INTERPRETING A THREE-POINT BENDING TEST ON PRE-NOTCHED BITUMEN BEAM TO DETERMINE CRACKING BEHAVIOR AT LOW TEMPERATURE

Emmanuel Chailleux[1], Malo Le Guern[1], Fabienne Farcas[2], Sylvia Dreessen[3]
[1]M. Le Guern, E. Chailleux, Ifsttar, Département matériaux, 44341 Bouguenais, France
[2]F. Farcas, Ifsttar, Département matériaux, 75732 Paris Cedex 15, France
[3]S. Dreessen, TOTAL Centre de recherche de Solaize, Bitumen department, Solaize, France

ABSTRACT

Current specifications on the determination of the low-temperature cracking resistance of asphalt binders are based on empirical tests or tests involving the linear viscoelasticity (Fraass test, creep test, complex modulus). However, although these standard characteristics may work for pure bitumen but cannot be applied on all binders. A new test based on fracture mechanics principle has been standardized in Europe (CEN/TS 15963:2009). This standard, based on a three-points bending test on pre-notched bitumen beam, appears a promising solution that can be applied to all bitumnious binders. This article provides new elements for processing the results obtained by this test. Due to the viscoelastic nature of the materials tested, the concept of strain intensity factor is introduced in addition to the stress intensity factor. Hence, the description of the stress state and the shape of the pre-notch make possible to calculate easily the critical energy release rate (Gc). The theoretical approach is applied to test results obtained with 9 bitumens, non-aged and PAV aged, tested at several temperatures. Measurements show that above a certain temperature, named Limiting Cracking Temperature (LCT), crack can not propagate. A new way to rank binder is proposed using the LCT and Gc. It appears that this ranking differs from Bending Beam Rheometer output. Results highlight also the importance to test aged binder.

Keywords: bitumen, low temperature performance, aging, cracking, fracture toughness

1. INTRODUCTION

Current European and American specifications on the determination of the low-temperature cracking resistance of bitumen binders are based on empirical tests or tests involving linear viscoelasticity theory (FRAASS test, creep test, complex modulus). However, although these standard characteristics may work for pure bitumens, they cannot be applied on all bitumens. For example, adding polymer (which has good compatibility with bitumen) gives a strong increase in the binder's cold properties that is reproduced in field conditions, yet there is still very little variation in binder stiffness obtained by Bending Beam Rheometer (BBR) according to AASHTO T313-02 [1]. In this context, the standard criteria (300 MPa creep stiffness (S) temperature, creep rate (m) of 0.3) cannot differentiate pure and modified binders, prompting analysts to turn to a test based on the principles of rupture mechanics. For that, a fracture strength test (three point bending test on pre-notched bar, (TPBT)), which allows to work in localized big deformations, was adapted to bitumen and developed by Hesp et al. (2-4). Research shows that it is possible to better describe the cracking resistance of bituminous binders by obtaining intrinsic characteristics such as fracture toughness (KIc) or critical strain energy release rate (GIc) [2-4]. However, these researches have used linear elastic fracture mechanic principles, where the bitumen, at low temperature, is considered a brittle, elastic material. However, while this assumption may well appear valid at very low temperatures (under -20°C), it is important when higher temperatures are involved to factor in the bitumen viscoelasticity, especially during "soft-to-brittle" transition.
The study reported here proposes a theoretical approach to calculate the energy release rate from test parameters (force and displacement according to time) taking into account the viscoelastic nature of the material. For that, calculations are driven by distinguishing between stress intensity factors ($K\sigma$) and crack opening ($K\varepsilon$). Then, we propose to compare BBR and the three point bending experiments on eight bitumen (aged and non-aged) in order to evaluate the reliability of the tests.

2. EXPERIMENTAL DESIGN

2.1 Bitumens

This study used eight bitumens selected according to origin of the crude petroleum, manufacturing process, and type of modifiers used. Three direct-distilled bitumens of different origins (B1, B2 et B3) and one semi-blown bitumen (B4) with the same 35/50 penetration (standard NF EN 12591) were used. Four types of adjuvant were used to modify the B1 bitumen: Fischer-Tropsch-wax (BM1), polyphosphoric acid at 105-118% (BM2), crosslinker-free SBS polymer (BM3) and crosslinked SBS polymer (BM4).
Binders are tested in two ageing state: non aged and PAV aged. The PAV ageing procedures are not performed after RTFOT. It is only used to give another level of ageing compared to the virgin binders.

2.2 Three-Point Bending Test (TPBT)

In this study, the three-point bending test on pre-notched bitumen beam was adapted to bituminous binders. The test specimen was a piece of pre-notched bitumen extended by two aluminum extender inserts (Figure 1). The aluminum inserts were employed to reduce the quantity of bitumen and make the bottom supports less sensitive to indentation phenomenon. The test samples were produced by molding at 150°C around two 25 μm-thick Teflon sheets bonded with mineral grease to form a reproducible pre-notch. Before adding the binder, the film is tightened to produce the straightest possible pre-notch and thus trigger mode I fracture (opening). However, Chailleux et al. [5] have showed that presence of the inserts may influence the mechanical fields at the pit of the notch. They have showed that for a L longer than 40 mm, the aluminum extenders had no influence on the mechanical fields around the crack.
The test was conducted in set-rate displacement mode (0.6 mm/min). The press used was a Zwick tensile–compression tester machine. The test was conducted in a potassium acetate bath able to carry the test temperature down to -30°C. TPBT are performed following the European experimental standard CEN/TS 15936.

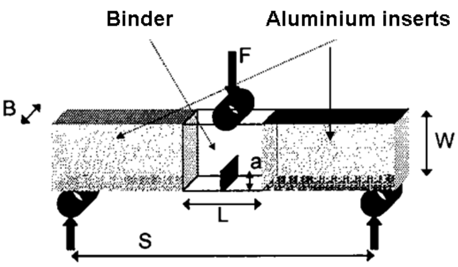

Figure 1 : Geometry of test specimen

2.3 Bending Beam Rheometer

The Bending Beam Rheometer (BBR) provides a measure for low-temperature creep tests. Tests are carried out at different temperatures (-24, -18 and -12°C) (AASHTO T313-02). Bitumen beams are prepared in an aluminum mold. Storage time for each sample was 24 hours. After one hour at the test temperature, a constant load of 100 g was applied for 240 seconds to the rectangular beam supported at both ends by stainless steel half-rounds (set 102 mm apart). Center-point deflection is measured continuously. By using a linear interpolation, these tests give a measure of creep stiffness at any moment and any temperature (AASHTO T313-02).

3. Calculation of critical energy release rate from TPBT

Given that the three-point bending fracture test is conducted in mode I (opening mode), the various equations and calculations used in this paper are only valid for mode-I cracking.
In case of elastic material, cracking propagation criterion can be determined from the critical stress intensity factor (tenacity). But, for a material subjected to viscoelastic dissipation, a local stress criterion is not able alone to describe the condition for which propagation could occur. Another way to determine a critical criterion is to perform energy balance of the mechanical problem from which a global criterion can be defined: the critical energy release rate. This global criterion can be generalized to non elastic problem.
In our case, the energy release rate has to be calculated from test outputs: F(t) and d(t), without knowledge of the material viscoelastic time dependent stress/strain law. A solution is to consider the following formulation of the energy release rate (G(t)) during loading, developed by Chazal and Dubois [6, 7]:

$$G(t) = \frac{K^{\sigma}(t) \cdot K^{\varepsilon}(t)}{8}$$

Where $K^{\sigma}(t)$ is the usual stress intensity factor representing the stress field σ_{yy}^{θ} at ay time around the crack tip.

Considering notation of figure 2, K^{σ} is defined by:

$$\sigma_{yy}^{\theta} = \frac{K^{\sigma}}{\sqrt{2 \cdot \pi \cdot r}} \cos\frac{\theta}{2}\left(1 + \sin\frac{\theta}{2} \cdot \sin\frac{3\theta}{2}\right)$$

And can be also defined by:

$$u_y^{\theta} = \frac{K^{\sigma} \cdot (1+\upsilon)}{E} \sqrt{\frac{r}{2\pi}} \sin\frac{\theta}{2}\left(\kappa + 1 - 2\cos^2\frac{\theta}{2}\right)$$

$K^{\varepsilon}(t)$ is a new introduced factor, named: opening crack intensity factor. This last factor allows a geometric description of the crack form at any time. It is defining by the following equation:

$$u_y = \sqrt{\frac{r(\theta = \pi)}{2\pi}} \cdot K^{\varepsilon}$$

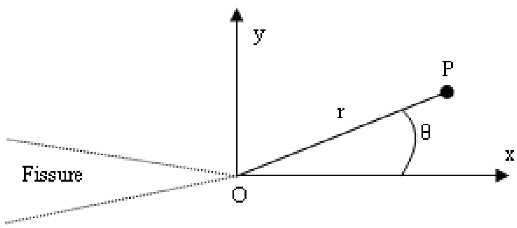

Figure 2 : Notations for a planar crack

Authors have previously show how $K^{\sigma}(t)$ and $K^{\varepsilon}(t)$ can be calculated for the three point bending test [8].
Finally, energy release rate can be deduced from force and displacement according to time by the following equation:

$$G(t) = 409.7 \cdot F(t) \cdot d(t)$$

When G is calculated at a time corresponding to crack propagation (when F(t)=Fr and d(t)=dr), G is equal to Gc, the critical energy release rate.

4. Experimental results

Tests in three points bending mode are performed on the eight bitumens, on two ageing states. As an example, the time-course of the Force=f(displacement) curve according to different temperatures for non-aged BM2 is plotted on Figure 3. The thermal dependence of bitumen is clearly highlighted on the curves: when the temperature increases, the stiffness decreases. After a certain displacement, force dramatically decreases up to a value close to zero. This event is attributed to the crack propagation onset (what was previously shown using acoustic emission [9, 10]).

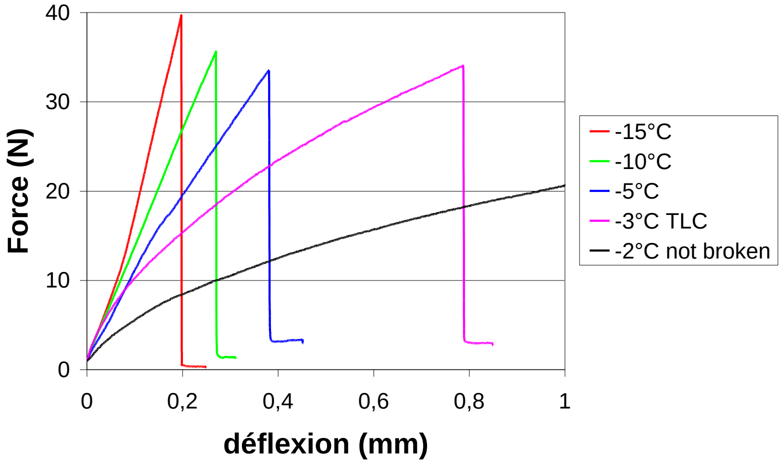

Figure 3 : Curve plotting three-point bending fracture tests for BM2 at different temperatures.

4.1 Determination of a new parameter: the LCT

What appears very interesting for each binder, is that above a certain temperature, -3°C in the example shown on figure 4, displacement increases whereas no crack propagation occurs. Hence, for the test condition used here (0.6 mm/min) a limit cracking temperature (LCT) can be defined above which no crack propagation seems to be possible. This temperature is determined with an accuracy of 1°C. Figure 4 depicted what is assumed to happen: at a certain temperature, relaxation time of the material is of the same order of magnitude of the strain rate. Hence, energy can't be accumulated anymore at the crack tip and the pre-crack is deforming without possibility to propagate. Considering this explanation, the LCT determined here, is only valuable for the displacement speed used in the present study.

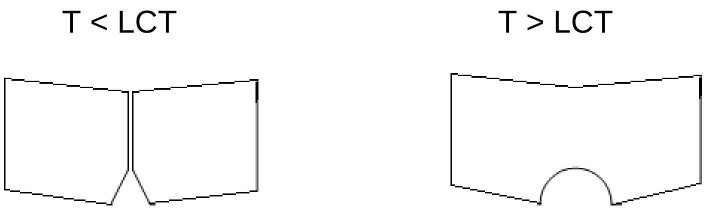

Figure 4 : Shematic view of the sample after loading above and below the limit cracking temperature (LCT)

3.3 Critical energy release rate measurements

All the binder, aged and non aged are tested at several temperatures. For each temperature, three tests are performed in order to evaluate the repeatability of the results. The average value and the standard deviation of G_c are given on the figure 5 and 6. Temperatures are chosen between the LCT and the brittle domain. For the non-aged bitumen brittle temperature is reached below-10°C or -15°C depending on the binder. For aged bitumen, the limit appears to be -5°C whatever the binder. Brittle state appears to be characterized by a low and relatively constant Gc, around 10 J/m² . From the brittle state, up to the LCT, the energy release rate increases. Gc measured at LCT varies from 8 J/m² to 100 J/m² depending on the binder nature and ageing state. Concerning the non aged binder, one group of bitumen (B1, B3, BM1, BM2, BM3, BM4) shows a small increase of Gc and another group (B2, B4) shows a high drop of G_c (from 10 to 80 and 100 J/m²). Gc measured on the PAV aged bitumens also show this type of transition but G_c measured at LCT are, for all binder, above 20 J/m². Hence, binders with the same penetration grade (35/50 here) show important difference regarding real cracking properties.

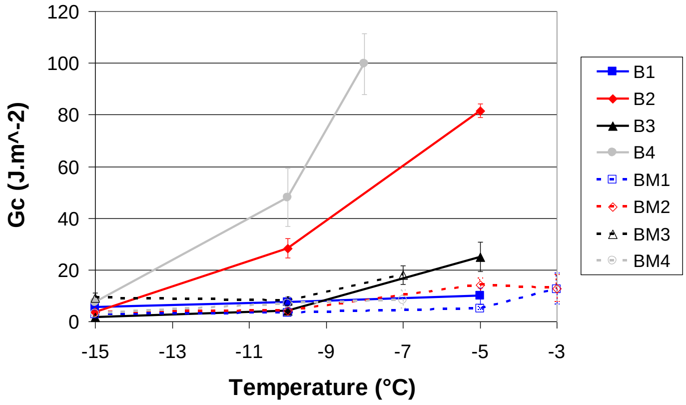

Figure 5 : Critical energy release rate according to temperature for the eight non-aged bitumens

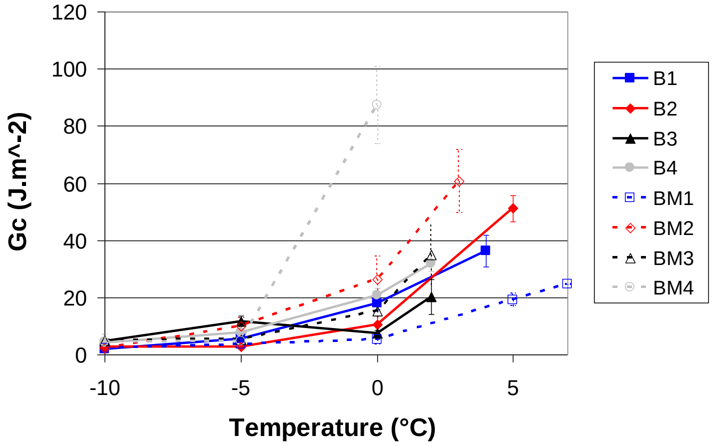

Figure 6 : Critical energy release rate according to temperature for the eight PAV aged bitumens

3.3 Ranking binders: BBR versus TPBT

The LCT will be considered as the main cracking characteristic obtained by three points bending test. Indeed, it corresponds to the temperature from which a crack could propagate into the material. It has to be mentioned that the LCT measured in three point bending mode do not correlated with iso-modulus and critical temperatures. This remark does not agree with the explanation given previously. Critical temperature is directly linked to relaxation time since it is calculated from the slope of the creep curve. Consequently, it should strongly be linked to the LCT which also involves relaxation phenomena versus loading condition. This non-correlation could be the consequence of the strain level reached into both test. BBR is performed in the small strain domain whereas very high strain is localized at the crack tip in the three points bending test. Consequently, non linear phenomena could strongly influence the relaxation time.

To rank binders using the three points bending test results, LCT will be firstly considered. Then, if some samples have the same limit cracking temperature, we will use G_C values (measured at LCT) in order to establish a ranking which take into account both parameters. On a practical point of view, we first consider the condition (temperature, loading rate) from which a crack has the possibility to propagate in the bitumen. Secondly, we consider the mechanical energy necessary to propagate this crack.

LCT and G_C are compared to BBR iso-modulus and iso-slope temperature on the table 3. Ranking of binders are given on table 4 using BBR critical temperature and the TPBT procedure. Even if both methods give BM1 bitumen (with Fischer-Tropsch-wax) as the worst binder, ranking of the other bitumens depends on the tests used. Increase in

LCT and critical temperatures during ageing are on the same order of magnitude, around 10°C, showing the translation of the main relaxation time and the stiffening effect of the materials during ageing. However, ranking appears to be ageing dependent whatever the test used.
It is particularly interesting to note that the non-aged semi-blown bitumen B4 is ranked in the first position by the TPBT but decreases down to the third position after ageing. Critical energy release rate of B4 falls from 99.7 J/m² down to 32 J/m². The inverse phenomenon occurs for the PM4 (crosslinked SBS modified bitumen): G_c increases from 8.4 J/m² up to 87.2 J/m² during ageing.
Both Polymer modified bitumens (SBS and crosslinked SBS) are well ranked by the TPBT what is not the case if BBR critical temperature is considered. Indeed, BBR results on polymer modified binders seem equivalent to result found on the base binder B1. Once again, this results underlines the strong effect of the polymer when binder are subjected to high strain condition, what is not the case when it is subjected to small strain.
One can also note that B2 is not well ranked by TPBT but still have a high G_c : 81.6 J/m² for non-aged, 51.2 J/m² for PAV aged. The procedure to rank binder using LCT and G_c is perhaps too severe and could be in the future adapted in link with field observations.

Table 3: Comparisons Between Three-Points Bending and BBR Results for the eight bitumens

	Limit Cracking Temperature (°C)		G_{IC} (J.m^{-2}) at LCT		Iso-modulus (300MPa) temperature (°C)		Iso_slope temperature (m=0.3) (°C)	
	Non aged	PAV aged	Non aged	PAV aged	Non aged	PAV aged	Non aged	PAV aged
B_1	-5	4	9.9	36.4	-15.9	-12.7	-16.2	-8.6
B_2	-5	5	81.6	51.2	-20.9	-17.9	-20.8	-10.7
B_3	-5	2	25.0	20.3	-16.0	-13.2	-17.3	-13.4
B_4	-8	2	99.7	32.0	-21.1	-19.7	-18.3	-7.1
B_{M1}	-3	7	12.5	24.6	-13.9	-11.1	-13.4	-4.6
B_{M2}	-3	3	12.8	60.6	-16.2	-14.3	-16.5	-9.9
B_{M3}	-7	2	18.0	34.8	-17.7	-14.3	-16.5	-9.4
B_{M4}	-7	0	8.4	87.2	-17.0	-14.3	-16.6	-9.8

Table 4: Comparisons Between Ranking from Three-Points Bending and BBR

Ranking	Three points bending (LCT, G_{IC})		BBR (critical temperature)	
	Non aged	PAV aged	Non aged	PAV aged
1	B_4 (-8°C; 99.7 J/m²)	B_{M4} (0°C; 87.2 J/m²)	B_2 (-20.8°C)	B_3 (-13.2°C)
2	B_{M3} (-7°C; 18 J/m²)	B_{M3} (2°C; 34.8 J/m²)	B_4 (-18.3°C)	B_2 (-10.7°C)
3	B_{M4} (-7°C; 8.4 J/m²)	B_4 (2°C; 32 J/m²)	B_{M4} (-16.6°C)	B_{M2} (-9.9°C)
4	B_2 (-5°C; 81.6 J/m²)	B_3 (2°C; 20.3 J/m²)	B_{M3} (-16.5°C)	B_{M4} (-9.8°C)
5	B_3 (-5°C; 9.9 J/m²)	B_{M2} (3°C; 60.6 J/m²)	B_{M2} (-16.5°C)	B_{M3} (-9.4°C)
6	B_1 (-5°C; 25 J/m²)	B_1 (4°C; 36.4 J/m²)	B_3 (-17.3°C)	B_1 (-8.6°C)
7	B_{M2} (-3°C; 12.8 J/m²)	B_2 (5°C; 51.2 J/m²)	B_1 (-16.2°C)	B_4 (-7.1°C)
8	B_{M1} (-3°C; 12.5 J/m²)	B_{M1} (7°C; 24.6 J/m²)	B_{M1} (-13.4°C)	B_{M1} (-4.6°C)

4. Conclusion

This study has established a framework for applying fracture mechanics-based criteria for employing a three-point bending fracture test on bituminous binders. The results show that critical energy release rate can be a discriminatory factor across different temperature ranges, regardless of the bitumens tested. From the TPBT, it is possible to observe a transition from the brittle state at low temperature to a viscoelastic state. During this transition, G_c increases from 10 J/m² to a value which depends on the binder nature and ageing state (from 10 J/m² to 100 J/m²). Moreover, a new criterion is introduced: the LCT which correspond to the last temperature where there is crack propagation. A new way to rank binder is proposed using first the LCT value and secondly the G_c value (for equal LCT).

Concerning cracking resistance ranking, three points bending test and bending beam rheometer gives different results. Results with binders modified by crosslinked SBS and crosslinker-free SBS seem to show that the TPBT gives a reliable ranking which takes into account the benefit of adding SBS in bitumen. The reliability of the TPBT is certainly due to the concept used, inspired by fracture mechanics, which involves localized high strain, contrary to BBR.

REFERENCES

[1] Lu X., and U. Isacsson. Effect of binder rheology on the low-temperature cracking of asphalt mixtures. International journal of road materials and pavement design, Vol. 2, n°1, 2001, p.29-47.

[2] Lee N.K., S.A.M. Hesp. Low-temperature fracture toughness of polyethylene-modified asphalt binders. Transportation Research record, vol.1436, 1994, p. 54-59.

[3] Morrison G.R., N.K. Lee, and S.A.M. Hesp. Chlorinated polyolefins for asphalt binder modification. Journal of Applied Polymer Science, vol.54, 1994, p.231-240.

[4] Ponniah J.E. and S.A.M. Hesp. Use of fracture energy in performance-based specifications of asphalt binders. Proceedings, Canadian Technical Asphalt Association, 1996, vol. 41, p.127-144.

[5] Chailleux E., D. Hamon, and V. Mouillet, Determination of the low temperature Bitumen Cracking Properties: Fracture Mechanics Principle Applied to a Three Points Bending Test using a Non Homogeneous Geometry, 10th International Conference on Asphalt Pavements, Québec, 12-17 August 2006, Canada, vol. 1, p.419-428

[6] Chazal C., and F. Dubois. A new incremental formulation in the time domain of crack initiation in an orthotropic linearly viscoelastic solid, Mechanics of Time-Depend Materials, vol. 5, 2001, p. 3–21.

[7] Dubois F., and C. Petit. Modeling of the crack growth initiation in viscoelastic media by the Gθv-integral. Engineering Fracture Mechanics, vol. 72, n°18, 2005, p. 2821-2836.

[8] M Le Guern, E Chailleux, S Dreessen, F Farcas, Essai de flexion trois points sur barreau entaillé de bitume., AUGC, 2010

[9] Chailleux E., Mouillet V., Gaillet L., Hamon D, Towards a Better Understanding of the Three Points Bending Test Performed on Bituminous Binders, Advanced Characterisation of Pavement and Soil Engineering Materials (proceedings). Taylor & Francis Group, ISBN 978-0-415-44882-6, 1075-1084, London, 2007.

[10] Chailleux E., V. Mouillet, E. Scholten, T. Blomberg, and S. Dreessen. Evaluation of the three-point bending test as a tool to qualify the low-temperature behaviour of bituminous binder. Eurasphalt & Eurobitume congress, Copenhague, 21-23 May 2008, Danemark.