



METHODS AND CRITERIA FOR EVALUATION OF ASPHALT MIXTURE RESISTANCE TO LOW TEMPERATURE CRACKING

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Abstract. In cold regions and areas where there is a huge difference between high and low temperatures asphalt pavements are subject to low temperature cracking. The appeared cracks form pavement discontinuities, through which water penetrates into pavement structure. It reduces the bearing capacity of the whole pavement structure, weakens adhesion between bitumen and aggregate, affects bonding between layers and increases the development of frost heaves. A sealing of cracks deals with these issues. However, additional inspections after each winter have to be carried out to identify both cracks that have newly appeared and cracks that need to be resealed. These activities significantly increase road maintenance cost. Selection of the appropriate asphalt mixture by its performance at low temperatures reduces or even prevents low temperature cracking of asphalt pavements. A number of methods such as the Indirect Tensile Test, the Bending Beam Rheometer Test, the Thermal Stress Restrained Specimen Test, Asphalt Thermal Cracking Analyser, the Single-Edge-Notched Beam Test, the Disc-Shaped Compact Tension Test, the Semi-Circular Bend Test, the Fenix Test, Asphalt Concrete Cracking Device and Spectral Analysis of Acoustic Emission are developed to evaluate asphalt mixture resistance to low temperature cracking. This paper presents an analysis of these tests, emphasizes their advantages and disadvantages and gives limiting criteria to evaluate asphalt mixture resistance to low temperature cracking. The test advantages and disadvantages are deciding factors in a test selection. Some tests such as the Thermal Stress Restrained Specimen Test and Spectral Analysis of acoustic emission can directly reveal the lowest temperature at which asphalt mixture can withstand induced thermal stresses.

Keywords: asphalt mixture, critical cracking temperature, fracture mechanics, low temperature cracking, spectral analysis of acoustic emission.

1. Introduction

In cold regions and areas where a huge difference between high and low temperatures prevails, low temperature cracking is one of the primary distresses in asphalt pavements if asphalt mixture is susceptible to low temperatures. Low temperature cracking occurs when a single low temperature induces thermal stresses higher than the tensile strength of the material (Shahin, McCullough 1972). Thus, there exists a specific low temperature that defines asphalt mixture resistance to low temperature cracking. This temperature is usually referred to critical cracking temperature. A repetition of many temperature cycles can also be a reason for asphalt pavement cracking. This phenomenon is known as thermal fatigue cracking. However, it is difficult to simulate it in the laboratory, and tests for the evaluation of asphalt mixture resistance to thermal

fatigue cracking have not been developed yet. Thus, thermal fatigue cracking is not addressed in this paper.

Low temperature cracking results in pavement discontinuities, through which water penetrates into pavement structure. It reduces the bearing capacity of the whole pavement structure, weakens adhesion between bitumen and aggregate, increases the development of frost heaves and leads to faster pavement deterioration. A sealing of cracks restricts water penetration into the pavement structure. However, after a few years, depending on the sealing method, the sealing fails, and previously sealed cracks have to be resealed. Thus, additional inspections after each winter have to be carried out to identify both cracks that have newly appeared and cracks that need to be resealed. These activities connected with sealing significantly increase maintenance cost.

Selection of the appropriate asphalt mixture on the basis of its performance at low temperatures prevents asphalt pavements from low temperature cracking and results in lower maintenance cost. Researchers have developed a number of tests (e.g. the Indirect Tensile Test (IDT), the Bending Beam Rheometer (BBR) test, the Thermal Stress Restrained Specimen Test (TSRST), Asphalt Thermal Cracking Analyser (ATCA), the Single-Edge-Notched Beam (SE(B)) test, the Semi-Circular Bending (SCB) test, the Disc-Shaped Compact Tension (DC(T)) test, the Fenix test, Asphalt Concrete Cracking Device (ACCD) and Spectral Analysis of Acoustic Emission (AE)) addressing low temperature cracking. These tests differ from each other by specimen geometry, loading, and climatic conditions and have different limiting criteria for the evaluation of asphalt mixture resistance to low temperature cracking. Thus, a comprehensive knowledge of both test principles and limiting criteria is vital. Otherwise, the asphalt mixture performance can be incorrectly evaluated, leading to low temperature cracking.

This paper focuses on the asphalt mixture tests used to determine the asphalt mixture performance at low temperatures. The analysis of these tests revealed their advantages and disadvantages and limiting criteria for the evaluation of asphalt mixture resistance to low temperature cracking.

2. Asphalt mixture tests at low temperatures

Tests that are used to determine asphalt mixture performance at low temperatures are grouped into the following categories:

- continuum-based tests;
- fracture mechanics-based tests;
- acoustic emission-based tests.

2.1. Continuum-based tests

Many studies have shown that continuum-based tests can be used to evaluate asphalt mixture resistance to low temperature cracking (Chehab, Kim 2005; Monismith *et al.* 1965; Romero *et al.* 1999; Sebaaly *et al.* 2002). The main idea is that asphalt pavement cracks when asphalt mixture cannot withstand thermal stresses induced by a single low temperature. These tests use a specimen without a pre-existing crack. The test methods based on the continuum are as follows:

- Indirect Tensile Test (IDT);
- Bending Beam Rheometer (BBR) test;
- Thermal Stress Restrained Specimen Test (TSRST);
- Asphalt Thermal Cracking Analyser (ATCA).

IDT is most widely used to evaluate asphalt mixture performance at low temperatures. It simulates a state of stress similar to the state induced under the wheel in the asphalt mixture (Roque, Buttlar 1992). IDT was developed during the Strategic Highway Research Program (SHRP) (Buttlar, Roque 1994; Lytton *et al.* 1993; Vinson *et al.* 1989). Later, it was enhanced according to research results by Christensen and Bonaquist (2004). IDT is used for the

determination of both creep compliance and strength of asphalt mixture. These data are vital for the currently used the Thermal Cracking (TC) model included in the Mechanistic-Empirical Pavement Design Guide (MEPDG) (Hallin 2004). This TC model is an enhanced version of the approach developed under the SHRP A-005 research contract (Lytton *et al.* 1993; Vinson *et al.* 1989). The IDT creep test is conducted at three temperatures, depending on the bitumen grade in the asphalt mixture, while IDT strength is performed at the middle temperature used for the creep tests. An intersection of the thermal stress–temperature curve, which is calculated from creep compliance, with determined strength is referred to as the critical cracking temperature. However, the method of calculating thermal stress from creep compliance is complicated. It is also time consuming because each specimen has to be left at the test temperature for 3 ± 1 hours before being tested.

Zofka *et al.* (2005) introduced a new method to determine the creep compliance of asphalt mixture, which is based on 3-point bending (BBR). The same BBR as for the bitumen test can be used if it is capable of applying a high load (450–500 g). However, BBR for asphalt mixtures violates the concept of the Representative Volume Element (RVE) because the thickness of the beam is often smaller than the maximum aggregate size in the asphalt mixture. Nevertheless, many studies have demonstrated the suitability of BBR to determine the creep compliance of asphalt mixtures (Ho, Romero 2011; Velasquez *et al.* 2011; Zofka *et al.* 2005; Zofka *et al.* 2008a, 2008b). Besides, Weissman *et al.* (1999) and Romero and Masad (2001) showed that RVE could be significantly reduced at low temperatures. Furthermore, Marasteanu *et al.* (2016) confirmed that representative results could be obtained by BBR testing at least three beams even if the maximum aggregate size in asphalt mixture is larger than the smallest dimension of the beam. A dimensional range (tolerance) of 0.5 mm is recommended for asphalt mixture beam preparation. It results in a coefficient of variation of 9.43%, which is significantly lower than what is typical of asphalt mixtures (20%) (Ho, Romero 2011). In general, a repeatability of asphalt mixture stiffness determined by BBR varies from 4% to 13% (Velasquez *et al.* 2011).

The stiffness from BBR is converted to the creep compliance by taking its inverse. Creep compliance curves from BBR and IDT differ slightly depending on loading time and test temperature, but calculations have shown that creep compliance determined by the BBR results can be successfully used in the TC model instead of IDT data (Zofka *et al.* 2008b). A linear viscoelastic analysis conducted by Ho and Romero (2011) revealed that the effect of aggregate size on the low temperature properties of asphalt mixture beams with different nominal maximum aggregate size (12.5 mm, 9.5 mm and 4.75 mm) is not significant. It validates the theoretical work by Zofka *et al.* (2005, 2008a, b). Velasquez *et al.* (2011) analysed the effect of cooling medium on the stiffness and concluded that stiffness in the air is 8% larger than in ethanol. Falchetto *et al.*

(2014) suggested the use of BBR for the determination of asphalt mixture strength. It is possible only if the loading frame is able to use load as high as 44 N. However, research conducted by Marasteanu *et al.* (2016) showed that for the strength test BBR beams do not represent asphalt mixture's RVE.

The idea of TSRST was proposed by Monismith *et al.* in 1965 and developed under the SHRP A-400 contract by Jung and Vinson in 1994. It is the only test for asphalt mixtures in which temperature and loading vary simultaneously. There a fracture stress (strength), fracture temperature and transition temperature are determined. The fracture temperature is defined as the temperature at which the specimen breaks. The transition temperature is referred to as the temperature at which the asphalt mixture changes from elastic to viscoelastic behaviour or vice versa. A strong linear correlation between the fracture temperature and the transition temperature was revealed. Although TSRST is not a part of asphalt mixture specifications, it has been widely used in Europe. Usually, the fracture temperature instead of fracture stress (strength) is used to rank asphalt mixtures according to resistance to low temperature cracking since its coefficient of variation is lower (Marasteanu *et al.* 2007). However, the results of the test depend on the grade of the base bitumen and ageing (Isacsson, Zeng 1998b; Lu, Isacsson 2001). The harder the bitumen and the more aged the asphalt mixture, the higher the fracture temperature is. Polymer type, binder source and mixture type (air void content) also become significant factors if specimens are aged (Isacsson, Zeng 1998a; Isacsson, Zeng 1998b). The Thermal Stress Restrained Specimen Test can use either a beam or a cylindrical specimen. Cylindrical specimens show slightly lower fracture temperature than beam (Marasteanu *et al.* 2007). A cooling rate is one of the most important test conditions. Typically, the cooling rate in the field is about 1–2 °C/h, depending on the climate. This cooling rate leads to an enormous amount of time to conduct TSRST. Studies have shown that an increase in the cooling rate from 1 °C/h to 10 °C/h results in an increase in fracture temperature of 5 °C (Jung, Vinson 1993). Nevertheless, the cooling rate of 10 °C/h is usually used. It enables TSRTS to be conducted in a reasonable time (about 4 h).

One of the biggest issues in TSRST is a specimen alignment because even perfect centring causes bending in the specimen what leads to a non-uniform stress distribution. Thus, special methods to correct the stress obtained from TSRST have to be applied. It enhances the correlation between TSRST fracture stress and the severity of low temperature cracking (Velásquez *et al.* 2009).

The Asphalt Thermal Cracking Analyser is a significantly improved version of TSRST that can simultaneously test two specimens at the same temperature regime. The first specimen (beam) is unrestrained, and thus the glass transition temperature (T_g) and coefficients of thermal expansion or contraction can be obtained. The second one is restrained similar to that of the TSRST specimen, and fracture temperature and fracture strength are determined.

Besides, the relaxation modulus of asphalt mixture can be calculated, and resistance to thermal fatigue and physical hardening can be evaluated because thermal cycles and isothermal conditioning can be applied (Baglieri *et al.* 2012; Bahia *et al.* 2012a; Bahia *et al.* 2012b; Tabatabaee *et al.* 2012). Bahia *et al.* (2012b) showed the importance of physical hardening. The difference among temperatures at which stress in the specimen, cooled at a constant rate, is the same as the maximum stress in the specimen held isothermally was 12 °C.

During the development of the device, the low adhesion between the metal end plates used for the restrained specimen and beam was observed. Consequently, these metal end plates were retextured, making them much coarser. It enhanced adhesion and permanently solved the de-bonding issue. A misalignment of the end plates with the specimen was removed by placing the plates on a rail and using a set of guide rods to ensure the plates were placed completely parallel and aligned (Bahia *et al.* 2012a).

2.2. Fracture mechanics-based tests

Continuum-based tests do not evaluate crack propagation. Besides, in TSRST thermally induced stresses can concentrate near the ends of the specimen, and failure can occur at any location. It is undesirable because there is an assumption that cracks occur in the middle of the specimen and failure plane is perpendicular to the cross section of the specimen. Consequently, tests based on fracture mechanics were developed. A specimen with pre-existing crack (notch) is used. Typically, cracks propagate at the notch and thus crack propagation can be evaluated. Three modes exist, i.e. Mode I – tensile; Mode II – shear; Mode III – torsion (Jayatilaka 1979). The test methods based on fracture mechanics are the following:

- Single-Edge-Notched Beam (SE(B)) test;
- Semi-Circular Bending (SCB) test;
- Disc-Shaped Compact Tension (DC(T)) test;
- Fenix test;
- Asphalt Concrete Cracking Device (ACCD).

Single-Edge-Notched Beam is the most popular test to determine fracture properties (fracture toughness (K_{IC}) and fracture energy (G_f)) of asphalt mixture based on linear elastic fracture mechanics conditions. Two rollers symmetrically support a beam with a notch in the middle, and the load is applied in the middle of the beam top side. It simulates a crack propagation according to Mode I. For the first time this concept was used in 1967 (Moavenzadeh 1967). Studies showed that mixed mode (Mode I and Mode II) could also be applied if the notch is offset from the middle of the beam (Guo *et al.* 1995; John, Shah 1990). It is important since asphalt pavements usually fail because of both thermal loading (tension) and wheel loading (bending tension and shear). Beam size meets the RVE concept but it is not suitable for laboratory compacted specimens and field cores. This is the main reason why SE(B) is not so widely used. Besides, there is no standardized test procedure, and researchers use different specimen sizes, notch lengths and even loading modes (Bhurke *et al.* 1997; Kim,

El Hussein 1997; Marasteanu *et al.* 2002; Wagoner *et al.* 2005a). All these factors influence results. However, a good repeatability has been found. The coefficient of variation varies from 3% to 28% (Mobasher *et al.* 1997). The SE(B) test can also be used to estimate fatigue cracking (Hofman *et al.* 2003).

The Semi-Circular Bending test was proposed by Chong and Kuruppu (1984) and later developed by Molenaar, J. and Molenaar, A. (2000). They used a semi-circular specimen with a vertical notch along the symmetrical axis of the specimen. Thus, specimen geometry is suitable for laboratory compacted specimens and field cores. Crack propagation is controlled by a constant crack mouth opening displacement (CMOD). The load is applied on top of the specimen, which is symmetrically supported by two rollers at the bottom. K_{IC} and G_f are determined by recorded load, load line displacement (LLD) and CMOD. However, this loading type generates an arch effect with high compressive stress near the crack, which affects crack propagation. Besides, laboratory compacted specimens, or field cores of 150 mm diameter result in a relatively short ligament in the specimen. It has to be as large as possible to produce a reliable test result.

Nevertheless, a good repeatability has been found. The coefficient of variation varies from 15% to 34% (Li, Marasteanu 2004). Besides, the SCB test showed the best correlation between the G_f and field performance compared to the IDT and DC(T) tests (Zofka, Braham 2009). However, results are affected by aggregate type, air voids, temperature, and the interaction of temperature and air voids content (Li *et al.* 2008; Marasteanu *et al.* 2012). Asphalt mixtures with granite resist low temperature cracking more than those with limestone. Additionally, higher air void content results in less sensitivity to temperature change.

Marasteanu *et al.* (2012) suggested the use of a standard notched SCB specimen to determine both creep compliance and fracture parameters. The creep function computed from displacement measured at the upper segment of the SCB specimen, which was prepared cutting the specimen used in IDT creep test in half, was in good agreement with creep functions from the BBR and IDT creep tests.

The Disc-Shaped Compact Tension test was developed by Wagoner *et al.* (2005b). Cylindrically shaped specimen with a notch is tensioned ensuring a constant CMOD, which is measured using a clip-on gauge on the face of the crack mouth. Specimen geometry is suitable for laboratory compacted specimens and field cores. At the beginning of the DC(T) test development, some issues related to specimen geometry had to be solved. Firstly, the loading holes were quite close to the specimen edge to create a longer ligament. However, about 50% of the specimens resulted in a failure at the loading holes since there was an insufficient amount of material between the holes and the specimen edge. Consequently, the loading holes were moved towards the centre of the specimen. It led to a failure at the notch (Wagoner *et al.* 2005b). Secondly, the notch length had to be selected. Wagoner *et al.* (2005b) proposed

an appropriate specimen geometry, which maximizes the ligament and prevents the specimen from rupturing at the loading holes. Nevertheless, microcracks may form around the loading holes during specimen preparation.

The Disc-Shaped Compact Tension test shows the best repeatability among the fracture mechanics-based tests. The coefficient of variation varies from 4% to 17%, depending on test temperature. The lower the test temperature, the higher the coefficient of variation (Wagoner *et al.* 2005b). Li *et al.* (2008) suggested how to lower test variability and make easier computation procedure of G_f . The extensometers should be located at the crack tip rather than the crack mouth. Softening curves from SCB and DC(T) indicate that asphalt mixtures fail in the same type. However, DC(T) shows slightly higher G_f than SCB (Marasteanu *et al.* 2012). The DC(T) results are sensitive to the specimen geometry, but air voids are not a significant factor (Li *et al.* 2008; Wagoner, Buttlar 2007). The higher the specimen diameter or thickness, the higher G_f . Nevertheless, the correlation between G_f determined from SCB and DC(T) is low and depends on the test temperature since different CMOD rates, specimen geometry and ligament area are used (Zofka, Braham 2009).

Marasteanu *et al.* (2012) suggested the use of the DC(T) specimen to determine creep compliance. There was no statistical difference between the G_f of the DC(T) specimens tested only for G_f and those tested for both creep compliance and G_f .

At the end of the low temperature cracking pooled fund study, conducted in the USA, the DC(T) test was proposed as an appropriate fracture test for asphalt mixture to evaluate its resistance to low temperature cracking (Marasteanu *et al.* 2012). At that time, it was the only standardized method for determination of asphalt mixture G_f . As a result, the SCB test was suggested as an alternative test, particularly when only thin specimens are available. Currently, the SCB test for the determination of asphalt mixture G_f is also standardized. Besides, Mandal *et al.* (2017) reported that DC(T) should not be used as specification procedure for low temperature cracking because it was unable to differentiate between the specific asphalt mixture and bitumen factors such as content of reclaimed asphalt pavement (RAP), traffic level, modification of bitumens and ageing of asphalt mixtures.

The fracture energy (G_f) is an essential input into TC model developed at the University of Illinois Urbana-Champaign which is called IlliTC. This model uses a 2D, cohesive zone fracture modelling approach implemented within a viscoelastic finite element modelling framework. The cohesive zone approach considers both material strength and G_f in computing crack initiation and propagation using fundamental fracture mechanics principles (Dave *et al.* 2013; Marasteanu *et al.* 2012).

Recently, the Fenix test was developed by Pérez-Jiménez *et al.* (2010). It is a direct tensile test in which a half-cylindrical specimen with a notch in the middle of its flat side is placed on the two steel plates attached to

the loading platen in a way they can rotate about fixing points. The test is done under controlled displacement. The dissipated energy, which is a combination of all energies released during material deformation and cracking, is determined. Test results are sensitive to bitumen content and test temperature; however, a loading rate has a minimal effect on them (Pérez-Jiménez *et al.* 2010, 2013). The higher the bitumen content, the higher the dissipated energy (Pérez-Jiménez *et al.* 2010). The difference among test results obtained at different low temperatures decreases as lower temperatures are used. At very low temperatures asphalt mixture starts to behave as an elastic solid that G_f and creep compliance keep practically constant (Pérez-Jiménez *et al.* 2013).

The Fenix test combines the advantages of both the SCB and DC(T) tests. It shows similar results to the SCB test and has good repeatability (Pérez-Jiménez *et al.* 2010, 2013). However, at very low temperatures the coefficient of variation is higher than in the SCB test. The difference at $-15\text{ }^\circ\text{C}$ is 7%, but the average coefficient of variation is less than 17% (Pérez-Jiménez *et al.* 2013).

The Asphalt Concrete Cracking Device was developed as a simple method to directly determine the cracking temperature of asphalt mixture under field-like conditions (Kim *et al.* 2009). The low thermal expansion coefficient of Invar steel was used to induce tensile stresses in a notched ring-shaped specimen of asphalt concrete as the temperature was lowered at a rate of $60\text{ }^\circ\text{C}/\text{hour}$. For various tested asphalt mixtures, standard deviations of cracking temperature were less than $1\text{ }^\circ\text{C}$. Besides, ACCD correlates well with TSRST. A correlation coefficient is 0.87 (Kim *et al.* 2010).

2.3. Acoustic emission-based tests

Previously discussed continuum-based tests and fracture mechanics-based tests assess low temperature cracking but are time consuming, inconvenient and economically ineffective. Consequently, the AE-based test was developed (Buttlar *et al.* 2011). The concept is that stressed material during the cracking suddenly releases energy in the form of transient mechanical elastic waves, which are recorded using sensitive surface-mounted acoustic sensors. These sensors convert the mechanical wave energy to voltage (AE signal). The temperature at which the first major acoustic event occurs is referred to as the embrittlement temperature (T_{EMB}) of the material. It is related to local micro-scale thermally induced damages (Apeageyi *et al.* 2009; Behnia *et al.* 2011). Additional to T_{EMB} , the temperature at which a maximum acoustic energy release (T_{MAX}) is determined. It is related to macro-scale thermally induced cracks. T_{EMB} is always higher than T_{MAX} . A study conducted by Behnia (2013) showed that all laboratory compacted specimens have higher T_{EMB} than bitumen's performance grade (PG) low temperature, whereas in most cases T_{MAX} is close to bitumen's PG low temperature. Besides, the more aged the specimen, the warmer the T_{EMB} of that asphalt mixture (Buttlar *et al.* 2011).

Different locations of AE sensors enable one to detect, locate and identify cracks (Li, Marasteanu 2004).

Furthermore, the AE test can be used to detect whether RAP was used in asphalt mixture (Behnia *et al.* 2011; Buttlar *et al.* 2011). It is vital for asphalt mixture quality control.

The AE test uses a semi-circular specimen of 150 mm diameter and 50 mm thickness that is cooled down at a constant rate until macrocracking occurs. The coefficient of variation varies from 2.69% to 9.74% for T_{EMB} and from 1.40% to 6.24% for T_{MAX} (Buttlar *et al.* 2011). It is much lower than for mechanical tests such as TSRST, SCB, and DC(T).

Behnia (2013) investigated temperature distribution within a specimen during cooling and found that the thermal lag between the surface and the middle of the specimen at temperatures lower than $-10\text{ }^\circ\text{C}$ is negligible. AE usually starts at a significantly lower temperature than $-10\text{ }^\circ\text{C}$; hence, the specimen surface is a proper location to measure the temperature of asphalt mixture during the AE test. The study of the thickness influence on the T_{EMB} showed that at least a 40 mm thick specimen has to be used to yield repeatable and reliable results (Behnia 2013).

The AE method was also used in SCB and IDT creep and strength tests (Li *et al.* 2006; Li, Marasteanu 2004, 2006; Marasteanu *et al.* 2008; Nesvijski, Marasteanu 2006). The SCB test combined with the AE method indicated that macrocracking initiates from 35% to 95% of the peak load, but propagates only after 95% of the peak load (Li, Marasteanu 2006). IDT creep and strength tests combined with the AE method showed that in both tests a damage zone develops. It changes with the test temperature and the loading level applied during creep test. In general, more AE events were recorded at higher load levels for all test temperatures during the creep test, suggesting that microcracking occurs during the creep phase (Marasteanu *et al.* 2008).

Table 1 presents the advantages and disadvantages of each the previously discussed test used to evaluate asphalt mixture resistance to low temperature cracking.

3. Limiting criteria addressing low temperature cracking

Studies have shown that bitumen's PG low temperature does not always restrict low temperature cracking, and criteria for asphalt mixture have to be determined. Low temperature cracking can be restricted, limiting stiffness of asphalt mixture or increasing relaxation modulus. Deme and Young (1987) analysed the relationship between stiffness of asphalt mixture and pavement performance. They suggested that asphalt pavement is susceptible to low temperature cracking if the stiffness of asphalt mixture at 180 seconds is higher than 10 GPa. It coincides with results obtained during the SHRP.

Another approach to the restriction of low temperature cracking is based on IDT creep and strength tests. A critical cracking temperature, which has to be lower than the lowest pavement temperature to prevent asphalt pavement from low temperature cracking, is determined at the intersection between the thermal stress–temperature curve and the tensile strength–temperature curve (Lytton *et al.* 1993; Vinson *et al.*

Table 1. Advantages and disadvantages of tests used to evaluate asphalt mixture resistance to low temperature cracking

Advantages	Disadvantages
Indirect tensile test (IDT)	
<ul style="list-style-type: none"> – ability to simulate a state of stress to the state induced under the wheel – creep compliance and strength can be determined – reasonable repeatability and reproducibility – failure plane is known (if strength test is conducted) – specimen geometry is suitable for laboratory compacted specimens and field cores 	<ul style="list-style-type: none"> – time-consuming test – calculation procedure requires highly qualified specialists – expensive equipment and extensometers – time-consuming calibration – does not simulate low temperature cracking
Bending beam rheometer (BBR) test	
<ul style="list-style-type: none"> – the very easy test procedure – small specimen size – reasonable test duration – reasonable device price – extensometers are not used – user-friendly calibration verification – reasonable repeatability and reproducibility – effect of ageing at very small pavement depth can be evaluated 	<ul style="list-style-type: none"> – the thickness of beam is smaller than maximum aggregate size (for almost all asphalt mixtures) – results depend on cooling medium (air, potassium acetate or ethanol)
Thermal stress restrained specimen test (TSRST)	
<ul style="list-style-type: none"> – a strong correlation between transition temperature and fracture temperature – reasonable repeatability and reproducibility – reasonable test duration – field conditions are simulated (low temperature cracking) – temperature and loading vary simultaneously – either a beam or cylindrical specimen can be used 	<ul style="list-style-type: none"> – difficult specimen preparation – bending in the specimen, which leads to a non-uniform stress distribution – expensive equipment and extensometers – stress concentration near the ends of the specimen (almost all the time) – sample failure can occur owing to misalignment – failure plane usually occurs at any location over the specimen
Asphalt thermal cracking analyser (ATCA)	
<ul style="list-style-type: none"> – two beams can be simultaneously tested – glass transition temperature (T_g) and coefficients of thermal expansion and contraction are obtained – evaluate thermal fatigue (thermal cycles) and physical hardening (isothermal conditioning) – there is an appropriate alignment of the end plates with specimen – relaxation modulus can be determined 	<ul style="list-style-type: none"> – is not widely used (only in the USA) – has been recently developed, and test results have to be compared to field performance
Single-edge-notched beam (SE(B)) test	
<ul style="list-style-type: none"> – reasonable repeatability and reproducibility – materials can be tested in mixed mode (mode I and mode II) – specimen size meets RVE concept 	<ul style="list-style-type: none"> – difficult specimen preparation – specimen geometry (beam) is not suitable for laboratory compacted specimens and field cores – researchers use different specimen sizes and loading modes
Semi-circular bending (SCB) test	
<ul style="list-style-type: none"> – specimen geometry is suitable for laboratory compacted specimens and field cores – two specimens per core or slice – reasonable repeatability and reproducibility – specimen size meets RVE concept – can be used to determine creep compliance 	<ul style="list-style-type: none"> – issues related to loading head compression testing – expensive equipment and displacement transducers (both LLD and CMOD are required) – an arch effect with high compressive stress near the crack – moderate repeatability and reproducibility – quite small a ligament area
Disc-shaped compact tension (DC(T)) test	
<ul style="list-style-type: none"> – specimen geometry is suitable for laboratory compacted specimens and field cores – reasonable repeatability and reproducibility – specimen size meets RVE concept – quite large a ligament area – can be used to determine creep compliance 	<ul style="list-style-type: none"> – expensive equipment and displacement transducers – microcracks can appear around the loading holes during specimen preparation – possible cracking close to loading holes

Continued Table 1

Fenix	
<ul style="list-style-type: none"> – specimen geometry is suitable for laboratory compacted specimens and field cores – a wide range of test temperatures (from ≥ 20 °C to ≤ 25 °C) – reasonable repeatability and reproducibility 	<ul style="list-style-type: none"> – is not widely used – results are affected by bitumen content
Asphalt concrete cracking device (ACCD)	
<ul style="list-style-type: none"> – field-like conditions – reasonable repeatability and reproducibility – reasonable test duration – four or more specimens can be tested at once – no alignment problem 	<ul style="list-style-type: none"> – is not widely used – results are affected by the amount of polymers (their concentration)
Spectral analysis of acoustic emission	
<ul style="list-style-type: none"> – rapid, convenient – reasonable repeatability and reproducibility – assess the RAP presence in the asphalt mixture – non-destructive test – air void content does not affect results 	<ul style="list-style-type: none"> – sensitive to ageing level and bitumen grade – depends on the thermal load application – sensitive to noises coming from surrounding environment

1989). This approach is incorporated in the TC model, which is included in the current used MEPDG (Hallin 2004). However, it incorrectly assesses asphalt mixture performance. Research has shown that critical cracking temperature determined by IDT results was consistently lower than PG low temperature and was unable to differentiate among asphalt mixtures (Zofka, Braham 2009).

Jones *et al.* (2014) conducted field surveys and BBR tests with asphalt mixtures from the field. According to the results, they created the Black Space diagram and revealed a possible thermal stress failure envelope, which indicates a critical stiffness and m -value. The higher the stiffness or the lower the m -value, the more prone to low temperature cracking asphalt mixture is.

After the development of fracture mechanics-based tests, new criteria had to be determined for asphalt mixture resistance to low temperature cracking. In the USA a huge low temperature cracking pooled fund study consisting of two phases was conducted for this purpose. Field performance (low temperature cracking) was correlated with SCB and DC(T) results for the same asphalt mixtures used in the field. Specimens for laboratory tests were prepared from the original loose mixture.

A minimum G_f of 350 J/m² determined at a temperature 10 °C higher than PG low temperature was suggested as the criterion for the SCB test. This limit was increased up to 400 J/m² to estimate the ageing effect on asphalt pavement performance. A minimum K_{IC} of 800 kPa·m^{0.5} was also introduced as an additional check for good fracture resistance. However, any adjustment because of the ageing effect was not proposed for K_{IC} (Marasteanu *et al.* 2012).

A minimum G_f of 400 J/m² determined at a temperature 10 °C higher than PG low temperature was suggested as the criterion for the DC(T) test. G_f from 350 J/m² to 400 J/m² was considered an acceptable limit in projects of lesser importance, where a low or moderate degree of low temperature cracking is allowed. However, in projects

of high importance, where high smoothness has to be achieved, a minimum G_f of 600 J/m² was specified. Since these specifications were based on cores taken out of older pavements rather than laboratory compacted specimens and specimens were prepared from loose mixtures, a 15% increase in G_f was proposed. Consequently, the G_f criterion for projects of low importance, where the equivalent single axle loads (ESALs) are less than 10 million, is 400 J/m². If it is a project of moderate importance, where ESALs are from 10 million to 30 million, the G_f criterion is 460 J/m². For projects of high importance, where ESALs are more than 30 million, the G_f criterion is 690 J/m². These requirements are valid for laboratory compacted specimens and have to be met at a temperature 10 °C higher than the PG low temperature (Marasteanu *et al.* 2012).

Table 2 presents the limiting criteria for asphalt mixture resistance to low temperature cracking. If asphalt mixture meets these requirements, it is resistant to low temperature cracking. The given limiting values can also be used to determine the critical cracking temperature, which is defined as the lowest temperature at which asphalt mixture can withstand induced thermal stresses.

4. Conclusions

1. An appropriate evaluation of asphalt mixture's performance at low temperatures enables to deal with low temperature cracking. However, a comprehensive knowledge of both test principle and limiting criteria is vital seeking to assure proper performance of asphalt pavements at low temperatures.

2. Tests for the evaluation of asphalt mixture performance at low temperatures are based on the:

- continuum (Indirect Tensile Test creep and strength, the Bending Beam Rheometer test, the Thermal Stress Restrained Specimen Test, the Asphalt Thermal Cracking Analyser);

Table 2. Limiting criteria for asphalt mixture resistance to low temperature cracking

Criteria	Limiting value/condition	Test	Reference
Stiffness at 180 s	≤ 10 GPa		Deme, Young 1987
Fracture temperature	lower than the lowest pavement temperature	TSRST	Jung, Vinson 1994
Critical cracking temperature	lower than the lowest pavement temperature	IDT creep compliance and IDT strength	Vinson et al. 1989 Lytton et al. 1993
Stiffness at 60 s ($S(60)$) ¹⁾	the specific envelope is suggested	BBR	Jones et al. 2014
m-value at 60 s ($m(60)$) ¹⁾	specific envelope is suggested	BBR	Jones et al. 2014
Fracture energy at $PG_{LT}+10^{\circ}C$ (G_f)	≥ 400 J/m ²	SCB	Marasteanu et al. 2012
Fracture toughness at $PG_{LT}+10^{\circ}C$ (K_{IC})	≥ 800 kPa·m ^{0.5}	SCB	Marasteanu et al. 2012
Fracture energy at $PG_{LT}+10^{\circ}C$ (G_f)	≥ 400 J/m ²	DC(T)	Marasteanu et al. 2012
Cracking temperature	lower than the lowest pavement temperature	ACCD	Kim et al. 2010
Embrittlement temperature	lower than the lowest pavement temperature	AE	Buttlar et al. 2011

Notes: ¹⁾ – time–temperature superposition principle is applied.

- fracture mechanics (Single-Edge-Notched Beam test, the Semi-Circular Bending test, the Disc-Shaped Compact Tension test and the Fenix test);
- acoustic emission (Spectral Analysis of Acoustic Emission).

A correlation between laboratory and field results, test repeatability and reproducibility, test duration, specimen geometry, and size are the decisive factors in the test selection.

3. Based on the results of studies conducted on the asphalt mixture resistance to low temperature cracking and the development of test methods used to evaluate its performance, advantages and disadvantages of these tests are provided in this paper.

4. Looking further spectral analysis of acoustic emission could be defined as the most promising approach for the evaluation of asphalt mixture resistance to low temperature cracking. It is non-destructive, rapid and convenient and has the best repeatability and reproducibility (coefficient of variation is less than 10%). Besides, it can detect, locate and identify cracks as well as the presence of Reclaimed Asphalt Pavement.

5. The Semi-Circular Bending test and the Disc-Shaped Compact Tension test can be used for the determination of both fracture properties and creep compliance. However, only the determination of fracture properties is standardized.

6. Creep compliance and strength are the main parameters used in current Thermal Cracking models of Mechanistic-Empirical Pavement Design Guide. However, they do not directly assess asphalt mixture performance at low temperatures. Therefore, fracture energy is a necessary criterion dealing with low temperature cracking and an essential input to thermal cracking model IlliTC, which was developed at the University of Illinois Urbana-Champaign. In addition, the fracture toughness can be used as the additional criterion to the fracture energy.

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