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

Task 3 Report

Prepared by:

Mihai Marasteanu
Eyoab Zegeye Teshale
Ki Hoon Moon
Mugur Turos
University of Minnesota

William Buttlar
Eshan Dave
Sarfraz Ahmed
University of Illinois

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Prepared for:

Minnesota Department of Transportation
Research Services of MS 330
395 John Ireland Boulevard
St.Paul, MN 55155

1. INTRODUCTION

The main objective of this task is the development of low temperature performance specification for asphalt mixtures to control thermal cracking. This specification does not involve the use of a computer program as part of routine design. An optional, more rigorous specification, which requires running the ILLI-TC program, will be developed under Task 4. In order to accomplish this objective, the following subtasks were 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.

2. SUBTASK 1 – DEVELOP TEST METHOD

Two fracture tests were used in this study to investigate the low temperature properties of asphalt mixtures. A summary of the two methods is provided next.

Summary of Fracture Testing Methods

Disc-shaped Compact Tension DC(T)Test

The Disc-Shaped Compact Tension DC(T) test was developed as a practical method for the determination of low-temperature fracture properties of cylindrically-shaped asphalt concrete test specimens. The DCT's advantages include easy specimen fabrication, from both field and gyratory samples, and it is a standard fracture test configuration (3; 4). The specimen configuration is shown in Figure . The DCT specimen are placed in a controlled chamber and conditioned for a minimum of 2 hours at the desired temperature. The test is performed under tensile loading and the crack mouth opening displacement (CMOD) is measured with a clip-on gage at the face of the crack mouth. After temperature conditioning, the specimens are inserted in loading fixtures, subjected to a preload, no greater than 0.2 kN, and then tested with a constant CMOD of 1mm/min (0.017 mm/s or 0.00067 in/s). The test is completed when the post peak level has reduced to 0.1 kN.

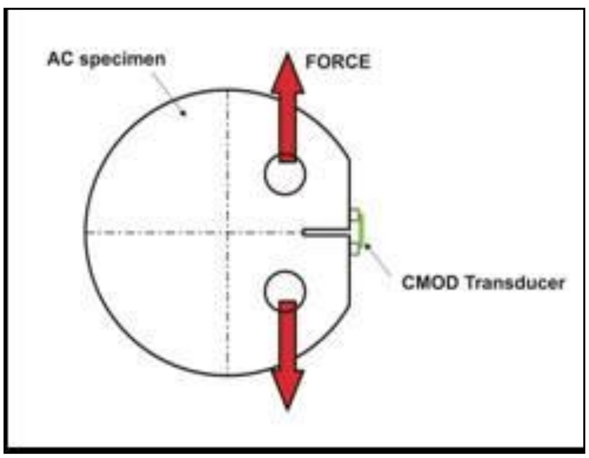


Figure 1. DC(T) testing scheme

Typical plots of Load vs. CMOD are shown in Figure . The fracture energy is calculated by determining the area under the Load-CMOD curve normalized by the initial ligament length and thickness.

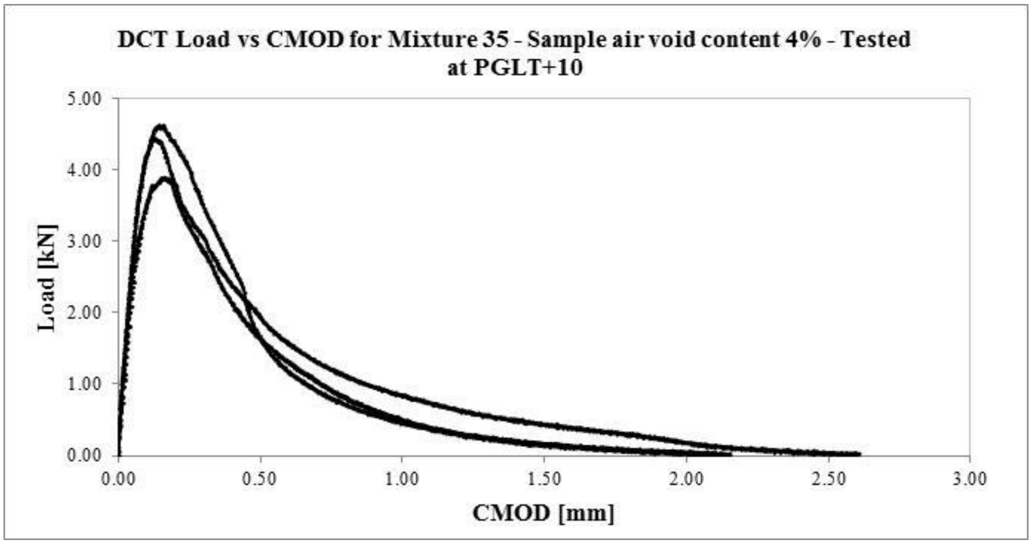


Figure 2. Typical Load-CMOD plots from DCT tests of three replicates

Semi Circular Bend (SCB) Test

A schematic of the SCB specimen and loading is shown in Figure 3. Since loading is applied vertically to the specimen, the load line displacement (LLD), used to calculate fracture energy, is measured using vertically mounted extensometers on both faces of the specimen; one end of the extensometer is mounted on a button that is permanently fixed on a specially made frame, and the other end is attached to a metal button glued to the face of the specimen. The loading (cracking) is controlled by a crack mouth opening displacement (CMOD) attached at the bottom of the specimen. A constant CMOD rate of 0.0005mm/s is used for testing and the load and load line displacement are recorded and used to calculate Fracture toughness K_{IC} and fracture energy G_f.

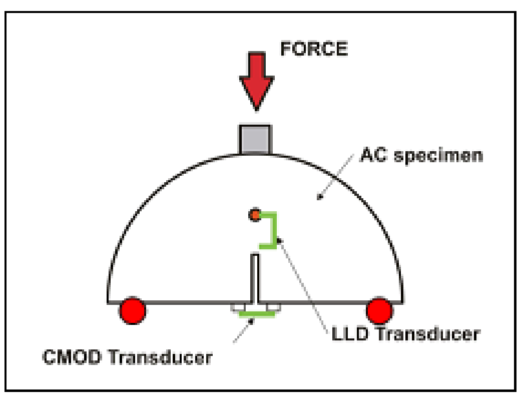


Figure 3. SCB testing scheme

A contact load with maximum load of 0.3 kN is applied before the actual loading to ensure uniform contact between the loading plate and the specimen. The testing is stopped when the load dropped to 0.5 kN in the post peak region. The tail part of the load-LLD curve can be reasonably obtained by fitting the data curve in post peak region following a method described elsewhere (5). Typical load versus LLD plots obtained from SCB tests are shown in Figure .

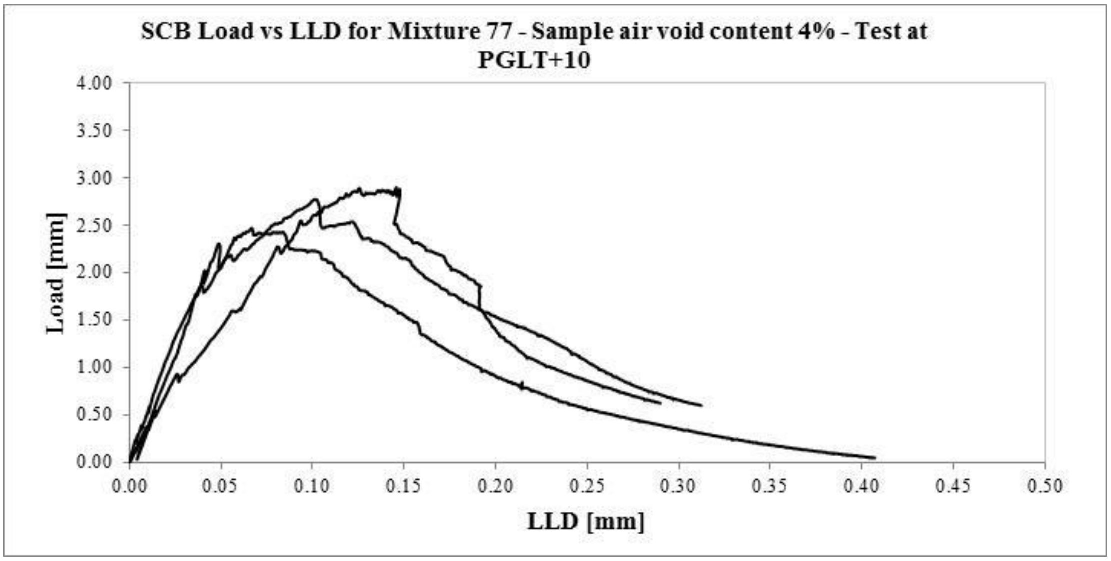
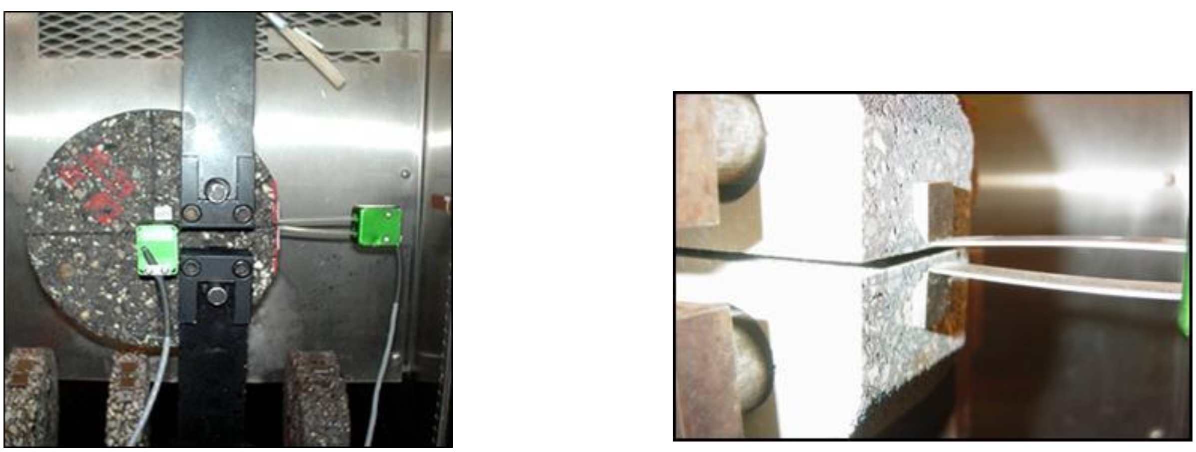


Figure 4. Typical Load-LLD plots from SCB tests of three replicates

Proposed Standard Fracture Test Method

A simple comparison of the two fracture test method was performed to determine which method is less costly and time consuming and can be readily implemented as a standard fracture test for evaluating asphalt mixtures cracking resistance at low temperatures.

The Disk-Shaped Compact Tension Test, shown in Figure 5, is already specified in ASTM D7313(07), which is provided in Appendix A.



(1a) (1b)

Figure 5. a) DC(T) test and b) CMOD gage attached to gage points

The test is used to obtain the fracture energy of asphalt mixture lab or field specimens, which can be used in performance-type specifications to control various forms of cracking, such as thermal, reflective, and block cracking of pavements surfaced with asphalt concrete. Standard testing is conducted at 10ºC warmer than the PG low temperature limit. The DC(T) test is run in crack mouth opening displacement (CMOD) control mode at a rate of 1 mm/min. Typically, specimens are completely failed in the range of 1 to 6 mm of CMOD travel. Although the actual test takes only 1 to 6 minutes to perform, the actual amount of testing time per specimen is probably more akin to 15 minutes, accounting for stabilization of test temperature, loading samples into the test apparatus, etc.

Sample preparation involves sawing and coring operations. First, a water-cooled masonry saw (14 or 20 inch blade) is used to create the flat, circular faces, similar to the production of an indirect tension test specimen or simple performance test specimen. A single or dual saw system may be used. A dual saw system, while more costly, will produce more parallel faces and uniform thickness specimens, which may improve test repeatability. A marking template is used to indicate the location of the 1.0 inch loading holes to be drilled, see Figure 6.

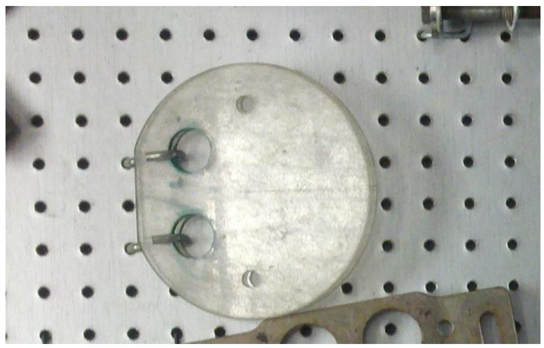


Figure 6. DC(T) marking template

A water-cooled drilling device is then used to fabricate the loading holes, and a smaller masonry table saw is used to produce the final two cuts: a flattened face to facilitate the placement of the CMOD gage and a notch, which is a necessary feature of a true fracture mechanics based test.

Researchers at the University of Illinois have determined the average fabrication time per specimen to be in the 10 to 15 minute range for DC(T) testing, which includes the four saw cuts and two cored holes. This is based upon mass production of at least a dozen test specimens. The fabrication of fewer test specimens will obviously lead to a longer per-specimen preparation time. Thus, combined with testing time, each DC(T) test will take approximately 30 minutes of technician time for specimen preparation and testing when larger batches of specimens are tested. Material testing labs are currently charging in the neighborhood of $200 per test specimen (replicate) for DC(T) testing, and somewhat less for larger quantities of specimens ($150 per test). This is similar to the cost to perform other mixture and binder performance tests. The typical COV associated with DC(T) testing is around 10%; less for carefully controlled lab experiments with precisely fabricated specimens and uniform materials, and more for less carefully prepared and/or less homogeneous lab specimens and field cores. A COV level of 10% is excellent when compared to other fracture tests performed on infrastructure materials, which can have COV levels of 20 or even 30% or more.

Estimated individual costs of the components required to build a DC(T) apparatus on an existing servo-hydraulic loading machine are shown in Table 1 below. For comparison purposes the estimated costs for the SCB test are also included in the table. Some equipment cost scenarios are shown below:

1. Lab with existing loading frame, existing cooling chamber, existing saws and coring rig, without optional dual saws: **$10,000.00** ($13,000 if Labview programming costs are to be included).
2. Same as estimate #1, except cooling chamber purchase required: **$30,000.00.** A lower estimate should be used if a simpler cooling chamber configuration is to be specified.
3. Purchase all components, including cooling chamber and both dual-saw systems: **$47,000.00.**

At least two equipment manufacturers have recently developed or are in the process of developing DC(T) test apparatus, the most notable being James Cox and Sons, Inc. Although exact cost estimates should be pursued by contacting the equipment manufacturers directly, it is estimated that a future, simplified DC(T) test based upon a screw-type actuator system, would cost in the range of $50k, not including dual-saw devices for sample prep. A more elaborate DC(T) test device, with a universal servo-hydraulic load frame capable of performing other tests, such as the simple performance test, IDT test, etc., would be expected to be in the $140k range. Dual-saw sample preparation apparatus is currently being manufactured by Precision Machine Works (PMW) out of Salinas, KS. PMW also manufactures a version of the Hamburg Wheel track test.

Table 1. Estimated costs for DC(T) and SCB tests

Item	**DC(T)**	**SCB**
Loading fixtures	$3,000	$1,000
X-Y tables to facilitate coring and sawing	$1,500	0
CMOD extensometer (Epsilon)	$1,400	$1,400
LLD extensometers (SCB only)	0	$4,000
Environmental chamber*	$20,000	$20,000
Temperature modules and thermocouples	$400	$400
Coring barrels (five)	$500	0
PC for data acquisition	$1,000	$1,000
Labview based interface board	$700	$700
Labview software for data acquisition	$1,500	$1,500
Labview programming**	$3,000	$3,000
*Dual water cooled masonry saws****	*$10,000*	*$10,000*
*Dual saw system for flat face and notching****	*$7,000*	*$7,000*

*A temperature chamber can be a major expense in low temperature performance testing of asphalt mixtures. The $20,000 estimate is for a high-power, condenser-type cooling chamber, capable of testing down to -30C. A lower cooling chamber cost can result, if a less stringent cooling capacity is specified, or if a liquid-nitrogen based system is used.
** A simple Labview based data acquisition program can be provided to the participating states by the research team free of charge.
*** These items are optional, but recommended for labs conducting a high volume of testing

The Semi Circular Bend Test (SCB) is shown in Figure 7; a draft AASHTO specification was developed at University of Minnesota and a copy is provided in Appendix B.

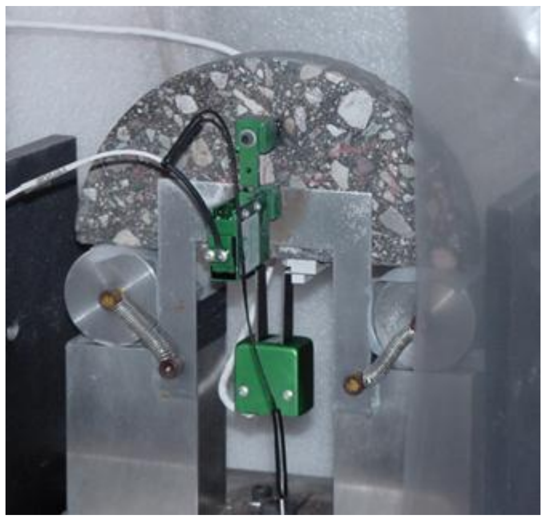


Figure 7 – The SCB test

SCB test is used to obtain the fracture energy of asphalt mixture lab or field specimens, which can be used in performance-type specifications to control various forms of cracking, such as thermal, reflective, and block cracking of pavements surfaced with asphalt concrete. Standard testing is conducted at 10ºC warmer than the PG low temperature grade. Similar to DC(T) test, the SCB test is run in crack mouth opening displacement (CMOD) control mode. However, the rate is 0.03 mm/min, 33 times slower than the DCT loading rate, which increases the duration of the test to as much as 30 minutes. Another significant difference is in the thickness of the specimen: DC(T) is 2" thick, while SCB is 1" thick.

Sample preparation is similar to DCT except that no coring is required. The only additional operation is gluing one IDT-type button on each face of the specimen; the buttons are used for holding the extensometers used to measure load line displacement (the displacement in the direction of the applied force) required to calculate fracture energy.

Researchers at the University of Minnesota have determined the average fabrication time per specimen to be in the 10 to 15 minute range, similar to the time for DC(T) specimens preparation at University of Illinois. The typical coefficient of variation (COV) associated with SCB testing is around 20%; less for carefully controlled lab experiments with precisely fabricated specimens and uniform materials, and more for less carefully prepared and/or less homogeneous lab specimens and field cores. This is higher than the COV level of 10% reported for DCT.

Based on the existing information, it can be concluded that the two methods have similar costs associated with required equipment to perform the test and with specimen preparation and testing. **Since the DC(T) test for asphalt mixtures is already covered by an existing ASTM standard and follows a procedure that has been used for many years for other materials as part of the well accepted ASTM E399 fracture standard for testing metals, it is proposed to select the DC(T) as a fracture testing method for asphalt mixtures.** The SCB test can also be used as an alternative testing method, especially for situations in which only thinner specimens are available, such as testing for forensic studies. The research team will develop correlations between DC(T) fracture energy and SCB fracture energy based on the test data obtained as part of this research effort.

3. SUBTASK 2 – DEVELOP SPECIFICATION

Revisit Performance Grade (PG) Specification for Asphalt Binders

Asphalt binder is a highly temperature susceptible viscoelastic material. Prior to the introduction of the PG specifications, empirical test methods based on the measurements of viscosity, penetration, and ductility were largely adopted to characterize the binder properties (1). The current asphalt binder Performance Grade (PG) specification was developed during the Strategic Highway Research Program (SHRP). The new specification is based on fundamental rheological and failure parameters that can be related to pavement performance. The new parameters included complex shear modulus G*, phase angle δ, creep stiffness S(t), and logarithmic creep rate m(t)). New testing and aging methods were developed, such as Dynamic Shear Rheometer (DSR), Bending Beam Rheometer (BBR), Direct Tension Test (DTT), and Pressure Aging Vessel (PAV) (2). In the next section, the development of the limiting criteria for low temperature cracking is summarized and discussed, since the development of these criteria was based on asphalt mixture field and laboratory data extrapolated to asphalt binder behavior.

Development of PG Low Temperature Cracking Criteria

In very cold climates, thermal cracking is the main distress that affects asphalt pavements. At these temperatures, asphalt binder becomes very stiff and reaches stress values higher than its strength, and cracks form and propagate. Cracking can occur due to a single critical low-temperature excursion or due to thermal cycling fatigue without necessarily reaching the critical low temperature. In the SHRP specification, only the former was considered.

The development of the SHRP asphalt binder criterion for low temperature cracking was based on the assumption that the 2-hour mixture stiffness correlated well with the severity of thermal cracking in the field (1). This assumption was extended to asphalt binder stiffness obtained in low-temperature creep tests. To expedite the testing process the time-temperature superposition principle was used to show that, for asphalt binders in general, the stiffness at 60 seconds at T_1ºC is approximately equal to the stiffness at 2 hours at T_1-10ºC (1). To keep the PG binder specification to a reasonable level of simplicity the effects of physical hardening were not considered although one of the major findings during SHRP was the significant effect of physical hardening on binder physical properties.

The slope at 60 seconds of the stiffness vs. time curve on a double logarithmic scale, the m-value, was introduced as an additional parameter to control the rheological type of asphalt binders and to eliminate heavily blown asphalts, which in fact were associated with poor fatigue performance. This additional criterion was based on the idea that a low m-value corresponded to slower relaxation of the thermal stresses that build up at low temperatures, which was detrimental for performance.

A simple fracture test was also required as part of the original SHRP binder specification. A dog bone shaped specimen was pulled with a constant strain rate and the tensile fracture stress and strain were obtained. A second critical temperature was obtained as the temperature at which the failure strain was 1%. The 10ºC shift was also applied to this temperature. Due to the low repeatability of the results, the direct tension test was made optional in the most recent version of the specifications. However, fracture experiments are known to be less repeatable than other material characterization experiments that do not involve fracture; in addition test data indicates that the repeatability issue is significant only for certain types of binders, which indicates that the poor repeatability may be a material property or a specimen preparation problem and not a testing problem.

A review of the two papers used in the development of the BBR creep stiffness criterion, reveals some important information about mixture properties. Most of the results were obtained at the Ste. Anne Road Test, conducted by Shell Canada and the Manitoba Department of Highways (6) in late 1960's. Twenty-nine sections were constructed with four different asphalts on clay and sand subgrades. Temperatures were measured at different levels in the pavement structures. Observations of cracking frequency and analysis of the rheological properties of the bitumens using the Van der Poel nomograph, the penetration-temperature relationships and Hills and Brien's method of calculating cracking temperatures showed reasonable agreement except that the calculated values were lower than the temperature at which significant cracking occurred in the field. Based on this research, it was concluded that the critical stiffness of the bitumen was 240MPa for a ½-hr. loading time, and that cracking would not occur if the binder did not reach this value of stiffness at the service temperatures encountered. In Ontario, Fromm and Phang (7), presented a method of specifying the grade of asphalt used for a given service temperature. They assumed a critical stiffness of 138MPa with a loading time of 2.8 hours. In a later paper, Redshaw concluded that transverse pavement cracking can be largely controlled by the use of binders which do not exceed a critical stiffness of about 200MPa at their lowest service temperature, as computed from Van der Poel diagram. This value was later used by researchers at Penn State to propose the existing 300MPa limit at 60s loading time.

In both papers, there is no mention about the mixture stiffness values used in the calculations. These values are found at the end of the Ste. Anne 1971 AAPT paper in the discussion prepared by N. W. McLeod. He mentions that, for a loading time of 20,000 seconds or 5.55 hours, the authors' critical pavement modulus of stiffness at which low temperature transverse pavement cracking is likely to occur, is 2,000,000 psi or 14GPa. However, based on his observations, he tentatively concluded that the critical low temperature pavement modulus of stiffness at which transverse pavement cracking is likely to occur is 1,000,000 psi or 7GPa, for a loading time of 20,000 seconds or 5.5 hours, a C_v value of 0.88, and 3 percent air voids. This limiting value was imposed on asphalt pavements at any time during its service life and "particularly as it nears the end of its service life." This information will be used in subtask 3 to propose a creep stiffness limiting value for low temperature cracking.

Develop Asphalt Mixture Low Temperature Specification

In this subtask, an approach similar to the one used to develop the current PG system is used to propose a low temperature mixture specification. The criterion is based on fracture tests performed on specimens prepared from original loose mix. This approach requires having both experimental fracture data as well as field performance for the same mixtures tested in the laboratory. Presently, the field sections constructed with the asphalt mixtures used in the experimental work performed in Task 2 have not cracked significantly to provide a wide range of values that can be used to develop a limiting criterion. This will be developed using the data obtained in the first phase of this research effort and the data obtained in task 2 will be used to verify that the proposed threshold values work.

It should be however noted that the main obstacle in proposing critical values for asphalt mixtures is reasonably quantifying the effect of aging on mixture fracture parameters, since field performance when cracking most likely occurs represents a later stage in pavement life. At this point, there is no fully accepted long term aging method for asphalt mixtures. Therefore, for the time being and until a long term project will provide such critical information, it is proposed to use a fixed value to quantify the reduction in fracture energy with aging.

Asphalt Mixture Low Temperature Specification Based on DC(T) Fracture Energy

Using data collected in the initial phase of this study, field thermal cracking data was correlated to DC(T) fracture data. From these results, a minimum fracture energy of 400 J/m^2 is suggested for protection against thermal cracking (Figure 1), as determined at a test temperature equal to the binder Performance Grade low temperature (PGLT) limit plus 10 degrees Celsius (e.g., the test temperature that is used for verifying the Superpave PGLT grade). Fracture energy in the range of 350-400 J/m^2 is considered borderline, and may be permissible on projects of lower criticality, where a low to moderate degree of thermal cracking can be tolerated. For projects of high criticality, a factor of safety can be achieved by specifying a minimum fracture energy of 600 J/m^2. Mixtures with this level of fracture energy have been found to be resistant to both thermal cracking and reflective cracking. However, reflective cracking will only be avoided if the underlying pavement has high load transfer efficiency.

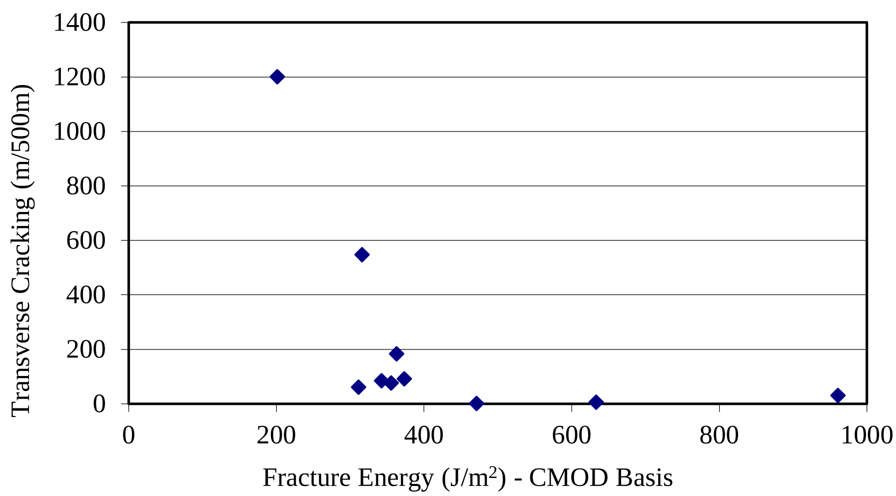


Figure 1. Field Data Suggesting a Minimum Fracture Energy of 400 J/m^2 at PGLT + 10ºC to Prevent Thermal Cracking

The computer program ILLI-TC, which will be developed in Task 4 of this project, uses fracture energy and creep compliance data, along with pavement structure and climatic information to predict thermal cracking versus time. For projects with high or moderate criticality, this program provides extra assurance that thermal cracking will be controlled, since the combined effects of mixture fracture properties, creep/relaxation behavior, thermal coefficient, and site-specific diurnal temperature cycling are considered. For high criticality projects, only negligible amounts of thermal cracking can be tolerated. Due to the characteristics of the probabilistic model that converts the single predicted thermal crack to amount of cracking, the specification of exactly zero predicted cracking is likely to be overly conservative (a very shallow predicted crack will yield a low amount of predicted cracking, but will not likely manifest itself as a visible crack in the field). Thus, a maximum predicted thermal cracking level of 4 m of cracking per 1 km of pavement (one crack per km) is specified. For projects of moderate criticality, a maximum predicted thermal cracking level of 64m/km is specified (assuming 4m wide pavement, this represents 16 cracks per km, or 1 lane-wide crack per 100 m). In addition, the use of ILLI-TC is specified as optional. For low criticality projects, the use of ILLI-TC is not required.

Based upon the results presented earlier, a thermal cracking specification is proposed. Since these results were based on cores taken out of older pavements, a 15% increase in fracture energy is proposed to take into account the fact that these requirements are specified for loose mixtures and short term aged laboratory mixtures (Braham et al., 2008). Specification limits for three levels of project criticality are provided. A higher fracture energy threshold is suggested in order to limit thermal cracking to lower levels on projects of high criticality. High criticality/high traffic pavement structures tend to involve thicker asphalt concrete layers, where the effects of thermal cracking on future maintenance and rehabilitation activities can be very significant. In addition, these pavements tend to have lower asphalt content, and higher in-place air voids, as a higher design gyration limit and stronger aggregate structure is required in order to mitigate rutting during summer months under heavy traffic. Thus, the potential for more rapid aging near the pavement surface exists, and can be addressed by specifying a higher fracture energy threshold. Finally, limiting thermal cracking on high traffic level facilities will serve to reduce the user costs associated with operating vehicles on rough pavement (Islam and Buttlar, TRB 2012).

Table 1. Recommended Low-Temperature Cracking Specification for Loose Mix

	Project Criticality/ Traffic Level		
	High >30M ESALS	Moderate 10-30M ESALS	Low <10M ESALS
Fracture Energy, minimum (J/m^2), PGLT + 10^{o}C	690	460	400
Predicted Thermal Cracking using ILLI-TC(m/km)	< 4	< 64	Not required

Alternative Asphalt Mixture Low Temperature Specification Based on SCB Fracture Energy

The same approach used to propose the DC(T) based specification was used to propose altenative limits for the SCB fracture energy. Summaries of the data obtained in the first phase of the pooled fund study are provided in the next two tables. All parameters were correlated with the total length of transverse cracking. The comparisons were made at temperatures representative for each site to take into account local climate conditions.

Table 2. LTPP low pavement temperature at 50% reliability level

Section	Station	Temperature, [°C]
IL I74	Urbana, IL	-16.4
MN75 2	Collegeville, MN	-24.4
MN75 4	Collegeville, MN	-24.4
MnROAD 03	Buffalo, MN	-23.8
MnROAD 19	Buffalo, MN	-23.8
MnROAD 33	Buffalo, MN	-23.8
MnROAD 34	Buffalo, MN	-23.8
MnROAD 35	Buffalo, MN	-23.8
US20 6	Freeport, IL	-19.7
US20 7	Freeport, IL	-19.7
WI STH 73	Stanley, WI	-24.7

Table 3. Mixture parameter and total length of transverse cracking in the field

	SCB Fracture Energy [J/m^2]	IDT Creep Stiff. [GPa]	SCB, Fracture Tough. [MPa m$^{0.5}$]	IDT Tensile Strength [MPa]	Transverse cracking [ft/500ft]
IL I74	161.7	-	0.591	-	**1200**
MN75 2	355.3	24.2	0.785	3.35	**76**
MN75 4	479.0	24.9	1.024	5.59	**30**
MnROAD 03	273.9	23.0	0.755	4.65	**182**
MnROAD 19	260.4	20.2	0.689	4.22	**547**
MnROAD 33	277.8	17.9	0.734	4.61	**91**
MnROAD 34	425.1	19.8	0.881	6.67	**5.5**
MnROAD 35	308.6	12.6	0.750	4.86	**747**
US20 6	341.0	-	0.711	-	**84**
US20 7	360.4	-	0.714	-	**60**
WI STH 73	295.0	22.2	0.881	5.68	**0**

Based on the results plotted in Figure 2, a limiting value of $350J/m^2$ is proposed. This value is adjusted to a limit of $400J/m^2$ to account for aging effects.

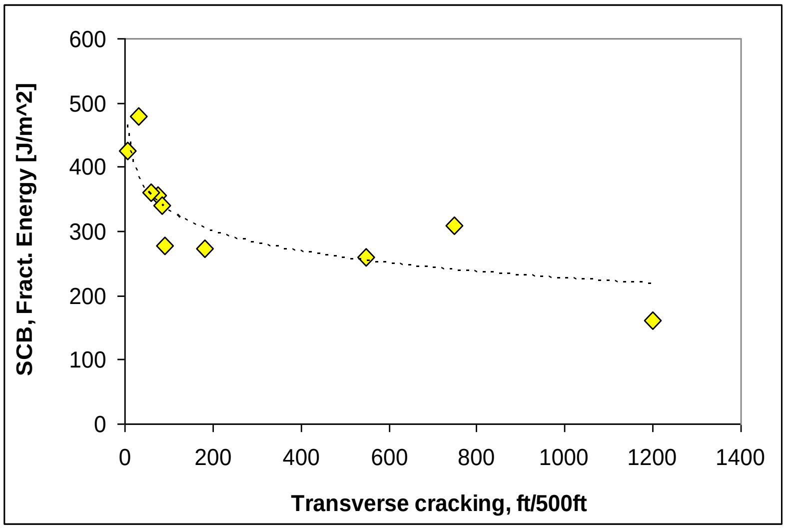


Figure 2. Field Data Suggesting a Minimum SCB Fracture Energy of 350 J/m^2 at PGLT + 10°C to Prevent Thermal Cracking

Since fracture toughness was also highly correlated to cracking occurrence, as seen in Figure 3, a value of 800 $kPa \times m^{0.5}$ is suggested as a possible limit that can be used in addition to fracture energy limit as an additional check for good fracture resistance. No age adjustment is proposed for fracture toughness.

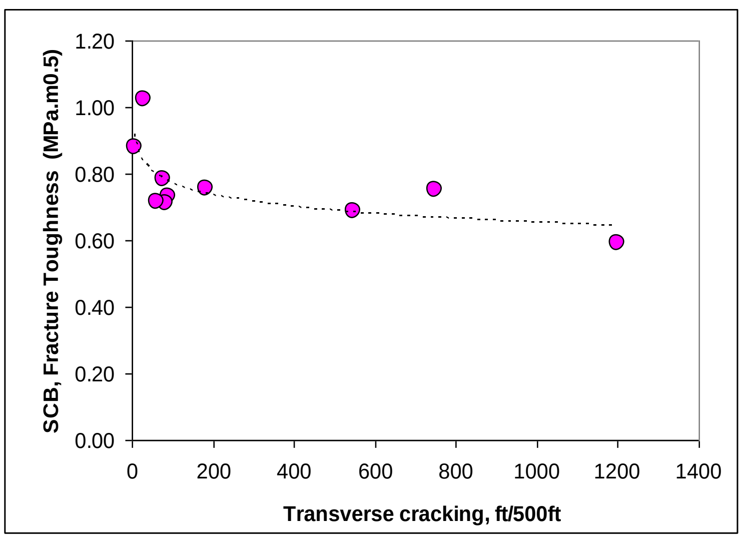


Figure 3. Field Data Suggesting a Minimum Fracture Toughness of 800$kPa \times m^{0.5}$ at PGLT + 10°C to Prevent Thermal Cracking

Braham, A.F., Buttlar, W.G., Clyne, T., Marasteanu, M., and M. Turos, "The Effect of Long-Term Laboratory Aging on Asphalt Concrete Fracture Energy," *Journal of the Association of Asphalt Paving Technologists*, pp. 417-454, 2009.