"Environmental Engineering" 10th International Conference
Vilnius Gediminas Technical University
Lithuania, 27–28 April 2017
http://enviro.vgtu.lt

eISSN 2029-7092 / eISBN 978-609-476-044-0

Article ID: enviro.2017.137
DOI: https://doi.org/10.3846/enviro.2017.137

Analysis of Methods and Criteria for Evaluation of Bitumen Performance at Low Temperatures

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Abstract. Thermal cracking is the dominant pavement failure in the cold regions. After each winter, the newly appeared cracks have to be sealed. However, after a few years depending on the sealing method the previously sealed cracks have to be resealed. It results in high maintenance budget and human resources. The appropriate bitumen selection on the basis of bitumen performance at low temperatures can reduce the effect of thermal cracking. For this purpose, number of methods are developed such as Fraass test, bending beam rheometer (BBR) test, direct tension (DT) test, asphalt binder cracking device (ABCD), dynamic shear rheometer using 4 mm diameter parallel plates (4-mm DSR) test, single-edge-notched bending (SENB) test, double-edge-notched tension (DENT) test and spectral analysis of acoustic emission (AE). This paper presents the analysis of different tests for the evaluation of the bitumen performance at low temperatures, highlights their advantages and disadvantages and gives their limiting criteria. These limiting criteria are usually used to determine the critical cracking temperature, which is defined as the lowest temperature at which bitumen can withstand induced thermal stresses.

Keywords: bitumen performance, critical cracking temperature, fracture mechanics, low temperature, thermal cracking.

Conference topic: Roads and railways.

Introduction

In cold regions, asphalt pavements are subjected to thermal cracking. There exist two types of thermal cracking: thermal fatigue cracking and low temperature cracking (Shahin, McCullough 1972). Thermal fatigue cracking occurs because of thermal cycling. The daily thermal stresses are accumulated and over a sufficiently long time cracking may occur. Low temperature cracking occurs because of a single low temperature, which induces the thermal stresses higher than the tensile strength of material.

Thermal cracking leads to faster pavement deterioration, because water through cracks can penetrate into pavement structure and causes stripping, frost heaves, reduction in the bearing capacity and rough pavement surface. Thus, after each winter appeared thermal cracks are sealed. However, after a few years depending on the sealing method the previously sealed cracks have to be resealed. It results in high maintenance budget and human and time resources.

The control of factors affecting thermal cracking can prevent pavement from suffering this distress. However, often it is impossible (e.g. to control environmental conditions). Consequently, the other solutions have to be applied. The appropriate bitumen selection on the basis of its performance at low temperatures is one of them (Anderson, Kennedy 1993; Bouldin *et al.* 2000; Anderson *et al.* 2001; Bahia *et al.* 2012; Gražulytė *et al.* 2016; Vaitkus *et al.* 2017). Researchers have developed many tests (e.g. Fraass test, bending beam rheometer (BBR) test, direct tension (DT) test, asphalt binder cracking device (ABCD), dynamic shear rheometer using 4 mm diameter parallel plates (4-mm DSR) test, single-edge-notched bending (SENB) test, double-edge-notched tension (DENT), and spectral analysis of acoustic emission (AE)) to deal with low temperature cracking. However, the results from different tests can differ and cannot be compared with each other, because these tests are carried out at different loading and climatic conditions. Therefore, a comprehensive knowledge of test concept and limiting criterion for each test are vital. Otherwise, a selection of tests for the evaluation of bitumen resistance to low temperature cracking and an interpretation of the results can become an issue.

This paper focuses on the bitumen tests, which are used to evaluate its resistance to low temperature cracking. The limiting criterion for each test is also given. Thermal fatigue cracking is not an objective for this paper.

Bitumen tests addressing low temperature cracking

According to approach, which addresses low temperature cracking, bitumen tests can be grouped into:

- continuum-based tests (Fraass, BBR, DT, ABCD, 4-mm DSR);
- fracture mechanics-based tests (SENB, DENT);
- acoustic emission-based tests (AE).

Firstly, continuum-based tests were developed. However, the existing performance grade (PG) specification, which is based on the BBR and DT tests, failed in a low temperature cracking prediction, especially for modified bitumens (Hesp 2004; Iliuta *et al.* 2004, Hesp *et al.* 2009a, 2009b). Consequently, the fracture mechanics-based tests were proposed (Hoare, Hesp 2000; Anderson *et al.* 2001; Kim *et al.* 2006). Acoustic emission-based test were proposed as rapid, simple, portable test, which is applicable to modified bitumens. Besides, results are not susceptible to the specimen geometry (Apeagyei *et al.* 2009).

Continuum–based tests

Continuum-based tests are the most common used tests to evaluate bitumen performance at low temperatures. There is assumed that low temperature cracking occurs if low temperature induces thermal stresses higher than material's strength. In the case of continuum approach, specimen without a pre-existing crack is used.

Fraass test is one of the oldest tests used to evaluate bitumen susceptibility to low temperature. It was developed by Fraass in 1937. A steel plate coated with a 0.5 mm thick bitumen layer is bended and released every 1 °C while the air temperature is constantly decreased at a rate of 1 °C/minute. The temperature at which bitumen cracks is recorded and referred to the Fraass breaking point. The researchers found out that bitumen stiffness at the Fraass breaking point is approximately 2100 MPa (Thenoux *et al.* 1987). It is similar to the maximum bitumen stiffness suggested by Heukelom (1966). However, the Fraass breaking point does not show the actual bitumen performance at low temperatures especially if modified bitumen is used (Jellema *et al.* 2012; Radziszewski *et al.* 2014).

BBR and DT tests were developed within the Strategic Highway Research Program (SHRP) (Petersen *et al.* 1994). BBR are based on the elementary bending theory. An effect of shear is neglected because a ratio of span and beam thickness is not higher than 16. In the test a prismatic beam is placed on the two supports and in the middle constantly loaded of 980 mN. BBR test is conducted using a time-temperature superposition (TTS) principle. According to this, stiffness at a loading time of 60 s at T °C temperature is approximately equal to the stiffness at a loading time of 2 hours at T-10 °C temperature (Anderson, Kennedy 1993). However, results from BBR test are significantly affected by physical hardening (Lu, Isacsson 2000; Marasteanu *et al.* 2004b). Besides, criteria for stiffness and m-value at a loading time of 60 s were developed for neat bitumens. Thus, in most cases these criteria fail for modified bitumens (Dongré *et al.* 1997; Kluttz, Dongré 1997; Bouldin *et al.* 1999). Last researches showed that the benefit of a specified high m-value is questionable, because bitumen with lower m-values sometimes shows slower development of thermal stresses, which is desirable property (Marasteanu 2004; Marasteanu *et al.* 2004a). The cooling medium has a little effect on stiffness. However, if BBR is used to determine the strength, it becomes significant. The strength in ethanol is about 4.5 time lower than in portassium acetate (Falchetto *et al.* 2012). Air can also be used to control the test temperature, but it is more complicated than using fluid. Thus, BBR is typically conducted in fluid (ethanol) bath.

In DT test specimen shaped like a dog bone is stretched at a constant deformation rate of 1 mm/min until it fails. This test is valid when bitumen fails in a brittle-ductile mode, i.e. when failure strain is less than 10%. If bitumen is ductile, the failure stress and strength are assumed at deformation of 10%; otherwise it is recorded at failure (Anderson, Dongre 1995). DT test results depend on the cooling medium (air, portassium asetate or ethanol). The strength in ethanol is three to five times lower than in air or portassium acetate (Dongré, D'Angelo 1998).

A thermoviscoelastic model to calculate thermal stresses on the basis of BBR test data has been incorporated in American Association of State and Highway Transportation Officials (AASHTO) standards since 2002. The calculated thermal stresses from BBR test data are compared to the failure stress from the DT test. This mechanistic model was developed by Bouldin *et al.* (2000). However, this method also over predicts low temperature cracking as well as BBR and DT tests (Shenoy 2002).

A. Shenoy suggested a simple method to evaluate bitumen performance at low temperatures directly from BBR test data without the use of the DT test. A single or two asymptotes of thermal stresses curve computed from the BBR test data are used. An intersection of higher stress asymptote with x-axis is determined using single asymptote procedure while an intersection of higher stress asymptote and lower stress asymptote is determined using two asymptotes procedure. A good correlation ($R^2 = 0.9$) was obtained between proposed methods and Bouldin *et al.* (2000) method. However, proposed methods more accurate predict low temperature cracking than Bouldin *et al.* (2000) method and is less sensitive to physical hardening (Shenoy 2002; Marasteanu *et al.* 2004b).

The effect of physical hardening on susceptibility to low temperatures is evaluated by Extended Bending Beam Rheometer (ExBBR) test. Test procedure is similar to regular BBR test, however specimens are conditioned for periods of 1 h, 24 h and 72 h. Researchers determined a reasonable correlation between results of ExBBR test and field performance. Asphalt mixtures containing bitumens that had low grade loss in ExBBR test performed well in field while those that had high grade loss often failed prematurely. Besides, ExBBR test better predicted low temperature cracking than regular BBR and DT tests (Ou Zhao, Hesp 2006; Hesp *et al.* 2009a, 2009b).

In ABCD test is measured the thermal stresses of a restrained bitumen specimen shaped like a ring during the cooling and the cracking temperature is directly determined by the strain jump when crack appears (Kim 2005; Kim *et al.* 2006). Strain jump increases if modified bitumen is used and results in lower cracking temperature (Jellema *et al.* 2012). The invertors reported a strong correlation of cracking temperature and PG specifications. However, a poor correlations between cracking temperature and results from BBR and SENB tests were determined

(Velasquez *et al.* 2011; Marasteanu *et al.* 2012). It is not clear which of these tests gives better prediction of low temperature cracking.

DSR test with 4 mm diameter parallel plates was developed to evaluate bitumen performance at low temperatures (Sui *et al.* 2010, 2011). Researchers reported that shear stress relaxation modulus at low temperatures correlates well with the stiffness from regular BBR test. In addition, the loss tangent can be used as surrogate performance indicator for control of low temperature cracking (Soleimani *et al.* 2009). The effect of physical hardening on complex shear modulus was observed within two hours. Later it dramatically slowed downed or stopped (Farras *et al.* 2015).

Fracture mechanics-based tests

Existing PG specification methods do not prevent asphalt pavements from thermal cracking especially if modified bitumen is used (Hesp 2004; Iliuta *et al.* 2004; Hesp *et al.* 2009a, 2009b). Thus, there was a need to invent new tests, which could better characterize bitumen performance regarding to low temperature cracking. Besides, the effect of physical hardening had to be incorporated. Fracture mechanics can deal with it. Moreover, fracture properties reveal the effect of modification (Hoare, Hesp 2000; Roy, Hesp 2001; Andriescu *et al.* 2004). In the fracture mechanics-based tests a specimen with a pre-existing crack is used. This pre-existing crack (notch) can significantly influence material behaviour and make it weaker. For example, unnotched specimen can show about 10 °C lower critical cracking temperature than notched specimens (Ponniah, Hesp 1996; Iliuta *et al.* 2004). There can be applied the linear or nonlinear fracture mechanics depending on the size of the process zone and specimen. Tests usually are conducted before and after physical hardening and the loss in grade temperature is also determined.

Fracture properties (fracture toughness (K_{IC}) and fracture energy (G_f)) of the bitumen in its brittle state is determined by SENB test, which is similar to regular BBR test, however, specimen has a notch (Lee, Hesp 1994; Hesp 2004; Iliuta *et al.* 2004). A strong correlation between a maximum deflection at fracture and field performance was determined. Thus, it was also proposed as a parameter that indicates the ductile to brittle transition of bitumen (Velasquez *et al.* 2011; Bahia *et al.* 2012). In SENB test is assumed that linear fracture mechanics conditions are hold. In order to reduce the amount of bitumen two metal bars were commonly used (Hoare, Hesp 2000; Hesp 2003). However, too little adhesion between the bitumen and these bars was observed and a new geometry based on the BBR moulds was proposed (Velasquez *et al.* 2011).

Fracture properties (essential work (w_e), plastic work (w_p) and crack tipo opening displacement (CTOD)) of the bitumen in its ductile state is determined by DENT test (Andriescu *et al.* 2004; Ou Zhao, Hesp 2006; Andriescu, Hesp 2009). DENT test can also be used for determination of K_{IC} and G_{IC}, however a different loading rate is used (Li *et al.* 2006; Zofka, Marasteanu 2007). In both tests is applied a linear elastic fracture mechanics. Bitumens that performed well in the DENT test showed little thermal cracking in the field (Hesp *et al.* 2009a). Failure stress and strain from DENT test are approximately 3 times lower than from the DT test (Zofka, Marasteanu 2007).

Acoustic emission-based tests

Acoustic emission approach is based on the sudden release of energy from localized damage (crack) in form of transient mechanical elastic waves within a stressed material. Emitted waves from micro-damage sites travel within the material and are detected by sensitive surface-mounted sensors (Maji *et al.* 1990). The acoustic emission usually occurs at a certain temperature which is referred to the "embrittlement temperature (T_{EMB})" of the material (Behnia *et al.* 2010; Apeagyei *et al.* 2009). Test procedure is described in these papers (Apeagyei *et al.* 2009; Buttlar *et al.* 2011). T_{EMB} better characterize bitumen performance than regular BBR and DT tests. T_{EMB} of five MnROAD test sections were higher than low temperature PG of their bitumens. In addition to this, the severity of thermal cracking was proportional to the difference between T_{EMB} and low temperature PG. The higher difference, the more cracked pavement was (Behnia *et al.* 2016).

In Table 1 are summarized the advantages and disadvantages of previously discussed tests used to evaluate bitumen resistance to low temperature cracking.

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

Test	Advantages	Disadvantages
Continuum-based tests		
Fraass	– easy to perform – direct mechanical test	– does not show actual bitumen behaviour in the pavement at low temperatures – difficult to visualise the crack (especially if modified bitumen is used) – poor repeatability and reproducibility
BBR (regular)	– effect of shear can be neglected – simple interpretation of the results – time-temperature superposition principle is applied – reasonable repeatability and reproducibility	– results highly depend on the beam geometry (especially on a thickness) – specimen preparation requires high precision – results are highly affected by physical hardening – in most cases test is suitable only for neat bitumen

End of Table 1

Test	Advantages	Disadvantages
	–	– m-value criterion is questionable – results depend on cooling medium (air, portassium asetate or ethanol) – fairly long time to reach test temperature – hard to apply to extracted bitumen, because there is a need approximately 15 g per beam – time consuming.
DT	– simple interpretation of the results – time-temperature superposition principle is applied	– results are highly affected by physical hardening – specimen preparation requires high precision – in most cases test is suitable only for neat bitumen – results depend on cooling medium (air, portassium asetate or ethanol) – poor repeatability and reproducibility – fairly long time to reach test temperature – time consuming
BBR and DT[1), 2)]	– thermal stresses are calculated – direct bitumen strength is determined – better correlation between laboratory results and field performance than using only BBR (regular) or DT	– specimen preparation requires high precision – calculation procedure requires highly-qualified specialists – over predict low temperature cracking
BBR with asymp-totes[1)]	– only BBB is required – thermal stresses are calculated – better correlation between laboratory results and field performance than using only BBR (regular) or DT	
ExBBR [1)]	– evaluate physical hardening	
ABCD	– test is suitable for both neat and modified bitumens – reasonable repeatability and reproducibility – critical temperature is directly determined	– cumbersome because strain gauges are used – hard to apply extracted bitumen, because there is a need approximately 15 g per specimen
DSR	– only 25 mg of bitumen is required for specimen – high premold temperature (above 135 °C) is not necessary; specimen can be directly loaded into the DSR at 50 °C to 70 °C – results are influenced by physical hardening only for specific period – test is suitable for both neat and modified bitumens – reasonable repeatability and reproducibility – time-temperature superposition principle can be ap-plied	– specimen preparation requires high precision – calculation procedure requires highly-qualified specialists
Fracture mechanics-based tests		
SENB	– test is suitable for both neat and modified bitumens – evaluate the degree of modification – reasonable repeatability and reproducibility – better correlation between laboratory results and field performance than using Superpave binder specification	– hard to apply to extracted bitumen, because there is a need approximately 15 g per beam – interpretation of the results requires highly-quali-fied specialists
DENT		– interpretation of the results requires highly-quali-fied specialists
Acoustic emission-based tests		
AE	– embrittlement temperature (T_{EMB}) is directly deter-mined – test is suitable for both neat and modified bitumens – reasonable repeatability and reproducibility – strong correlation between cracking temperature and PG system binder specification	– hard to apply to extracted bitumen, because there is a need approximately 15 g per beam – interpretation of the results requires highly-quali-fied specialists, who specializes in acoustics

Notes: 1) – advantages and disadvantages are the same as in BBR (regular) test.
2) – advantages and disadvantages are the same as in DT test.

Criteria for evaluation of bitumen resistance to low temperature cracking

Criteria for evaluation of bitumen resistance to low temperature cracking are constantly developed. Firstly, the bitumen properties such as penetration, softening point and kinematic viscosity were used to evaluate it. It was assumed that if McLedo's dimensionless Pen-Vis Number (PVN) is lower than –0.6, bitumen is susceptible to low temperature cracking and if PVN is lower than -1.0, bitumen susceptibility to it is high (Robertson 1987).

Later, the implemented research by SHRP resulted in PG specifications, where BBR test and DT test are used to evaluate bitumen resistance to low temperature cracking (Anderson, Kennedy 1993). A criterion for bitumen stiffness at a loading time of 60 seconds is based on Readshaw's research, which revealed that bitumen with stiffness lower than 200 MPa after a loading time of 2 hours at the lowest pavement service temperature is resistant to low temperature cracking (Readshaw 1972). Research team working under SHRP Contract A–005A raised this limit to 300 MPa and applied the time-temperature superposition principle (Lytton *et al.* 1993).

The criterion of m-value was based on the idea that high m-value leads to faster relaxation of the thermal stresses induced at low temperature. After a comparison of m-value of 0.35 proposed by research team working under SHRP Contract A-002A with the actual field performance, research team working under SHRP Contract A–005A reduced this limit to 0.30 (Lytton *et al.* 1993).

According to PG specifications, bitumen behaves as a brittle material at temperatures and loading rates where the failure strain is less than 1% in DT test.

Later, BBR and DT tests were combined and a new criterion was imposed on low temperature cracking.

Researchers found out a strong correlation between shear stress relaxation modulus at loading time of 7200 s (DSR test) and stiffness at loading time of 60 s (BBR test) as well as between apparent relaxation rate at loading time of 7200 s (DSR test) and m-value at loading time of 60 s (BBR test). According to this, the limiting criteria were determined (Sui *et al.* 2011). However, later the TTS principle was applied and criteria were adjusted regarding to 10 °C higher test temperature (Farras *et al.* 2015).

The last researches showed a good correlation between fracture properties and field performance (Hoare, Hesp 2000; Anderson *et al.* 2001; Kim *et al.* 2006). Thus, fracture toughness, fracture energy, displacement at the maximum load, essential work and plastic work were incorporated in bitumen's performance evaluation at low temperatures. However, limiting criteria of fracture toughness, essential work and plastic work have not been determined yet. It is an ongoing process. Nevertheless, the higher fracture properties, the more resistant to low temperature cracking bitumen is. In Table 2 are shown limiting criteria for bitumen resistance to low temperature cracking. If bitumen passes the limiting condition, it is resistance to low temperature cracking at a specific temperature. These limiting criteria are usually used to determine the critical cracking temperature which is defined as the lowest temperature at which bitumen can withstand induced thermal stresses.

Table 2. Limiting criteria for bitumen resistance to low temperature cracking

Criteria	Limiting value/condition	Test	Reference
Penetration index (I_P)	≥–1.5	Penetration at 25 °C Softening point	(Roireau 1986; Boutin, Lupien 2000)
McLedo's dimensionless Pen-Vis Number (PVN)	≥–0.6 ≥–1.0	Penetration at 25 °C Kinematic viscosity at 135 °C	(Robertson 1987)
Fraass breaking point	lower than the lowest pavement temperature	Fraass test	(Fraass 1937)
Stiffness at 60 s (S(60))[1)]	≤300 MPa	BBR	(Anderson, Kennedy 1993, Anderson *et al.* 2001)
m-value at 60 s (m(60))[1)]	≥0.30	BBR	(Anderson, Kennedy 1993; Anderson *et al.* 2001)
Failure strain	≥1%	DTT	(Anderson, Kennedy 1993)
Thermal stress from DT test	above the calculated thermal stress curve from BBR data	BBR DTT	(Bouldin *et al.* 2000)
Grade loss	≤6 °C	ExBBR	(Hesp *et al.* 2009a)
Shear stress relaxation modulus at 7200 s (G(7200))	≤160 MPa	DSR using 4 mm parallel plates	(Sui *et al.* 2011)
Apparent relaxation rate at 72000 s (m_r(7200))	≥0.26	DSR using 4 mm parallel plates	(Sui *et al.* 2011)
Shear stress relaxation modulus at 60 s (G(60))[1)]	≤140 MPa	DSR using 4 mm parallel plates	(Farras *et al.* 2015)
Apparent relaxation rate at 60 s (m_r(60))[1)]	≥0.28	DSR using 4 mm parallel plates	(Farras *et al.* 2015)
Fracture toughness (K_{IC})	–	SENB	–
Fracture energy (G_f)	≥100 J/m^2	SENB (loading rate of 0.01 mm/s)	(Hesp 2004)

End of Table 2

Criteria	Limiting value/condition	Test	Reference
Displacement at the maximum load	≥0.3 mm	SENB	2)
Fracture energy (G_{IC} or J)	≥100 J/m^2	DENT (loading rate of 0.01 or 0.001 mm/s)	(Hesp 2004)
Fracture toughness (K_{IC})	–	DENT (loading rate of 1.8%/min)	–
Essential work (w_e)	–	DENT (loading rate of 50 mm/min)	–
Plastic work (w_p)	–	DENT (loading rate of 50 mm/min)	–
Cracking temperature	lower than the lowest pavement temperature	ABCD	(Kim 2005; Kim *et al.* 2006)

Notes: 1) – TTS principle is applied.
2) – CEN/TS 15963 "Bitumen and bituminous binders - Determination of the fracture toughness temperature by a three point bending test on a notched specimen".

Conclusions

An appropriate evaluation of bitumen's performance at low temperatures indicates temperature limits at which asphalt pavements can perform without or with finite number of thermal cracks.

A strong correlation between laboratory test method results and field performance, reasonable repeatability and reproducibility, suitability for both neat and modified bitumens, specimen size and test cost are decisive factors in the selection of test method for bitumen's performance evaluation at low temperatures. The ability to assess physical hardening could be an additional factor.

Recently used bitumen's test methods addressing to low temperature cracking are based on continuum (Fraass, BBR, DT and DSR tests), fracture mechanics (SENB, DENT and ABCD tests) or acoustic emission (AE test).

Fracture mechanics-based test methods seem to be the most promising test methods for the evaluation of bitumen performance at low temperatures. The strong correlation between bitumen's fracture properties determined at laboratory and field was revealed. Besides, these methods are suitable for both neat and modified bitumens. However, limiting criteria for fracture toughness (SENB and DENT tests), essential work (DENT test) and plastic work (DENT test) have not been developed yet.

DSR test with 4 mm parallel plates enables the determination of bitumen's performance at any specific range of temperatures. Initial comparative experiments of bitumen test methods show sufficient correlation between DSR and BBR. However, there is a need for more tests to evaluate the correlation of DSR results obtained at low temperatures and field performance.

Acoustic emission test is a simple non-destructive testing method, which can directly determine at which specific temperature material cracks. Besides, it better characterizes bitumen performance at low temperatures than PG specifications and has lower coefficient of variation in comparison with mechanical tests (e.g. DT test).

Each test is performed at different loading and climatic conditions and has different limiting criterion. A strong correlation between limiting criterion and field performance is vital for the appropriate evaluation of bitumen resistance to low temperature cracking. Both stiffness at 60 s (≤300 MPa) and m-value at 60 s (≥0.3) are the most popular criteria despite the fact that they often fail in the restriction of low temperature cracking, especially if modified bitumens are used. These limits are also often used to determine criteria for other test methods (e.g. DSR test using 4 mm parallel plates).

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