NEW PROCEDURES AND CRITERIA FOR ASPHALT MIXES AND PAVEMENTS DESIGN REGARDING FATIGUE FAILURE AND THERMAL STRESSES

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ABSTRACT

Fatigue cracking and thermal shrinkage are two distress mechanisms that should be considered in asphalt mixtures and pavements design. Both distresses are complex and difficult to simulate in laboratory, especially the fatigue testing, which needs expensive and time-consuming equipment. This is the reason why these mechanisms are hardly taken into account for the asphalt mixtures design.

This paper is about two simple procedures developed at the Road Research Laboratory of the Technical University of Catalonia for the mixtures design and assessment facing fatigue failure: Fénix and EBADE tests. Moreover, EBADE test allows taking into consideration the thermal stresses caused by temperature decrease and the stresses caused by traffic cyclic loads at the same time during the cracking process. These tests show the significant effect of thermal stresses in the fatigue process.

1. INTRODUCTION

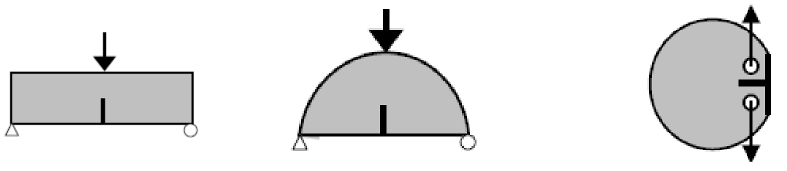
Asphalt cracking is one of the most common causes of pavement distress. The cracking behaviour of asphalt mixtures is difficult to analyze because of their rheological characteristics. Different factors contribute to crack formation and propagation. They are usually of environmental (thermal cycles and material aging) or mechanical (traffic loads) nature. These factors trigger mechanisms like top-down cracking, flexural cracking, fatigue (thermal and traffic) cracking, resulting in geometrical typologies or patterns such as longitudinal cracking, block cracking, transverse cracking, fatigue (or alligator) cracking, among many other types generally described in several pavement distress manuals along with causes and remedies [*1, 2, 3, 4*].

Different procedures and research lines have been used to evaluate cracking resistance of bituminous mixtures. Among these options are the concept of fracture mechanics and fracture energy as well as the experimental fatigue testing. These tests subject the material to stresses of less intensity than the ultimate tensile stress limit and however cause mixture cracking because of the application of a large number of cyclic stresses. This paper is about the theoretical basis of these procedures and also about the new tests developed at the Technical University of Catalonia to assess cracking resistance: Fénix fracture test and EBADE fatigue test.

2. FÉNIX TEST FOR FRACTURE ENERGY DETERMINATION

Nowadays, scientific community is using fracture mechanics concepts on quasi-brittle materials to understand cracking behaviour of bituminous mixtures, some of them by means of analytical models and others through experimental studies. These experimental studies try to simulate crack initiation and propagation, [5].

Literature search returned three tests of which the main target is to determine fracture properties of bituminous mixtures (Figure 1). The Single-edge notched beam, SE(B), has been used in several studies with this purpose. Test set up and sample geometry provide an adequate mode I fracture. However, it is not possible to apply the test to field cores, due to sample shape [6]. The Semi-Circular Bending test, SCB, has been used in several studies too, [5, 7, 8]. Samples shape make the test suitable to field cores and laboratory specimens, and test set up is simple, but the crack propagation with the SCB geometry creates an arching effect with high compressive stress as the crack approaches the top edge [6]. The Disk-shaped Compact Tension test, DC(T), has a standard fracture test configuration in ASTM D 7313-07. It also has a bigger sample fracture area which benefits tests results. On the other hand, during the sample fabrication it is possible debilitate the area around the loading points; moreover it is difficult to carry out the test at temperatures above 10ºC.



SE(B)
Single-edge
notched beam

SCB
Semicircular bend

DC(T)
Disk-shaped compact
tension

Figure 1 - Different specimen fracture geometries.

Following this research line, the Road Research Laboratory of the Technical University of Catalonia has developed a new test to evaluate bituminous mixtures cracking resistance, [9]. This test provides dissipated energy in test process, which is a combination of dissipated creep energy and fracture energy [5]. Dissipated energy evaluation is a way to measure the cracking resistance of bituminous mixtures. This test has been called Fénix and its set up is shown in Figure 2.

2.1. FÉNIX Test procedure

Fénix test is a tensile test applied to a half cylindrical sample with a 6mm depth notch, placed in the middle of the flat side of the specimen (Figure 2). This sample is fabricated through Marshall or gyratory-compactor procedures or field cores. Two steel plates are fixed on the flat side separated by the notch. Steel plates are attached to the loading platen, allowing plates to rotate around fixing points once test has begun. Test is carried out under controlled displacement conditions. Displacement velocity is established at 1 mm/min. Temperature is chosen according to the environmental conditions that have to be reproduced.

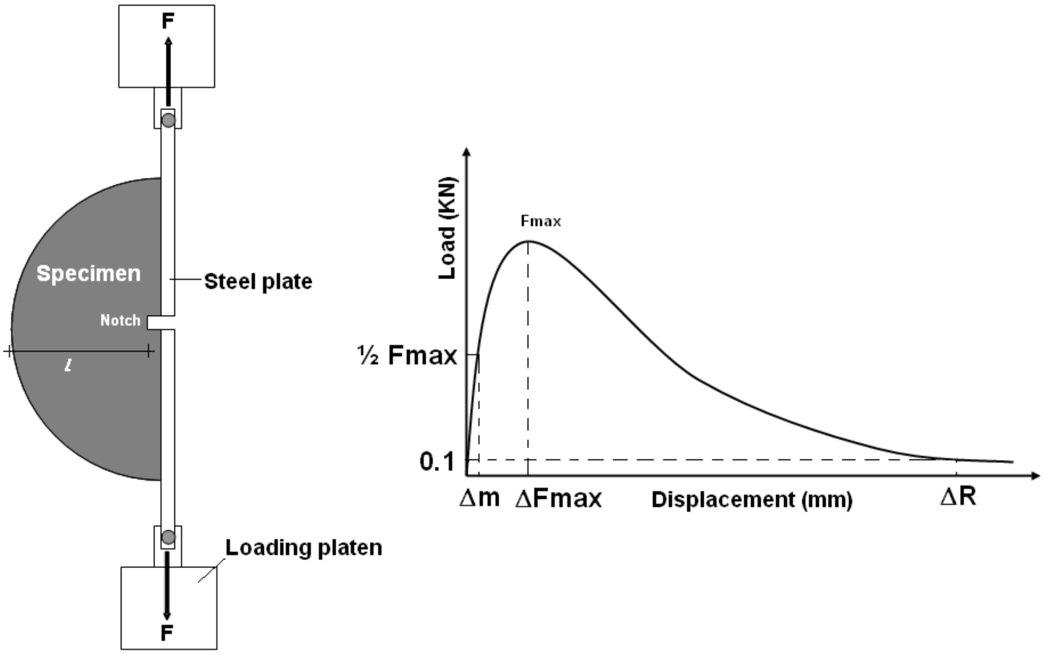


Figure 2 - Fénix test and typical load vs. displacement output curve.

Load and displacement data are recorded along the test. Dissipated energy during the test, G_D, can be obtained using Equation (1).

$$G_D = \frac{W_D}{h \cdot l} \qquad (1)$$

Where, G_D= dissipated energy during the test, J/m^2; W_D= dissipated work during the test, area under load-displacement curve, kN.mm; h= specimen thickness, m; l= initial ligament length, m.

Other parameters like peak load, Fmax, displacement at peak load, ΔFmax, failure displacement, ΔR, can be determined from load-displacement curve (Figure 2). Tensile stiffness index, IRT can be obtained, by means of Equation (2).

$$I_{RT} = \frac{\frac{1}{2} \cdot F_{\max}}{\Delta_m} \qquad (2)$$

Where, I_{RT} = tensile stiffness index, kN/mm; F_{max}= peak load, kN; Δm= displacement before peak load to ½ F_{max}, mm.

2.2. Sensitivity analysis

The experimental study carried out consisted in calibrating Fénix test through sensitivity analysis for different variables:

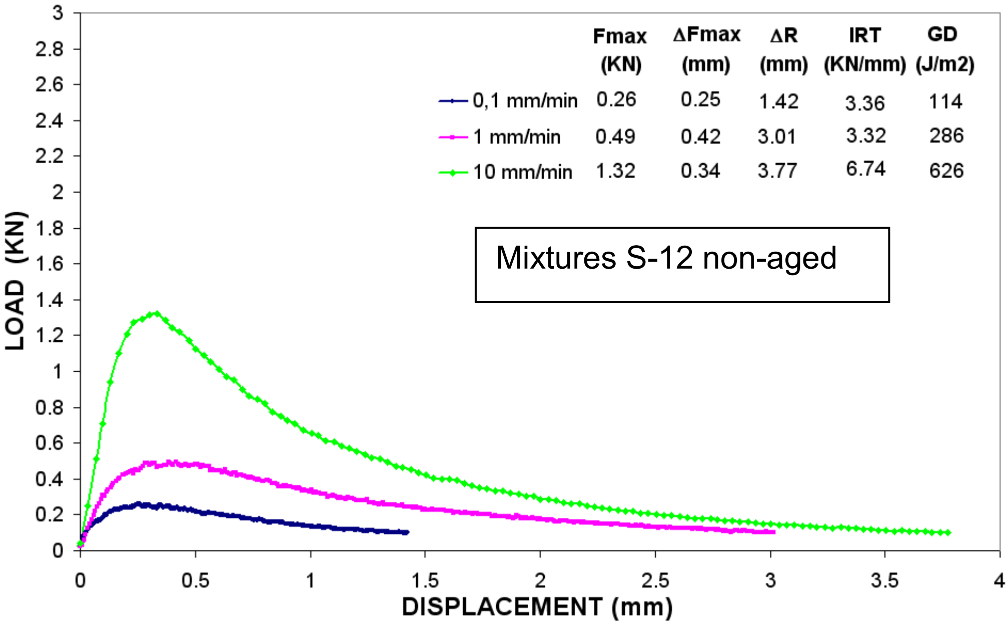
- Loading rate
- Mixture aging (SHRP protocol)
- Binder type
- Test temperature
- Mixture compaction temperature

Loading rate (0.1, 1 and 10 mm/min) and aging (SHRP protocol) have been studied using S-12 mixtures, while different types of binder, test temperature (-10ºC, 5ºC and 20ºC) and compaction temperature (120ºC, 135ºC and 155ºC) have been evaluated using S-20 mixtures. Finally G-20 mixtures have been used to evaluate binder content and test temperature (again -10ºC, 5ºC and 20ºC). All the mixtures studied are dense type and the number indicated after the letter S or G is the maximum aggregate size in (mm). Three Marshall samples have been tested for each variable studied.

All mixtures have been fabricated using limestone aggregates and different types of binders.

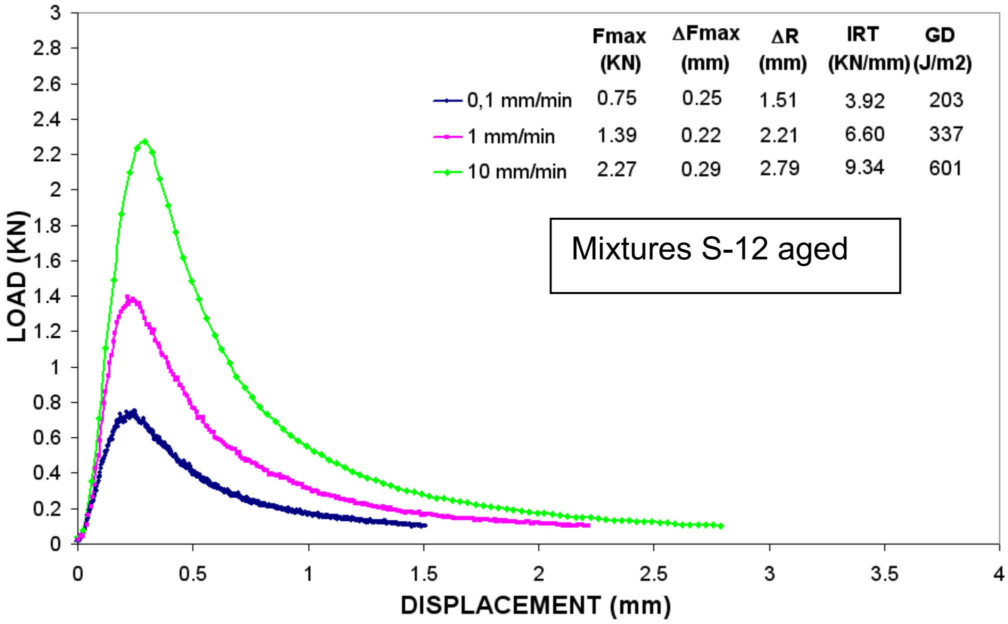
2.2.1. Loading rate and mixture aging

Figure 3 shows load-displacement curves obtained in tests carried out at different loading rates and 20ºC test temperature. Aged and non-aged mixtures curves are shown. Aging has been applied following SHRP procedure [10]. It consisted in 4 days period at 80ºC in a forced air oven. Both aged and non-aged mixtures have showed that dissipated energy and stiffness increase with loading rate at 20ºC. Aged samples have shown more fragile behaviour as their failure displacements have been lower at higher loading rates. 0.1 mm/min loading rate at 20ºC has proved to be not adequate as peak load values have not achieved significant magnitude, for non-aged conventional bituminous mixtures. Finally 1 mm/min loading rate has been chosen to carry out the rest of tests.



	Fmax (KN)	ΔFmax (mm)	ΔR (mm)	IRT (KN/mm)	GD (J/m2)
0,1 mm/min	0.26	0.25	1.42	3.36	114
1 mm/min	0.49	0.42	3.01	3.32	286
10 mm/min	1.32	0.34	3.77	6.74	626

(a)



(b)

Figure 3 - Influence of load application velocity in mixture S-12 non-aged (a) and aged (b), Fénix test at 20 ºC.

2.2.2. *Test temperature and binder type*

All mixtures have shown similar response to test temperature variation. At -10ºC, mixtures have shown brittle behaviour with high peak load and more quickly load loss with failure displacement. At 20ºC, more ductile behaviour has been observed, higher breaking displacement, ΔR, and lower peak load, F_{max}, and stiffness, I_{RT}. At 5ºC, an intermediate behaviour has been observed. As an example, Figure 4 shows S-20 mixtures with B40/50 binder behaviour at different test temperatures.

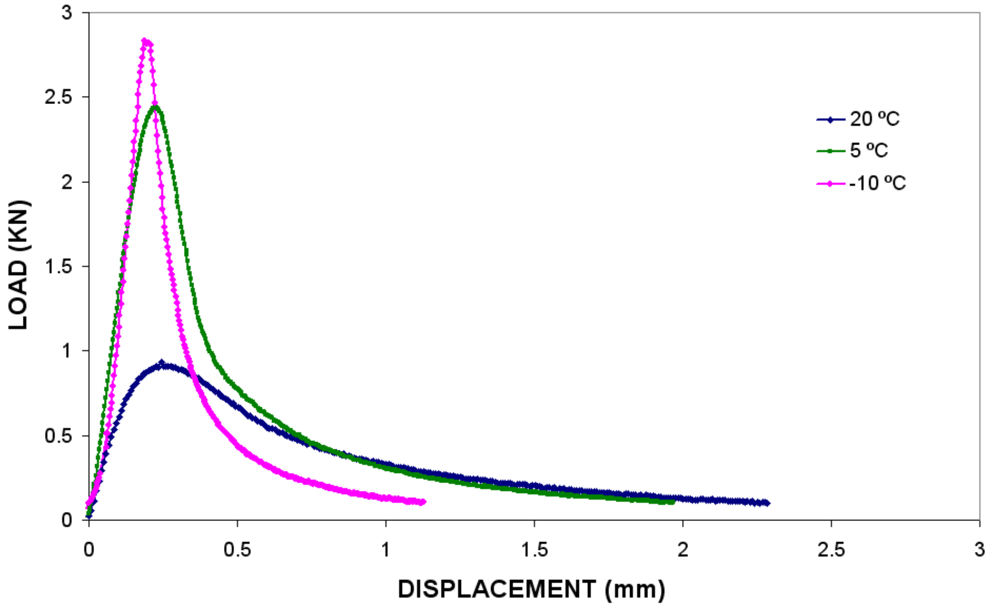


Figure 4 - Fénix test at different temperatures, S-20 mixture with B-40/50.

Figure 5 shows dissipated energy vs. test temperature for all types of binder studied. The polymer modified binder BM3c has obtained the highest value of dissipated energy, G_D, at all test temperatures showing the best cracking resistance. B60/70, B40/50, and BM3c have achieved their relative maximum value of dissipated energy at 5ºC. B13/22 has showed its highest dissipated energy at 20ºC due to its low penetration, as G. Valdés shows in his PhD thesis, [11].

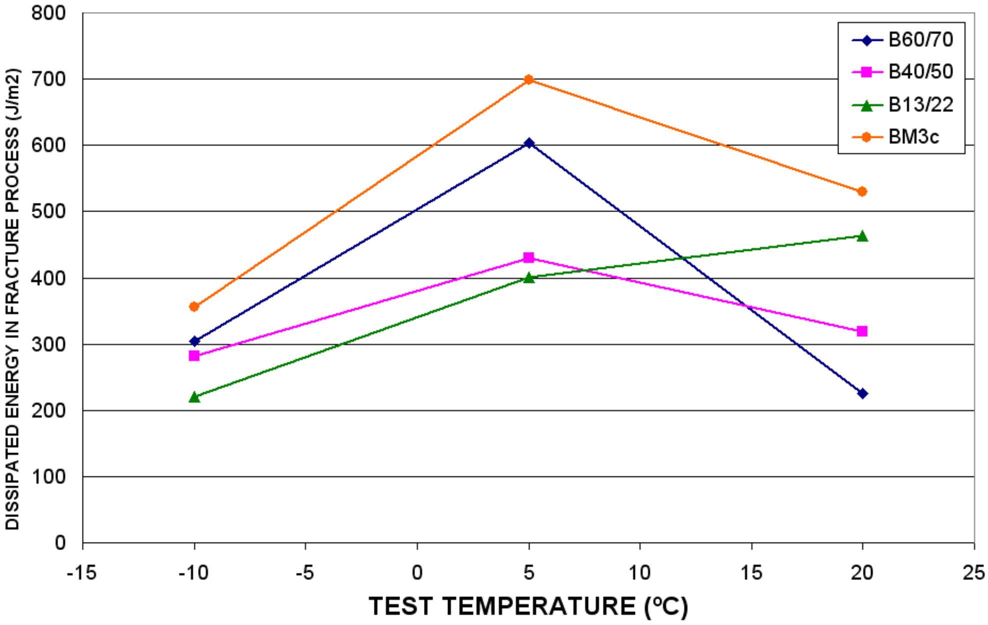


Figure 5 - Dissipated energy during the test at different test temperatures and for different bitumen types, S-20 mixture.

Figure 6 shows test temperature influence in fracture surfaces and cracks shape. At low temperature, -10ºC, fracture surface shows that crack crosses through bituminous mastic and large size aggregates, leaving those located on crack's path fractured. At intermediate temperatures, 5ºC, crack grows following bituminous mastic and fracturing only some of the large size aggregates. Finally, at 20ºC fracture takes place only in bituminous mastic.

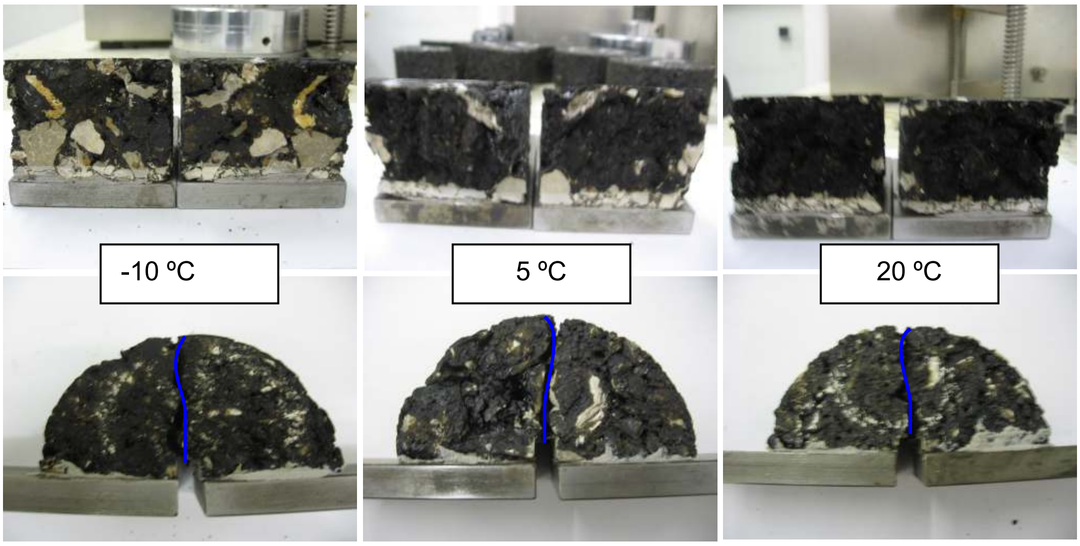
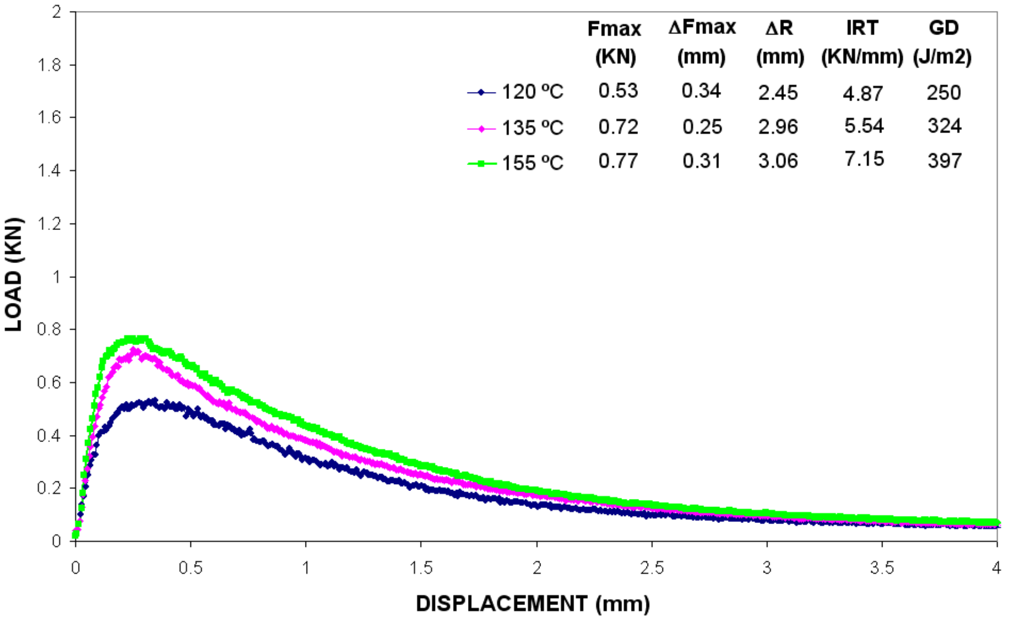


Figure 6 - Typical fracture images for mixture G-20 at different test temperatures (top images: view of fracture surface, bottom images: view of crack propagation).

2.2.3. Mixture compaction temperature

Load vs. displacement curves belonging to different compaction temperatures are shown in Figure 8. As can be seen from the graph, compaction temperature plays an important role in cracking resistance. Dissipated energy and peak load decrease 37% and 31%, respectively, as compaction temperature drops from 155ºC to 120ºC, while density only varies 1.4%.



	Fmax (KN)	ΔFmax (mm)	ΔR (mm)	IRT (KN/mm)	GD (J/m2)
120 ºC	0.53	0.34	2.45	4.87	250
135 ºC	0.72	0.25	2.96	5.54	324
155 ºC	0.77	0.31	3.06	7.15	397

Figure7 - Fénix test at 20ºC for different compaction temperatures, mixture S-20.

Fénix test repeatability has been evaluated through coefficient of variation (COV) obtained from the results. COV average values have been 15% and 8.5% for dissipated energy and peak load respectively. Based on COV values for dissipated energy the test has a good repeatability compared with SE(B) (3-18%), DC(T) (4-25%) and SCB (15-34%), [6].

2.3. Fénix test application to assess fatigue resistance of bituminous mixtures

The cracking resistance of a bituminous mixture is related to the fracture or the dissipated energy during the cracking process. The higher the fracture energy, the higher the resistance to crack propagation.

This fracture can be fragile, showing a small deformation, or ductile and tough, with a slow decrease of peak load during a significant deformation along the process.

Fatigue tests results are usually express by the following kind of equation:

$$\varepsilon = a \cdot N^{-b} \qquad (3)$$

Where ε = half peak-to-peak amplitude of strain function at cycle 200; N = total number of cycles; a and b = coefficients of the strain fatigue law.

Fragile materials are known because of the very little inclination of their fatigue laws, almost horizontal, being “b” coefficient very small. For these fragile materials there is a very limited strain range for the fatigue failure, below this range the material does not undergo fatigue phenomenon and above it fracture takes place rapidly. Moreover, cracking propagation occurs very quickly in these materials, with scarce deformation or settlement, being the cement concrete pavements the extreme case.

On the other hand, there are ductile and tough mixtures that usually have a lower modulus and a wider range of strain for the fatigue failure. These mixtures have a higher fatigue law slope, i.e., a higher “b” coefficient, and a higher initial strain, i.e., a higher “a” coefficient. Besides, these mixtures break with a higher strain that together with a higher deflection and settlement of the layer in the pavement, make it difficult for the crack to propagate. This fact is not taken into account in the calculation of the fatigue life of the bituminous mixtures layers with the analytical design methods.

To sum up, tough mixtures with a higher resistance to fatigue cracking should have higher fracture energy and higher ability to deform.

Figure 8 shows the relationship between dissipated energy during the fracture process, G_D, and tensile stiffness index, I_{RT}, for 13 mixtures tested at different temperatures. Zone 1 includes mixtures with a low stiffness index as a consequence of the low ductility and a low dissipated energy, G_D. Mixtures placed in Zone 2 are the ones that have intermediate stiffness but a significant difference of energy that can be dissipated during fracture process. Finally, mixtures in Zone 3 have higher I_{RT} but cannot dissipate large amounts of energy because of their fragility.

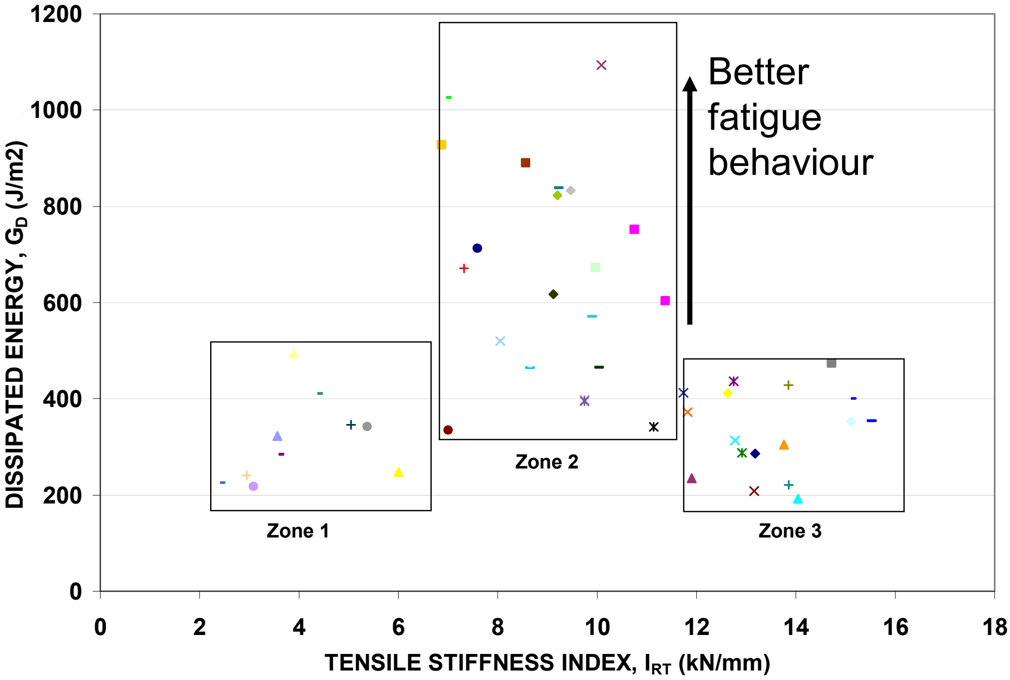


Figure 8- Effect of bitumen type and content on the relationship G_D versus I_{RT} at different testing temperatures.

From the analysis of the results obtained, it is deduced that Fénix test can be used to assess cracking resistance of the mixture during the design stage in laboratory. The fatigue cracking resistance could be valued as a function of dissipated energy G_D, and stiffness index, I_{RT}, by defining a zone with mixtures that have a better fatigue behaviour. For similar stiffness index, I_{RT}, it is clear that mixtures with higher dissipated energy, G_D, will have better behaviour.

3. STRAIN SWEEP FATIGUE TEST (EBADE)

Fatigue tests are time-consuming and expensive; this is the reason why we are trying to substitute them for other faster tests that allow the assessment of bituminous mixtures fatigue behaviour in a simple and quick way. Among them are the strain sweep tests, based on the application of a cyclic load at very low strain amplitude in the beginning of the test that increases progressively after a series of cycles.

This kind test is already being used to characterize bitumens with a Dynamic Shear Rheometer. Therefore, the idea of this study is to use the same procedure with bituminous mixtures through a tensile-compression test, EBADE test, [12].

Some researchers use the strain sweep test together with the viscoelastic continuum damage theory to determine the bitumen fatigue law. A new strain sweep test is shown in this paper as a new fatigue test that allows appreciating how the mixture properties vary with the imposed strain amplitude and the number of cycles. It is also useful to evaluate fracture resistance and energy, since the strain keeps increasing until failure, simulating traffic conditions as far as load frequency and speed is concerned.

3.1. EBADE procedure

The specimen is glued to two steel plates that transmit tension and compression loads. Additionally, two small notches are carved in two of the four faces of the specimen to help cracks to propagate through the middle cross section, Figure 9.

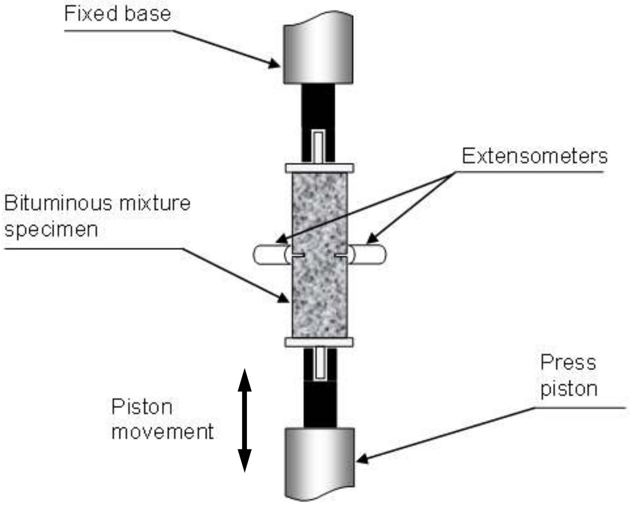


Figure 9 - Drawing of new fatigue test procedure in prismatic specimens.

The test consists in applying different strain steps. Each step contains a number of cycles. The specimen undergoes a sinusoidal strain during this number of cycles. When the number of cycles is achieved, then the strain applied increases for the same number of cycles, and so on until the specimen totally fails.

By doing so it is possible to obtain the behaviour of the mixture at different strain levels in one test. In the first steps, the stress response is linear with the strain applied, and the stress is almost constant during the step. As the strain increases, the behaviour deviates from the linearity; the specimen starts to accumulate damage and the stress decreases during the step. Finally, at a certain strain, the specimen fails.

3.2. Results

Figures 10 and 11 present the results obtained by applying the EBADE procedure at 5 and 20ºC to the mixtures studied. Each step had 5000 loading cycles. The right vertical axis represents the strain applied in each step and the left one the stress response. The stress was computed by dividing the load recorded by the test equipment by the area of the cross section of the specimen.

The mixtures employed in the study were fabricated using the same limestone aggregate and the same gradation. The only difference between them was the binder penetration: 13/22 and 60/70, hard and soft binders respectively, namely B13/22 and B60/70.

When the test is performed at 20ºC, the softer mixture increases its stress with each strain level applied until it achieves a maximum and the stress starts to decrease gradually. At a certain strain level the stress during the 5000 cycles of each step starts to decrease. The harder mixture fails at lower strains and before failing the stress is more or less kept constant within each step. When failure occurs there is a sudden drop in the stress recorded, Figure 10.

In tests performed at 5ºC (Figure 11) both mixtures showed less ductile behaviour. Both mixtures failed suddenly when a certain strain level was achieved. Focusing on the B60/70 mixture, in this case the steps with stress decrease were only the last three, while in tests performed at 20ºC nearly 75% of the steps carried out showed this trend.

Regarding the B13/22 mixture, no significant stress decrease was noticed in any of the steps performed, failure happened suddenly when the fifth strain step is applied at 5ºC. As a result, the temperature decrease affected considerably the soft mixture decreasing its critical strain by 50%, while the hard mixture showed a more fragile behaviour but failed at the same strain level at both temperatures.

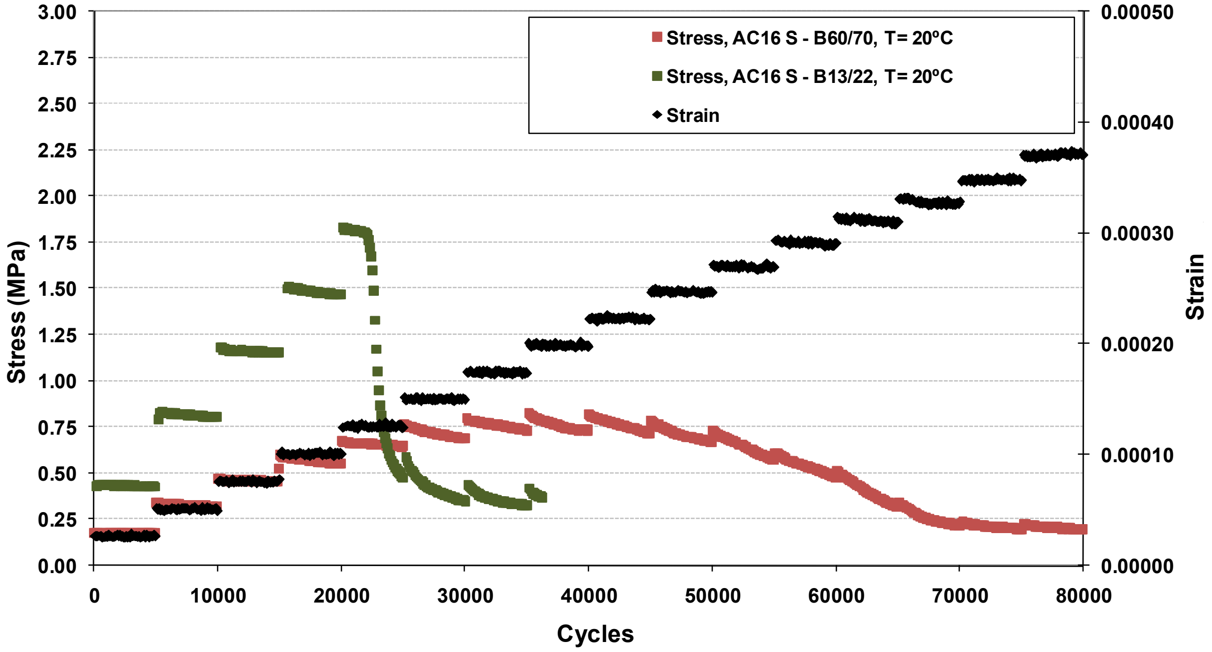


Figure 10 - Stresses and strains recorded in the EBADE tests carried out at 20ºC for the B60/70 and the B13/22 mixtures.

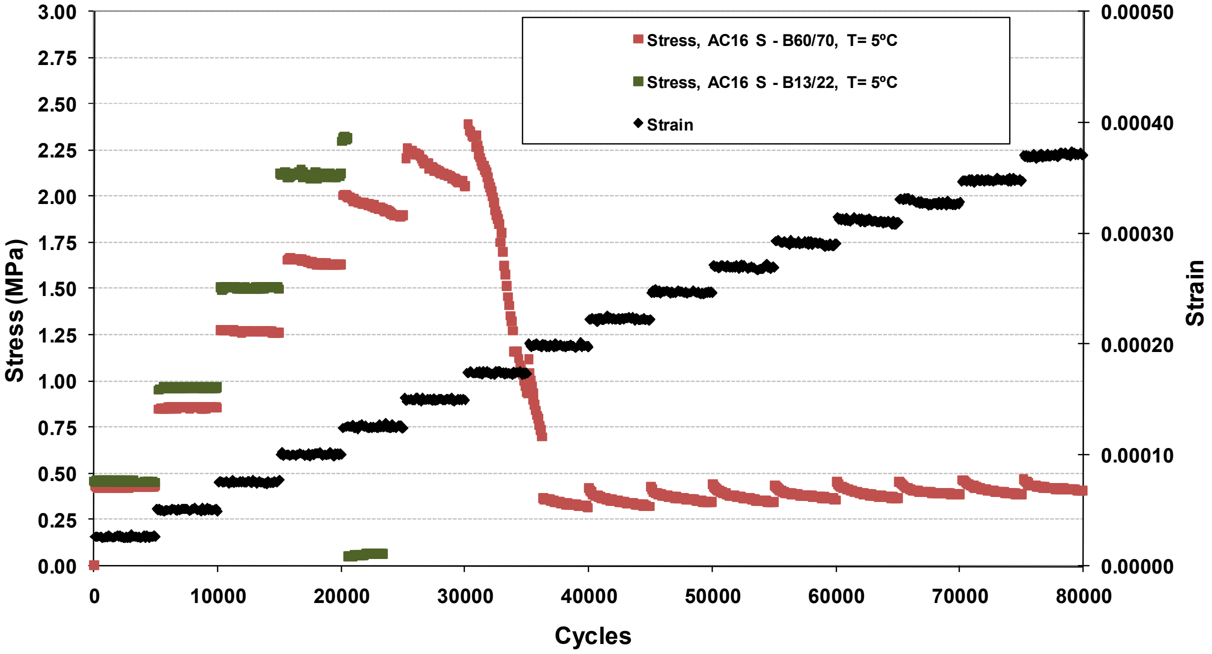


Figure 11 - Stresses and strains recorded in the EBADE tests carried out at 5ºC for the B60/70 and the B13/22 mixtures.

In Figures 12 and 13 the stiffness modulus has been plotted versus the number of cycles for both mixtures at 20 and 5ºC. Those graphics allow one to analyze the evolution of damage in the mixture during the fatigue process. As can be seen from the plots the higher the initial stiffness the more suddenly failure occurs. The B13/22 mixture tested at 5ºC presents a constant stiffness along the test until total failure. Concerning the stiffness, there is no damage and sudden failure takes place when a certain critical strain is achieved. On the other hand, the B60/70 mixture tested at 20ºC shows a decrease in the stiffness as soon as the test starts and keeps loosing stiffness until failure.

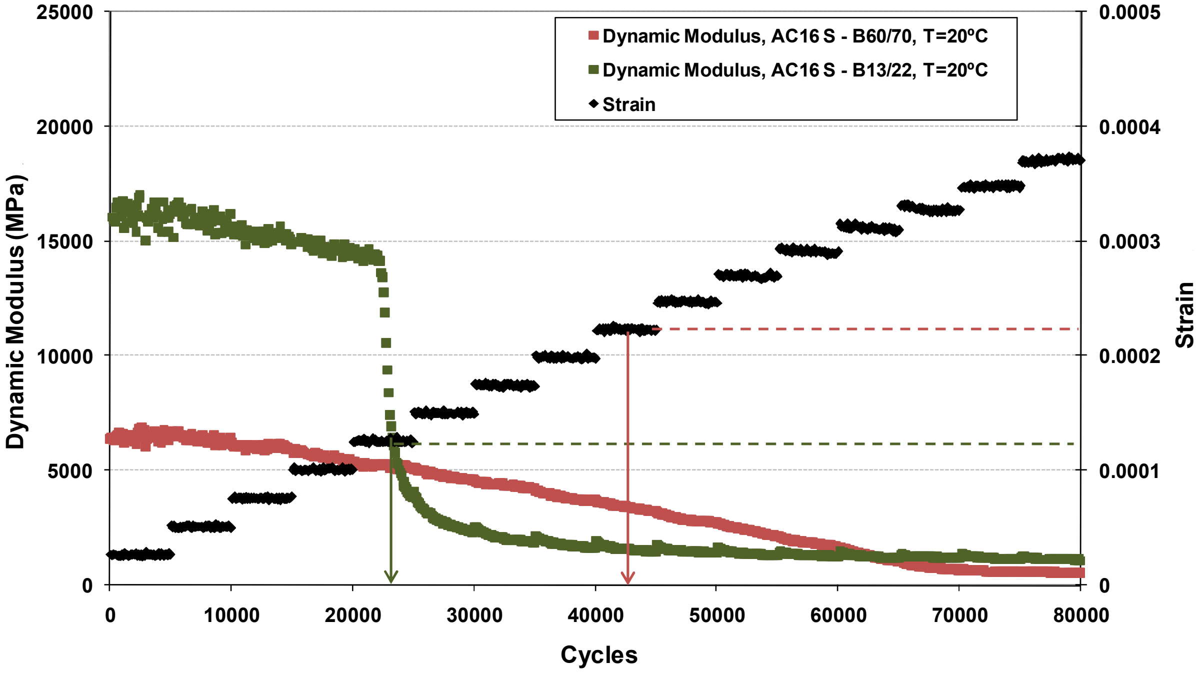


Figure 12 - Stiffness modulus versus number of cycles at 20ºC for the B60/70 and the B13/22 mixtures.

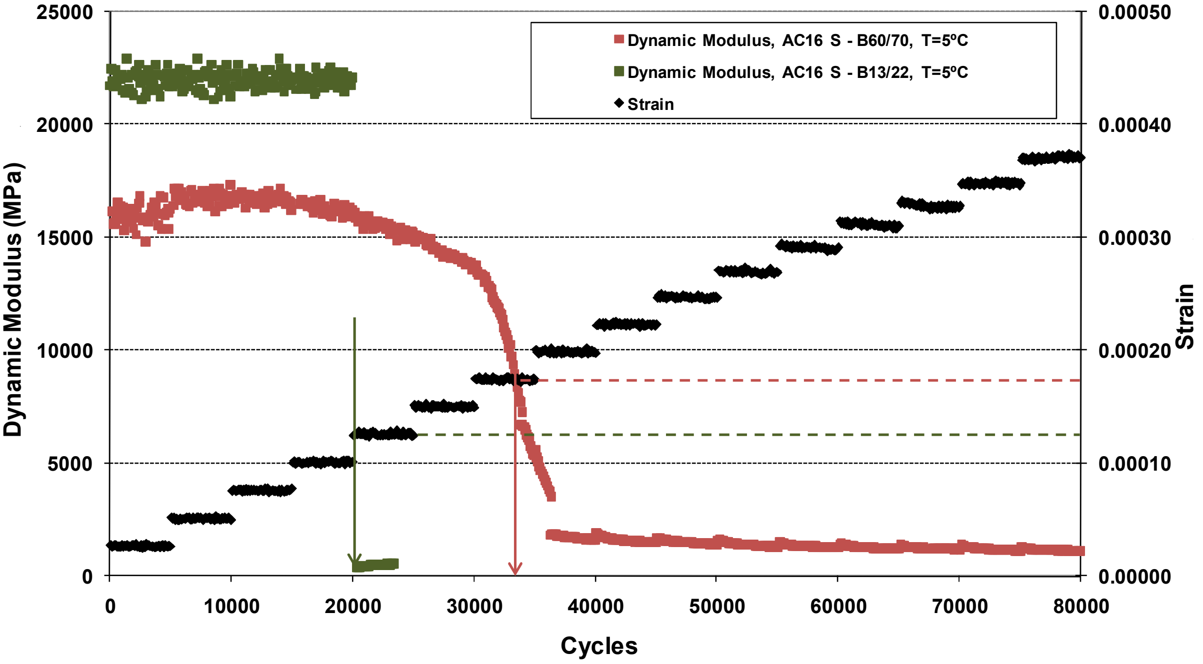


Figure 13 - Stiffness modulus versus number of cycles at 5ºC for the B60/70 and the B13/22 mixtures.

The results of the tests over specimens subjected to a previous thermal stress state caused by cooling them from 20 to 5ºC in one hour can be seen in Figure 14. This figure illustrates the results obtained for the specimens from the 13/22 mixture after applying the EBADE test with and without previous thermal stresses. It can be observed that, for the first series of strain cycles, the initial thermal stresses caused by the temperature decrease from 20 to 5ºC lead to stress values similar to those reached for the third series of strain cycles for the same mixture without subjection to initial thermal stresses. Also note that fracture occurs at lower strain levels. This means that, for very stiff mixtures, the fatigue response is strongly dependent on whether initial thermal stresses are induced, a factor not considered by current pavement design methodologies.

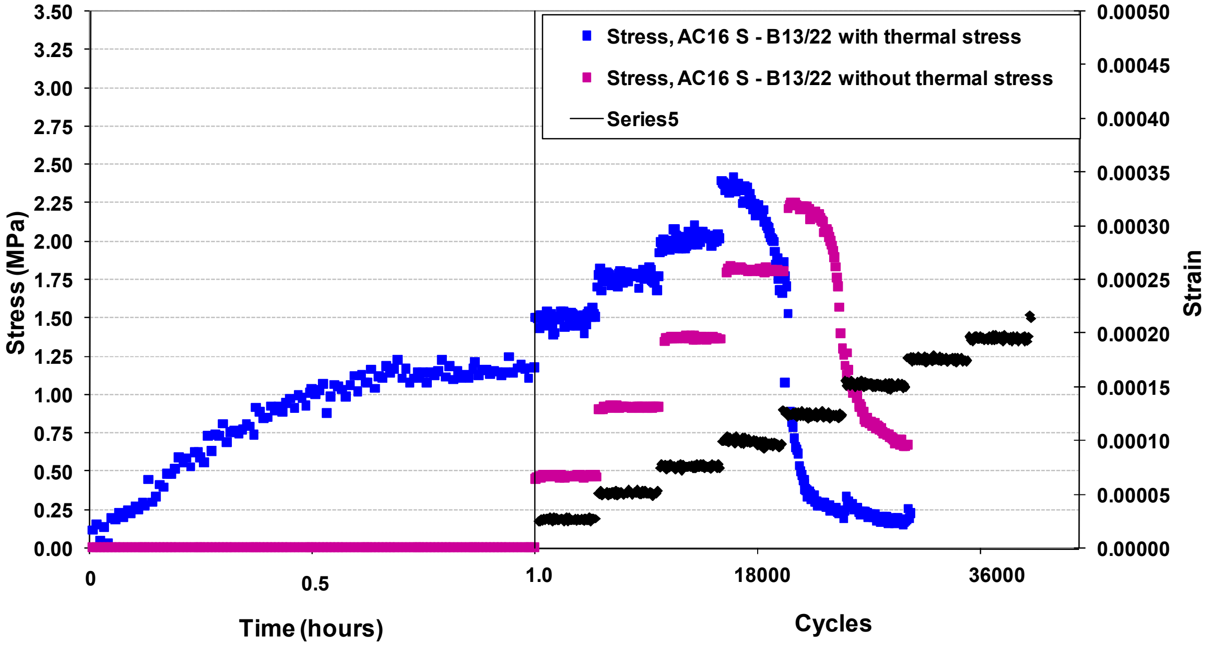


Figure 14 – Stresses of 13/22 mixtures subjected and not subjected to thermal stresses after a one-hour period, from 20ºC to 5ºC, and subsequent application of EBADE test.

4. CONCLUSIONS

Two simple procedures have been developed at the Road Research Laboratory of the Technical University of Catalonia for mixtures design and assessment facing fatigue failure: Fénix and EBADE tests. These tests show the significant effect of thermal stresses in the fatigue process. The following conclusions can be drawn from the results obtained in this study:

Fénix test has proved to be a good procedure to characterize cracking behaviour of bituminous mixtures due to its sensitivity and repeatability to test variables such as loading rate, mixture aging, binder type and content, test temperature and mixture compaction temperature. In addition, it can be applied at a wide range of test temperatures and it is possible to estimate fatigue behaviour by relationships between parameters obtained in Fénix test and bending beam tests.

EBADE test has also proved to be sensitive enough to characterize the fatigue behaviour of stiff and more flexible mixes. The possibility of including cyclic temperature variations in the proposed method to simulate the actual behaviour of pavements more accurately is under investigation.

ACKNOWLEDGMENTS

The authors would like to thank the Spanish Centre for the Development of Industrial Technology (CDTI) for its support in the development of Fénix test in the framework of the FENIX Project (www.proyectofenix.es).

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