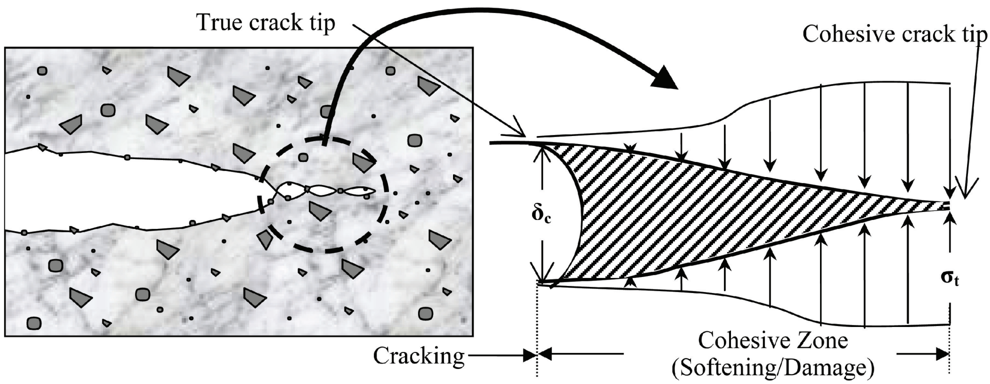


Figure 3.2. Schematic showing of fracture behavior near crack tip and the fracture process zone.

A bilinear model implementation developed by Song et al. [2006] is used in this study. This model allows for minimizing artificially-induced compliance by adjusting the initial slope of the cohesive law. The material parameters used in the cohesive fracture model are: material strength (σ_t) and fracture energy (G_f). These properties for each of the mixtures studied in this project were measured through laboratory testing and are described in the previous section. The bi-linear cohesive zone model was implemented in the commercial finite-element software ABAQUS in the form of a user subroutine.

3.4 *Loading conditions*

Pavements undergo relatively complicated loading conditions during the course of their service life. Two major load categories imposed on pavements during its course of service include temperature and tire loads. Thermal loads on the pavement structure are transient and depend on factors including air temperature, sunshine, precipitation, etc. The thermal loads for various pavement sections were evaluated using the Enhanced Integrated Climatic Model (EICM) originally proposed by Larson and Dempsey et al. [1999]. The EICM was used to generate the pavement temperature profiles as functions of depth and time. The temperature loads were applied to the model in terms of transient temperature values for each node in the mesh. A user-subroutine was developed to automatically evaluate the nodal temperatures values based on the node location and time in the simulation. A limited number of two-dimensional (2D) simulations were performed with tire loads simultaneously applied to the pavement. It is acknowledged that 2D simulation cannot accurately represent the tire load because of the lack of discretization across the width of the pavement. In the current set of simulations a single 40-KN (9-kip) tire load was modeled in the form of a uniformly loaded strip across the pavement width to evaluate relative trends in thermo mechanical response between test sections.

3.5 *Critical conditions approach*

By analyzing ambient and pavement temperature profiles throughout the lives of the test sections, the coolest pavement temperatures reached were identified. This approach represents a *critical condition*. In certain simulation cases, additional critical conditions were identified where the highest rates of pavement cooling occurred (in combination with very low temperatures, but perhaps not the coldest absolute temperature reached). The rationale for examining selected critical conditions revolving around low temperature events was as a result of following considerations:

- In general, experimental fracture energies dropped significantly at low temperatures
- The ability of the asphalt concrete to relax stress is greatly reduced at low temperatures
- Most cracking in the field sections was measured to have occurred over the winter months

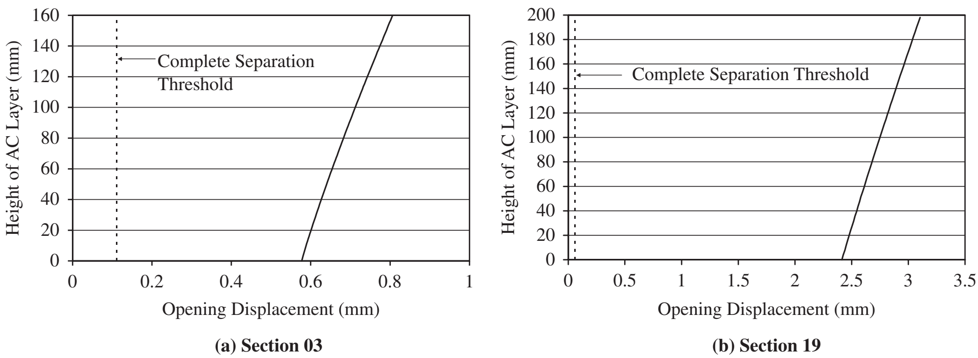


Figure 4.1. Opening displacement plots showing thermal cracking in sections 03 and 19 due to single event cooling.

- The critical conditions approach leads to the most practical simulation times and computational costs when using the FE technique, where model non-linearities (frictional contact interface) and time-dependent material properties are employed. Both of these necessitate an iterative type numerical solution scheme (solver) to be used. Typical simulation times ranged from 1 to 3-hours (not including pre- and post-processing and extracting results) on a workstation PC.

4 SIMULATON RESULTS

The MnROAD sections 03 and 19 are within the high volume traffic sections of MnROAD, located on the mainline of Interstate 94 near St. Cloud, MN and constructed in September 1992 and July 1993 respectively. Sections 33, 34 and 35 are within the low traffic volume test loop, and were constructed in August 1999. Sections 03 and 19 experienced a critical cooling event during 1st–2nd February, 1996. During this event the air temperature cooled to −39.7°C. The pavement surface temperature was predicted to reach a minimum of −33.8°C. The simulation results for thermal loading of sections 03 and 19 are presented in the form of cohesive zone displacement plots, as shown in Figure 4.1. The plot shows the opening displacement for the cohesive elements through the thickness of asphalt concrete layer. The simulation results are plotted with a solid line. The dashed line shows the displacement threshold which can be viewed as the onset of macro cracking. The plots show that for both section 03 and 19 the cohesive displacements are greater than the threshold, indicating that cracking occurred in the pavement due to thermal loading during the aforementioned cooling event. Thus, the FE-based thermal cracking model predicted cracking which occurred during this critical event at MnROAD. Explicit consideration for crack spacing was not pursued with the FE model in the current study. Furthermore, closed form solutions for thermal crack spacing, which were developed in earlier stages of the LTC project, would suggest that a close crack spacing would result from this degree of 'overstress' (Yin et al., [2007]).

For sections 33, 34, and 35 the critical coolest event occurred during 30th–31st of January, 2004. During the coolest event, the lowest air temperature reached −31.1°C. The pavement surface temperature was predicted to reach a minimum of −26.2°C. The simulations for this set of sections were performed for thermal loading as well as combined thermo-mechanical loading. For these simulations, a single 40-kN tire load was applied at the coolest pavement surface temperature to study relative thermo-mechanical responses. Sections 33, 34, and 35 showed very limited pavement damage under thermal loading. Under combined thermo-mechanical loading, the sections underwent significant softening (damage). Table 4.1 summarizes the simulation results for sections 33, 34, and 35. For example, under thermo-mechanical loading the simulations for section 33 predicted that a region extending 54-mm from the bottom of the layer (about half of the 103-mm thickness) would be damaged (softened). Interestingly, the section with the softest binder (section 35, with PG

Table 4.1. Extent of softening in sections 33, 34, and 35 under thermo-mechanical loading.

Section (Asphalt Grade)	Length of softened region (mm)
Section 33 (PG58-28)	54-mm from bottom
Section 34 (PG58-34)	24-mm from bottom
Section 35 (PG58-40)	63-mm from bottom

Table 5.1. Amount of cracking in selected MnROAD field sections.

Section	03	19	33	34	35
Observed Cracking (m/100 m)	36.4	109.4	18.2	1.2	149.4

58-40 binder) actually incurred the most cracking in the field. The pattern was that of short, transverse cracks, rather than traditional full-width, full-depth thermal cracks. The simulation model, which accounts for thermo-mechanical loading as well as creep and fracture material properties, did in fact predict the largest extent of bottom-up damage to occur in section 35, which had the largest pavement deflections.

5 DISCUSSION OF SIMULATION RESULTS AND FIELD PERFORMANCE

Table 5.1 shows the pavement cracking data for the five sections, based on field surveys performed in 2006. The data is presented in the form of amount of cracking per 100-m of pavement.

By comparing simulation results with amount of cracking observed in the field, the following observations can be made:

- Simulation results indicate that sections 03 and 19 are susceptible to low temperature thermal cracking during the coolest single event (24-hour) thermal cycle during the Winter of 1995-96. The field observations also indicated significant cracking in both sections.
- Simulations indicate that section 19 has higher thermal cracking potential compared to section 03. The higher thermal cracking potential of section 19 is attributed to an inferior asphalt binder grade for the mixture. Asphalt concrete fracture properties for section 19 are inferior to those of section 03, and the viscoelastic properties indicate that the mixture is less compliant. This prediction agreed with the field observations.
- Simulations of sections 33, 34 and 35 show very limited potential for thermal cracking under the critical cooling event that occurred during the Winter of 2003–04.
- Thermo-mechanical simulations for sections 33, 34 and 35 during the coolest event show that section 35 has the highest amount of potential for damage (softening), followed by section 33, and then section 34. This ranking follows the same order as the cracking observed in the field.
- The prediction of higher extent of softening in section 35 is due to highly compliant asphalt mixture (PG58-40), which causes excessive deformation under the tire load. At the same time, the fracture properties for this mixture are very similar to that of the section 33 (PG58-28) mixture.

6 SUMMARY

The integrated laboratory testing and computer simulation method presented in this paper was utilized in the investigation of low-temperature cracking in five test sections at MnROAD. In general, the simulation results were found to be in good agreement with field observations. This study demonstrates the importance of integrating both laboratory testing and numerical simulations when investigating a pavement distress mechanism such as low-temperature thermal cracking. The framework of the techniques presented herein has been recommended for phase II of the LTC pooled fund study, and for related airport reflective cracking studies. Planned model extensions include crack spacing prediction, three-dimensional modeling, and comprehensive model validation. The LTC data base will also provide a good opportunity to re-evaluate binder specifications and binder-to-mixture property relations.

ACKNOWLEDGEMENT

We are grateful for the support provided by the sponsors and partners of National Pooled Fund Study 776. Any opinions expressed herein are those of the writers and do not necessarily reflect the views of the sponsors.

REFERENCES

Artamendi, I., Khalid, H.A. "Effect of Specimen Geometry and Loading Rate on the Fracture Properties of Bituminous Materials," Proceedings of the Advance Characterization of Pavement and Soil Engineering Materials – 2007 (Athens, Greece), pp. 1183–1192 (2007).

Baek, J., and I. L. Al-Qadi, "Finite Element Method Modeling of Reflective Cracking Initiation and Propagation: investigation of the Effect of Steel Reinforcement Interlayer on Retarding Reflective Cracking in Hot-Mix Asphalt Overlay," Transportation Research Record, Record Number 1949, pp. 32–42 (2006).

Dave, E. V., S. H. Song, W. G. Buttlar, and G. H. Paulino, "Reflective and Thermal Cracking Modeling of Asphalt Concrete Overlays," Proceedings of the Advance Characterization of Pavement and Soil Engineering Materials – 2007 (Athens, Greece), pp. 1241–1252 (2007).

de Souza, F. V., J. B. Soares, D. H. Allen, and F. Evangelista, Jr., "Model for Predicting Damage Evolution in Heterogeneous Viscoelastic Asphaltic Mixtures," Transportation Research Record, Record Number: 1891, pp. 131–139 (2004).

Larson, G, and B. J. Dempsey, "Enhanced Integrated Climatic Model: Version 2.0", Report number DTFA MN/DOT 72114, Minnesota Road Research Project and Federal Highway Administration (1997).

Li, X., A. F. Braham, M. O. Marasteanu, W. G. Buttlar, and R. C. Williams, "Effect of Factors Affecting Fracture Energy of Asphalt Concrete at Low Temperature", Accepted to the 3rd European Asphalt Technology Association Conference, Lyon, France, April 14–15th, 2008.

Molenaar, A. A. A., A. Scarpas, X. Liu, and S.M.J.G. Erkens, "Semi-Circular Bend Test: Simple but Useful?" Proceedings of the Association of Asphalt Paving Technologists, Vol. 71, 2002, pp. 795–815.

Marasteanu M. O. et al., "Investigation of Low Temperature Cracking in Asphalt Pavements", National Pooled Fund Study 776, Final report, Minnesota Department of Transportation (2007).

Minnesota Department of Transportation, "MnROAD Aggregate Base Profile," Online Published Report, Office of Materials (2000).

Roque, R., D. R. Hiltunen, and W. G. Buttlar, "Thermal Cracking Performance and Design of Mixtures Using Superpave(TM)," Journal of the Association of Asphalt Paving Technologists, Vol. 64, pp. 718–735 (1995).

Soares, J. B., F. A. Colares de Freitas, and D. H. Allen, "Crack Modeling of Asphaltic Mixtures Considering Heterogeneity of the Material," Transportation Research Record, Record Number: 1832, pp. 113–120 (2004).

Song, S. H., G. H. Paulino, and W.G. Buttlar, "A Bilinear Cohesive Zone Model Tailored for Fracture of Asphalt Concrete considering Rate Effects in Bulk Materials," Engineering Fracture Mechanics, Volume 73, Number 18, pp. 2829–2848 (2006).

Wagoner, M.P., W.G. Buttlar, and G.H. Paulino, "Disk-Shaped Compact Tension Test for Asphalt Concrete Fracture," Experimental Mechanics, Vol. 45, pp. 270–277 (2005a).

Wagoner, M. P., W. G. Buttlar, and G. H. Paulino, "Development of a single-edge notched beam test for asphalt concrete mixtures," Journal of Testing and Evaluation, ASTM, Vol. 33, No. 6, pp. 452–460 (2005b).

Yin, H. M., W. G. Buttlar, and G. H. Paulino, "Simplified solution for periodic thermal discontinuities in asphalt overlays bonded to rigid pavements," Journal of Transportation Engineering, Vol. 133, Issue 1, pp. 39–46 (2007).