COMPARING COLD PERFORMANCE RESULTS USING FRACTURE TOUGHNESS TEST, ASPHALT BINDER CRACKING DEVICE, FRAASS BREAKING POINT AND BENDING BEAM RHEOMETER

Erica Jellema[1], Erik Scholten[1], Sherida De Vries[1], Sang Soo Kim[3], Bob Kluttz[2]
[1]Kraton Innovation Center, Amsterdam, The Netherlands
[2]Kraton Innovation Center, Houston, TX, United States
[3]EZ Asphalt Technology, Athens, OH, United States

ABSTRACT

The commonly applied low temperature binder tests Fraass Breaking point and Bending Beam Rheometer have a limited ability to demonstrate the increased toughness at low temperatures of SBS modified binders. New tests are being evaluated that better address the toughness of a binder. The fracture toughness test is a three point bending test on a notched bituminous bar that determines the resistance to crack propagation. The test is currently being reviewed by CEN TC336 Working Group 1. A separate paper about the round robin test has been submitted for this congress. The Asphalt Binder Cracking Device (ABCD) test has been developed at Ohio university, United States. With this test the fracture temperature of the binder is being determined under field-like conditions. In this paper results with these new tests are compared with the Fraass Breaking point test and BBR. Three bitumen grades, both unmodified and SBS modified, have been used. The results demonstrate that both the fracture toughness test and the ABCD test have a much better ability to distinguish SBS modified binders from unmodified binders.

Keywords: low temperature testing, Fracture Toughness, ABCD test, BBR and Fraass, PMB

1. INTRODUCTION

The standard tests currently used to characterize the low temperature performance of bituminous binders are still the Fraass Breaking Point and the performance in the Bending Beam Rheometer (BBR). It is commonly acknowledged that both these methods are not fully capable of predicting (in fact, under-estimate) the low temperature performance of Polymer Modified Binders (PMB). The Asphalt Institute Report ER-215 [1] clearly shows a significant beneficial effect of polymer modification on low temperature induced defects, which are not recognized by the BBR. One potential explanation is the fact that none of the standard tests takes into account the resistance to crack propagation and tensile strength.

In the mountainous Eastern and South-Eastern parts of Turkey, the differences between the high and low temperatures are quite extreme and although it is widely accepted that polymer modification provides a solution to combat high temperature rutting problems, the outcome of the current low temperature tests is not convincing to determine whether it is also the solution for the low temperature performance. To this end, a concentrated effort has been made to evaluate Turkish PMBs using the fracture toughness test and a newly developed test in the US: the Asphalt Binder Cracking Device (ABCD) test.

The fracture toughness is a fundamental material property used in materials engineering to determine the resistance to crack propagation of metals, plastics, ceramics, etc. by a three point bending test on a notched bar. The development of this test for bituminous binders was initiated by S. Hesp [2-4]. Currently, the test is being evaluated by CEN TC336 Working Group 1 for bituminous applications [5]. A separate paper about the round robin test has been submitted for this congress. The Asphalt Binder Cracking Device (ABCD) test has been developed at Ohio University, United States [6,7] and was recently adopted as AASHTO Standard TP 92 [8]. With this test the fracture temperature of the binder is being determined under field-like conditions.

2. MATERIALS

In this work, three Turkish bitumen grades from the Izmit refinery are used: 50/70, 75/100 and 160/220 (Table 1).

Table 1: Properties of the three bitumen grades (Izmit refinery, Turkey)

Bitumen	50/70	75/100	160/220
Penetration at 25 °C (dmm)	50	64	174
Softening point (°C)	51.5	50	42.5
Fraass breaking point (°C)	–15	–16	–23

For the modification Kraton^{TM} D1192 (linear, high vinyl SBS) is used in a 5% concentration. All three SBS modified binders have a polymer continuous phase. The dispersion of SBS in the two harder bitumen grades is coarser than the more compatible 160/220 bitumen, which has the finest morphology. These binders, both SBS modified and unmodified, are evaluated in four different low temperature tests: Fraass breaking point, BBR, fracture toughness test and Asphalt Binder Cracking Device (ABCD).

3. LOW TEMPERATURE TESTING OF BITUMINOUS BINDERS BY FRACTURE TOUGHNESS METHOD

3.1 Fracture toughness test method

The fracture toughness test on the Turkish binders was performed according to CEN/TS 15963 [5]. The pre-notched three point bending test is used to measure cracking performance of unmodified and modified bituminous binder samples. The test sample is a beam with a notch in the middle of one side of the beam (Figure 1). The sample is conditioned in a temperature controlled bath. The beam is placed on two supports with the notch facing downwards and a vertical downward force is applied on the middle of the upper face of the sample. The beam is loaded until failure with a displacement rate of 0.01 mm/s, whereby force is recorded versus displacement.

The notch is created by placing a thin PTFE film in a spacing in the mould. The dimensions are given in Figure 2.

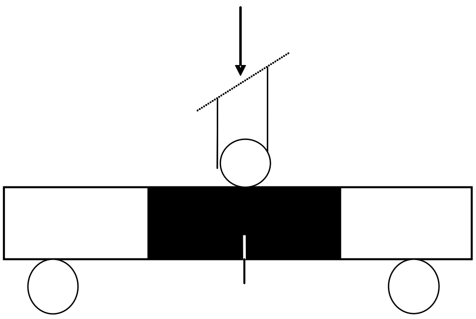

Figure 1: Schematic set-up of the fracture toughness test

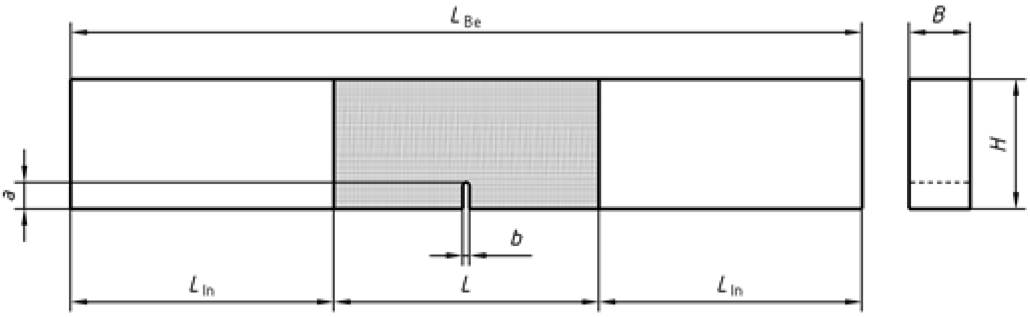

Figure 2: Specimen dimensions

Key

L_{Be}	beam length (120.0 ± 0.3)
L	specimen length (40.0 ± 0.2)
L_{In}	insert length (40.0 ± 0.1)
H	specimen height (25.0 ± 0.5)
B	specimen thickness (12.5 ± 0.3)
a	notch depth (5.0 ± 0.1)
b	notch width (2 × 25 µm)

A typical force-displacement curve is depicted in Figure 3. The fracture toughness temperature is determined as the temperature at which the displacement at break is 0.3 mm.

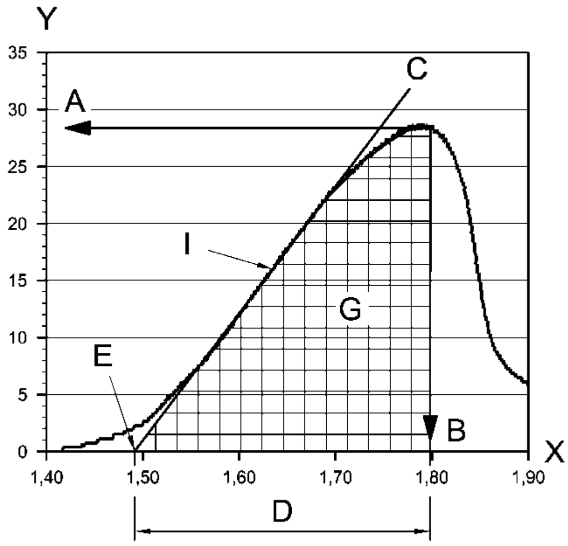

Figure 3: Typical force-displacement curve for the fracture toughness test (X = displacement, in millimetre (mm), Y = force, in Newton (N), A = maximum force (defined as *F*), B = X point at maximum force, C = tangent at the inflection point, D = displacement at maximum force, (*D* = B - E), E = zero point, G = work (defined as *W*), I = inflection point of *F* versus displacement)

3.2 Fracture toughness test results

All six binders (three grades, both unmodified and modified) were evaluated with the fracture toughness test. Force-displacement curves were obtained at several temperatures; the starting temperature for the pure 50/70 and 75/100 bitumen was –10 °C, while the testing of the SBS modified binders and the soft 160/220 bitumen started at –15 °C. For the unmodified and modified 160/220 bitumen based binders, the force-displacement curves at two different temperatures are shown in Figures 4, 5, 6 and 7 respectively. For the determination of the fracture toughness temperature, displacements larger than 1 mm were not taken into account. For example, the 160/220 bitumen shows a displacement of 1.2 mm at –15 °C and therefore only the results at –20 and –25 °C are used. At –25 °C, the displacement is smaller than 0.3 mm (Figure 5), which means that the fracture toughness temperature is between –20 and –25 °C.

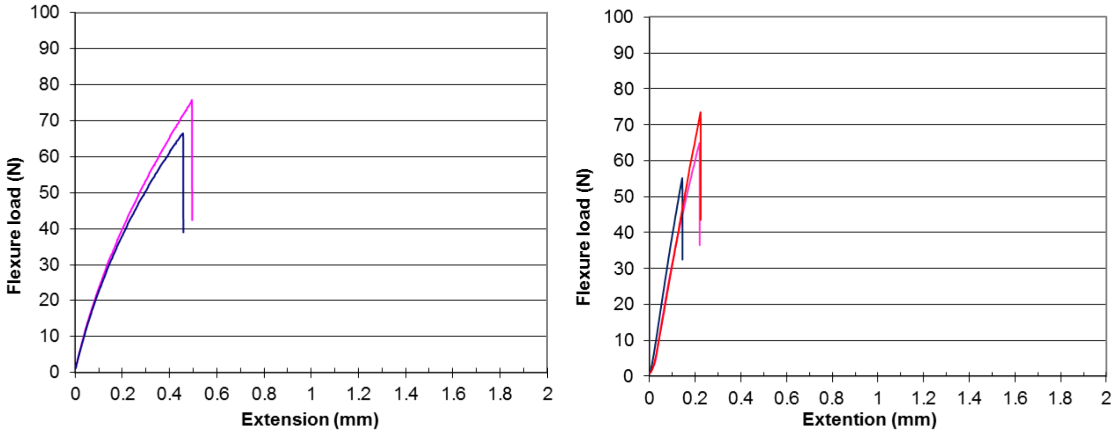

Figure 4 and 5: Force-displacement curves for 160/220 bitumen at –20 °C (left) and –25 °C (right)

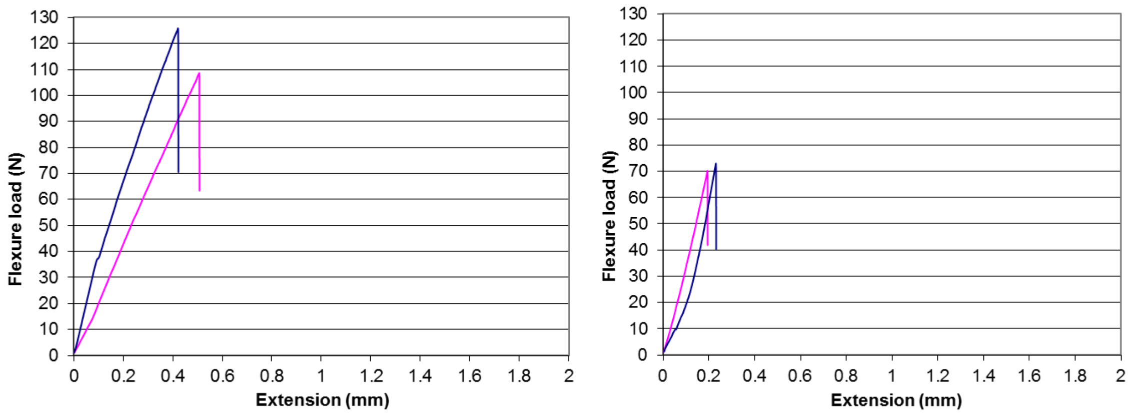

Figure 6 and 7: Force displacement curves for 5%m of D-1192 in 160/220 bitumen at –25 °C (left) and –35 °C (right)

Figures 5 and 6 clearly show the benefit of SBS modification; at –25 °C, the force needed to break the SBS modified sample (Figure 6) is significantly higher than the force needed to break the unmodified sample (Figure 5).

The found displacements at break (< 1 mm) as a function of the temperature for the 160/220 based binders are depicted in Figure 8. Interpolation of the data points enables to determine the fracture toughness temperature where the displacement is 0.3 mm. In this case the fracture toughness temperature for the unmodified binder is –23.5 °C, while modification leads to a lower fracture toughness temperature of –31 °C.

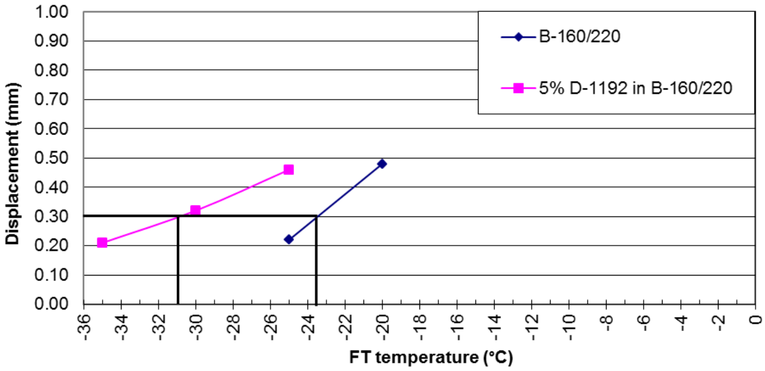

Figure 8: Fracture toughness temperature determination for the 160/220 bitumen based binders

For the four other binders, the unmodified and SBS modified 75/100 and 50/70 bitumen, the same experiments were performed. The difference between the maximum force levels of the 50/70 and 75/100 base bitumen grades is very small (see Figures 9 and 10), but the levels are significantly lower than those found for the 160/220 bitumen. The fracture toughness temperatures were determined by making use of the data shown in Figures 11 and 12, respectively.

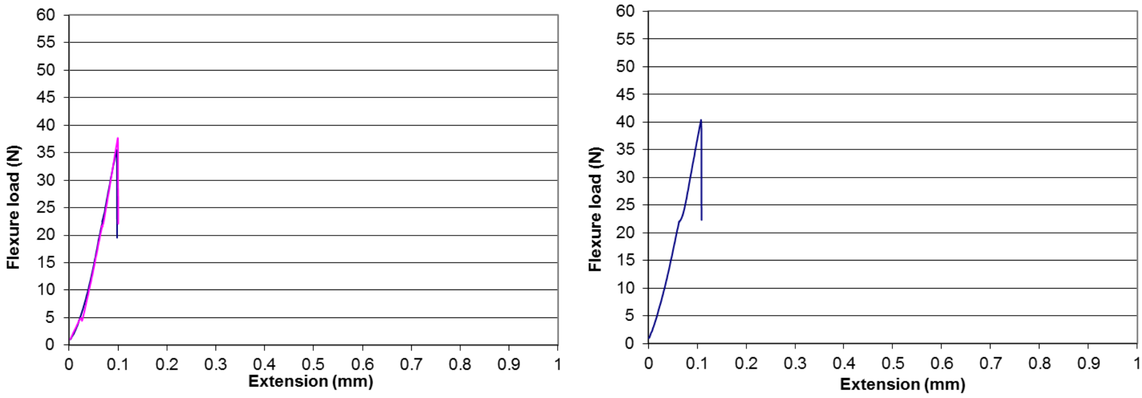

Figure 9 and 10: Force displacement curves at –25 °C for 50/70 bitumen (left) and 75/100 bitumen (right)

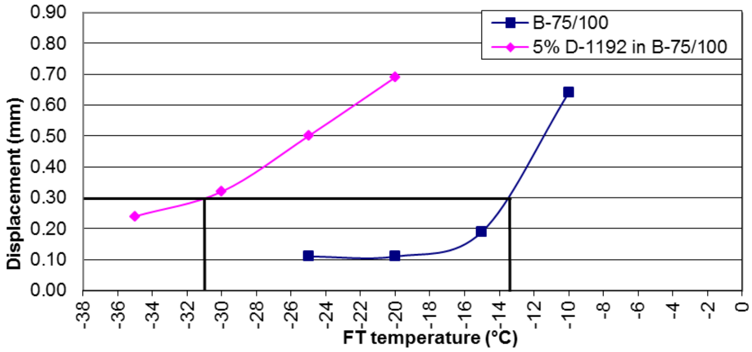

Figure 11: Fracture toughness temperature determination for the 75/100 bitumen based binders

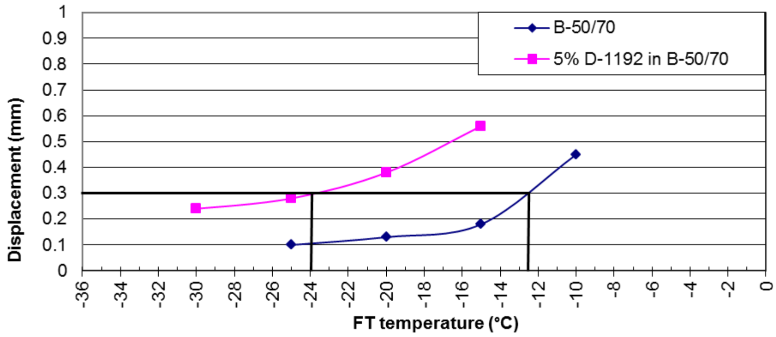

Figure 12: Fracture toughness temperature determination for the 50/70 bitumen based binders

The results of the fracture toughness tests on the Turkish bitumen based binders are summarized in Table 2. Clearly, the fracture toughness test is able to differentiate between different bitumen grades and SBS modified binders. The effect of SBS modification is shown by a drop in fracture toughness temperature. This reduction in fracture toughness temperature ranges from 7.5 °C for the 160/220 bitumen based binder to even 17.5 °C for the 75/100 bitumen based binder.

Table 2: Results of the fracture toughness test on the unmodified and modified Turkish binders

Binder	50/70	75/100	160/220	50/70 5% D1192	75/100 5% D1192	160/220 5% D1192
Fracture toughness temperature (°C)	–12.5	–13.5	–23.5	–24	–31	–31

4. LOW TEMPERATURE TESTING OF BITUMINOUS BINDERS WITH THE ASPHALT BINDER CRACKING DEVICE

4.1 Asphalt Binder Cracking Device (ABCD) test method
The asphalt binder cracking device (ABCD) was developed at the Ohio University (USA) [6-8] and measures the temperature and strain of a restrained asphalt binder ring subjected to a constant rate of cooling. Asphalt binder samples are heated and poured outside of an Invar ring placed in the centre of a silicone mould shown in Figure 13. The Invar ring includes a strain gauge to record the strain applied to it by contraction of the asphalt binder during cooling and a surface mounted resistance temperature detector (RTD) to record the temperature of the sample.

Figure 13: Silicone mould-ABCD ring assembly

Samples are cooled at a constant rate (typically 20 °C/h) and the cracking of the asphalt binder sample is represented as a jump in strain on a real-time plot. The ABCD cracking temperature of a test specimen is determined from the plot where the strain jumped abruptly, indicating the relief of thermal stress in the test specimen.

The ABCD strain jump is also determined from the temperature versus strain plot as shown in Figure 14. The strain jump is the post-crack strain minus the pre-crack strain. The pre-crack strain is the strain at the ABCD cracking temperature. The post-crack strain is estimated by the intersection of the vertical line at the ABCD cracking temperature and the tangential line of the straight portion of the temperature versus strain curve after crack.

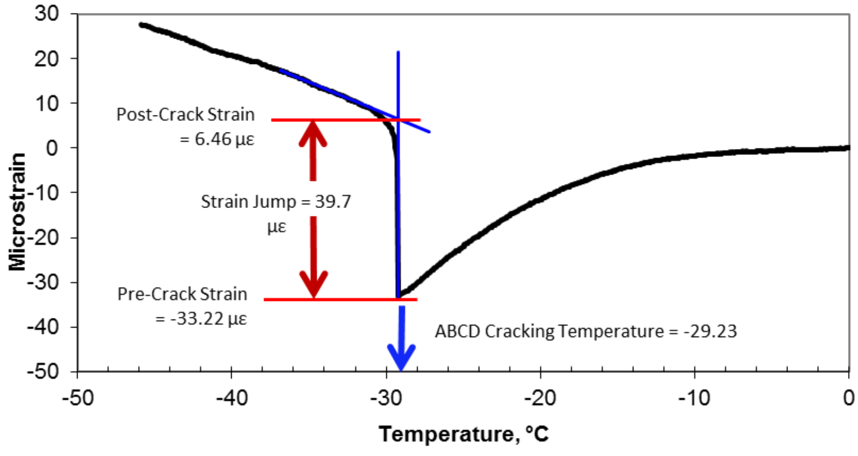

Figure 14: Typical ABCD test results: strain versus temperature

With the lubrication between the test specimen and the ABCD ring, the tensile force in the test specimen is assumed to be in equilibrium with the compressive force in the ABCD ring. Then, the fracture stress at the cracking temperature (σ_{AC}) is calculated using equation 1:

$$\sigma_{AC} = K \cdot F_{ABCD}/A_{AC} \qquad (1)$$

Where,

K = Stress Concentration Factor (approximately 2.0 for the dimensions of ABCD specimen and protrusion)
F_{ABCD} = thermal force in the ABCD ring, N
A_{AC} = cross-sectional area of the asphalt binder, m^2 (For the test specimen geometry, A = 4.03225 x 10^{-5} m^2)

For the specimen and ABCD ring geometries, the fracture stress (MPa) can be calculated by multiplying 0.157 to the strain jump (με). For example, the fracture stress of the test specimen in Figure 14 is 6.23 MPa (= 0.157 x 39.7).

4.2 Results of ABCD test with modified and unmodified Turkish bitumen

In this study, four binders have been tested with the ABCD: the 75/100 and the 160/220 bitumen with and without 5% of SBS. The unmodified binders showed more than usual scattering of the results. The clearest curves for the unmodified binders are depicted in Figure 15.

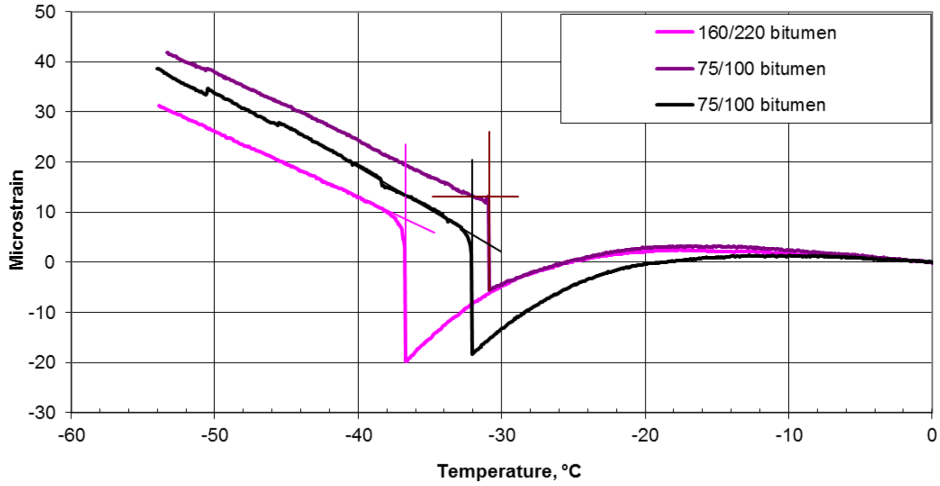

Figure 15: Strain versus temperature curve for unmodified 75/100 and 160/220 bitumen binders

Modification leads to lower cracking temperatures for these binders, which is shown in Figure 16 for the modified 160/220 bitumen and in Figure 17 for the modified 75/100 bitumen. Similarly, the strain jump increases due to the modification with SBS, corresponding with increased fracture strength.

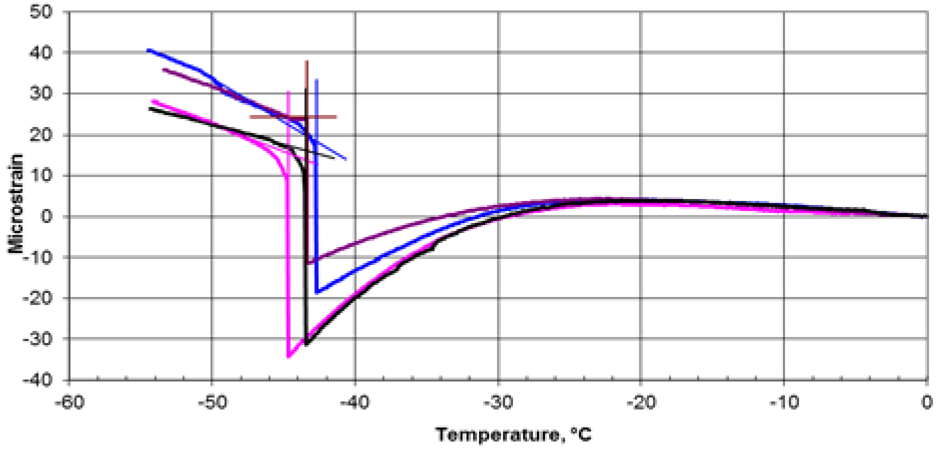

Figure 16: Strain versus temperature curve for 5% D1192 modified 160/220 bitumen (the lines indicate individual measurements)

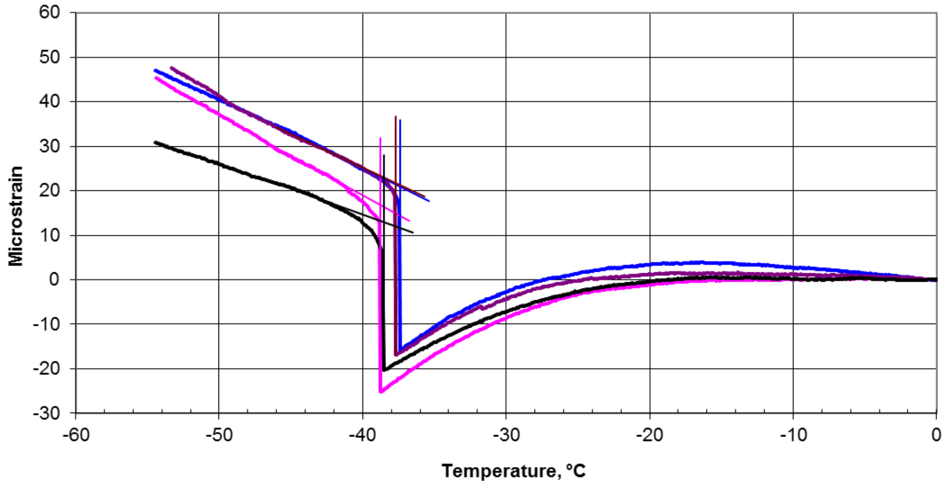

Figure 17: Strain versus temperature curve for 5% D1192 modified 75/100 bitumen

The results obtained with the ABCD are summarized in Table 3. The ABCD test results allow distinguishing the modified from the unmodified binders. The ABCD cracking temperatures are lower than those found with the fracture toughness test (Table 2).

Table 3: ABCD test results

Binder	Average cracking temperature in °C[a]	Average strain jump in microstrain[a]	Fracture strength in MPa[a]
160/220	–35.1 (1.55)	21.7 (5.34)	3.4 (0.84)
160/220 + 5% D1192	–43.5 (0.82)	42.5 (7.14)	6.7 (1.12)
75/100	–31.2 (1.57)	20.4 (2.34)	3.2 (0.37)
75/100 + 5% D1192	–38.1 (0.66)	37.6 (3.68)	5.9 (0.58)

a. Between brackets: standard deviation.

5. COMPARISON OF LOW TEMPERATURE TEST METHODS

5.1 Testing of modified and unmodified Turkish bitumen with BBR

All six binders were tested with the Bending Beam Rheometer (BBR) (Table 4). This method is standard in the USA, but gains more interest globally and focuses on stiffness and relaxation. For this study, the fresh binders were used for testing, which means that the materials were not aged in the rolling thin film oven (RTFO) and pressure aging vessel (PAV). Generally, RTFO and PAV aging leads to an increase of a full grade in the limit temperature.

Table 4: Results of evaluation of Turkish binders by BBR[a]

Binder	T (°C)	S, 60 s (MPa)[b]	m-value	S = 300, T (°C)[b]	m = 0.30, T (°C)	BBR limit, T(°C)
160/220	–18	128	0.414	–23.7	–27.4	–33.7
	–24	314	0.341			
160/220 + 5% D1192	–18	136	0.373	–23.7	–23.8	–33.7
	–24	314	0.297			
75/100	–18	226	0.356	–20.4	–22.4	–30.4
	–24	465	0.280			
75/100 + 5% D1192	–12	133	0.363	–18.6	–17.6	–27.6
	–28	279	0.296			
50/70	–12	146	0.382	–17.1	–18.8	–27.1
	–28	342	0.310			
50/70 + 5% D1192	–12	141	0.356	–17.9	–16.9	–26.9
	–28	303	0.287			

a. The binders were tested before RTFO and PAV aging. b. S = stiffness

The BBR low temperature grades rank with the penetration grades with about 3 °C difference between each. The 160/200 pen bitumens are limited by stiffness for both modified and unmodified while the 75/100 and 50/70 pen are limited by stiffness for the unmodified and m-value for the modified. That makes the combined BBR limit temperatures difficult to compare directly so this discussion will bear on comparisons of the stiffness values and m-values.

For all three base binders, SBS modification has a modest impact on stiffness. The significant impact is seen in the m-value. For all three bitumens, SBS modification reduces the limiting temperature by an average of 3 °C. While this difference is somewhat larger than normal, this effect, losing a degree in m-value temperature limit, is a well-known effect of SBS modification. This is a limitation of BBR theory which only accounts for rheological properties and does not account for increased strength or toughness.

5.2 Critical cracking temperature

In addition to the stiffness and m-value temperature limits, critical cracking temperatures (T_c) were calculated using the procedures defined in ASTM D 6816 [9]. In this practice, BBR isotherms are shifted to create the stiffness mastercurve which is converted to the relaxation modulus mastercurve using the Hopkins and Hamming method [10]. Numerically solving the convolution integral allows calculation of the thermally induced stress and the thermal stress build up can then be calculated based on Boltzmann superposition. Calculations were accomplished using the TSAR (Thermal Stress Analysis Routine) software from Abatech.

The BBR isotherms cited above were used for thermal stress calculation. Fracture stress values from the ABCD testing in Table 3 were used and the values were assumed to be constant over the temperature range that was considered. In addition, T_c was calculated assuming a constant failure stress of 4.0 MPa for all the bitumens to simulate BBR-alone analysis.

5.3 Fraass breaking point determination of modified and unmodified Turkish bitumen

The Fraass breaking point method is mainly used in Europe and focuses on crack initiation. The data in Table 5 show very similar temperatures for the 50/70 and 75/100 bitumen grades and also for the modified binders. The softer 160/220 binder has a significantly lower Fraass breaking temperature, which decreases further after modification.

5.4 Comparison of low temperature performance test methods

The average cracking temperatures obtained with the discussed methods (Fraass breaking point, BBR, fracture toughness, ABCD and T_c) are listed in Table 5.

Table 5: Average cracking temperatures determined with 4 methods: Fraass breaking point, BBR, fracture toughness and ABCD

Binder	Fraass breaking point (°C)	BBR limit T (°C)	Fracture toughness (°C)	ABCD (°C)	T_c^a (°C)	T_c^b (°C)
160/220	–23	–33.7	–23.5	–35.1	–32.4	–33.3
160/220 + 5% D1192	–27	–33.7	–31	–43.5	–35.4	–32.4
75/100	–16	–30.4	–13.5	–31.2	–29.0	–30.3
75/100 + 5% D1192	–17	–27.6	–31	–38.1	–29.9	–27.4
50/70	–15	–27.1	–12.5			
50/70 + 5% D1192	–18	–26.9	–24			

5.4.1 Unmodified Turkish binders

The Fraass breaking point and fracture toughness results of the pure bitumen grades show similar temperatures for the 50/70 and 75/100 bitumen and lower values for the softer 160/220 bitumen grade. Table 1 shows that the 75/100 bitumen grade is relatively hard with a penetration value of 64 dmm, which makes the small difference between these results more plausible.

The ABCD test results show lower absolute values than the other tests, but also here the softer bitumen has a lower cracking temperature. The BBR limit temperatures for the unmodified binders do show a ranking corresponding with hardness of the grade, but the differences are relatively small and do not show a much lower cracking temperature for the 160/220 bitumen.

5.4.2 Modified Turkish binders

The modification of the Turkish binders with SBS results in lower cracking temperatures when determined by Fraass breaking point, ABCD and fracture toughness tests. The BBR results do not show this trend at all; with the softest binder the BBR limit temperatures are the same and for the 75/100 bitumen based binder, modification leads to a slightly higher cracking temperature.

5.4.3 Critical cracking temperature

The calculated critical cracking temperatures show a trend similar to ABCD, though the differences between modified and unmodified are not nearly as pronounced. Note that the calculated temperatures assuming constant failure stress are very similar to the BBR limit temperatures. This reflects the balancing effects of SBS modification, a modest reduction in relaxation in rheological properties which is more than made up for by the increased toughness in tensile properties.

6. CONCLUSIONS

From field evaluations it has become clear that polymer modification has a positive effect on low temperature defects in roads, while the standard tests are hardly able to discriminate between unmodified and modified bitumens. Therefore, new tests are being developed both in Europe and in North-America to provide a better prediction of the low temperature performance of asphalt mixes. In order to verify which bitumen/polymer combination should be used in the Eastern and South-Eastern parts of Turkey, six different binders have been examined on low temperature performance in four different tests. Two tests are currently used as standards, while two other tests are currently under evaluation.

The outcome of the tests was interesting:

1. All tests were able to distinguish the harder from the softer grades.
2. The Fraass breaking point, the fracture toughness and the ABCD tests demonstrated a positive effect of polymer modification on the low temperature properties. The BBR gave at best equal results, although this test is usually performed on aged binders, while for this study the fresh materials were used. With the BBR the rheological properties are measured and these properties alone do not account for the low temperature performance of highly modified binders without the inclusion of fracture properties.
3. The new tests (fracture toughness and ABCD test) showed similar positive effects, albeit at different temperature levels.
4. The best performance was not surprisingly obtained with the softest base bitumen, but care must be taken that there will be a sufficient amount of polymer present to also resist the high temperature defects such as rutting and shoving.

REFERENCES

[1] Quantification of the Effects of Polymer-Modified Asphalt for Reducing Pavement Distress, Asphalt Institute, Engineering Report 215, 2005

[2] Laboratory Standard for Fracture Performance Grading of Asphalt Binders, Test Method LS-296, Laboratory Testing Manual, Ministry of Transportation Ontario, Downsview, Ontario, Canada, 2003

[3] Low-Temperature Fracture Testing of Asphalt Binders: Regular and Modified Systems, T. R. Hoare and S. A. M. Hesp, Transportation Research Record: Journal of the TRB, Vol 1728, 36-42, 2000

[4] Low-Temperature Fracture in Asphalt Binders, Mastics, and Mixtures, S. A. M. Hesp, Modeling of Asphalt Concrete (Ed.: Y. R. Kim), Chapter 15, 2008

[5] CEN TS/15963, Bitumen and bituminous binders – Determination of the fracture toughness temperature by a three point bending test on a notched specimen, European Committee for Standardization, Brussels, January 2010

[6] Direct Measurement of Asphalt Binder Thermal Cracking, S. S. Kim, Journal of Materials in Civil Engineering, Vol 17 (6), 632-639, 2005

[7] Determination of Low Temperature Thermal Cracking of Asphalt Binder by ABCD, S. S. Kim, Z. Wysong, J. Kovach, Journal of TRB, no. 1962, 28-35, 2006

[8] Determining the Cracking Temperatures of Asphalt Binder Using the Asphalt Binder Cracking Device (ABCD), AASHTO TP 92

[9] Overview of the Development of the New Low-Temperature Binder Specification, R. Dongré, M. G. Bouldin, D. A. Anderson, G. H. Reinke, J. D'Angelo, R. Q. Kluttz, L. Zanzotto, Report for the FHWA Binder ETG, Federal Highway Administration, Washington, DC, 1999

[10] On Creep and Relaxation, L. L. Hopkins, R. W. Hamming, Journal of Applied Physics, vol 28 (8), 906-909, 1957

Publication disclaimer:

We believe the information set forth above to be true and accurate, but any findings, recommendations or suggestions that may be made in the foregoing text are without any warranty or guarantee whatsoever, and shall establish no legal duty or responsibility on the part of the authors or any Kraton Polymers entity. Furthermore, nothing set forth above shall be construed as a recommendation to use any product in conflict with any existing patent rights. All Kraton Polymers entities expressly disclaim any and all liability for any damages or injuries arising out of any activities relating in any way to this publication or the information set forth herein.