APPLICATION OF A STRAIN SWEEP TEST TO CHARACTERIZE BITUMINOUS MIXTURES AND BINDERS

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ABSTRACT

The strain sweeps tests, employed in the 80's to characterize viscoelastic materials, consist of applying a cyclic strain signal with increasing amplitude. Initially they were used to establish the linear viscoelastic domain of these materials in terms of strains.

The data obtained in these kinds of tests make possible to sketch the behavior of the material in a wide range of strains, going from low strains at which the material does not suffer damage to high strains that cause failure almost instantly.

The Road Research Laboratory of the Technical University of Catalonia applied a cyclic uniaxial tension-compression test based on the strain sweep concept to characterize both asphalt binders and mixtures fracture proprieties. This paper presents this new procedure and its application to asphalt binders and bituminous mixtures implemented with those binders. By analyzing the evolution of the complex modulus and the dissipated energy density along the test authors were able to obtain the maximum strain that the materials can sustain and the strain levels that do not cause damage to the specimens. Furthermore, differences observed between the asphalt binders were similar to the differences between the mixtures manufactured with those same binders. Results obtained made possible to characterize the fatigue behavior of bituminous mixtures and binders.

Keywords: asphalt binder, bituminous mixture, strain sweep test, fatigue test, uniaxial tension-compression test

1. INTRODUCTION

One way of reducing the environmental impact produced by the fabrication of bituminous mixtures is by designing long lasting ones. By increasing their service life we reduce reparation operations, reducing at the same time the environmental cost. In order to achieve this goal, it is necessary to study the principal causes of damage bituminous mixtures suffer. The most common one is fatigue cracking, it is almost impossible to prevent a pavement from cracking after a long period of service, because of that, during the designing process, the service life is determined in terms of resistance to fatigue cracking by evaluating asphalt mixtures under fatigue conditions.

Fatigue properties of mixtures are strongly related to those of bitumen [1-6]. However, aggregates also play an important role in this matter. Gradation and aggregate properties affect mixture fatigue behavior as well; in particular, the smallest particles (typically smaller than 0.063 mm) blend with the bitumen, modifying its rheological properties [7,8].

Several authors have extensively studied the fatigue behavior of both, mixtures and binders. The most common procedure used to characterize fatigue behavior of bitumen is based on applying strain-controlled tests and evaluating the number of cycles to failure [9-13]. This is called time sweep test. The conventional failure criterion is based on the value of the stiffness modulus calculated in every cycle of the test. The initial modulus is set as a reference and the test stops when the value of the modulus is lower than a certain percentage of the initial value, the conventional criterion establishes 50% [14]. Each test performed represents a dot in the double logarithmic graph imposed strain versus number of cycles to failure. By carrying out several tests and plotting the data in the former representation, it is possible to obtain the so-called fatigue law of the material by fitting the equation 1.

$$\varepsilon = a \cdot N^{-b}, \tag{1}$$

where ε is the strain applied, *N* the number of cycles to failure, and *a* and *b* are the parameters to adjust.

Regarding bituminous mixtures, the main method currently employed to perform fatigue tests is the four-point bending beam test, [14]. This test follows the same procedure explained before, and applies the conventional failure criterion to obtain the number of cycles to fatigue failure and the fatigue law of the material. One of the most important drawbacks is that, when testing ductile mixtures, if the conventional criterion is used, in some cases the test is considered to be over before the specimen breaks [15], resulting in miscalculation of the fatigue law. Figure 1 shows the complex modulus loss experienced during a strain sweep fatigue test. The complex modulus dropped below 50% initial value, however, when the strain applied decreased the complex modulus recovered up until 90% its initial value, proving that the complex modulus loss it is not related to irreversible damage but to thixotropic effects in the most part of it [16]. Another disadvantage of this procedure is that several tests must be performed at different displacements each, and therefore at different strains. Because of the time needed to perform a single test, long time periods are required to obtain the fatigue characterization of bitumen.

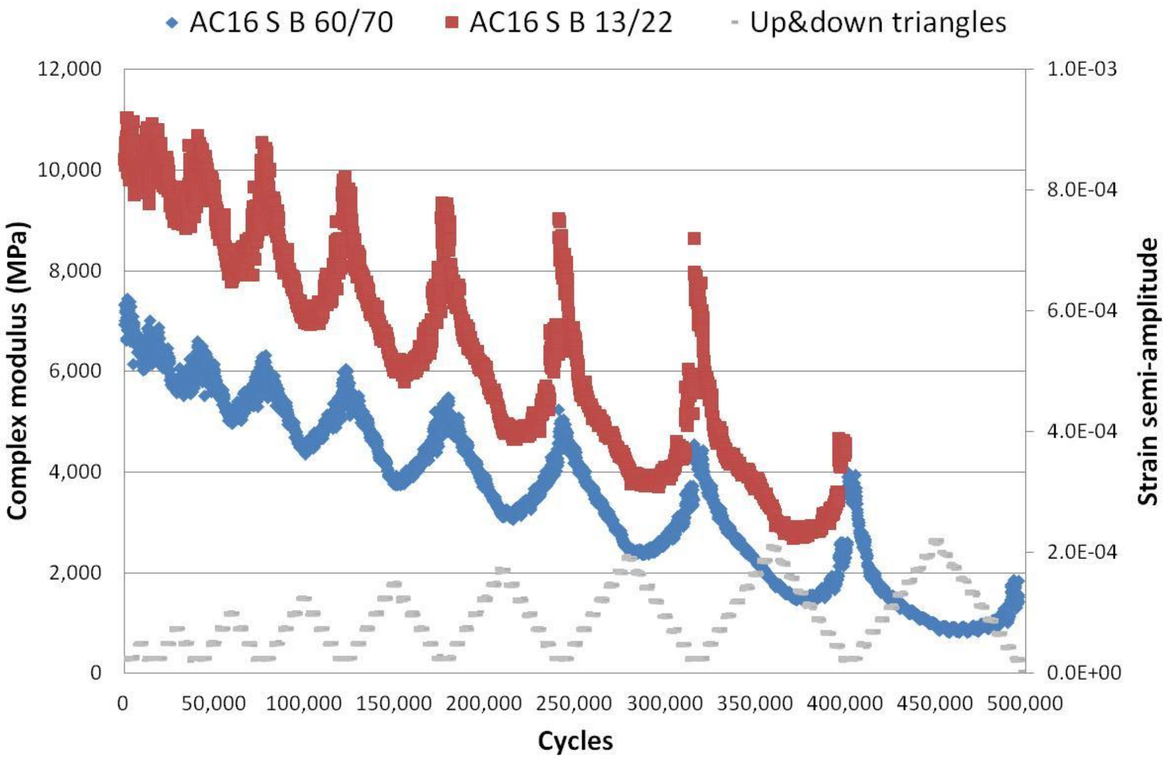


Figure 1 : Complex modulus evolution with the number of cycles in the up&down strain sweep tests on AC-16 S mixtures [16].

The Road Research Laboratory of the Technical University of Catalonia have employed a new experimental procedure to evaluate the fatigue properties of bitumen and mixture, using a cyclic uniaxial tension-compression test, i.e., the EBADE procedure (standing for *Ensayo de BArrido de DEformaciones*, which means strain sweep test in Spanish). Instead of applying a constant strain, the whole test is divided in different steps. At each step, the specimen undergoes a number of cycles at a given constant strain; after that the strain amplitude increases. In a single test, low and high strain levels are tested. The main objective of this research is to analyze fatigue behavior of mixtures applying the classic procedure, time sweep test, and this new procedure, the strain sweep test, and to show the advantages and disadvantages of both procedures.

2. TEST METHODS

The time sweep tests were performed using the four point bending beam (4PB) test as described in the CEN standard [14], while the strain sweep tests were performed using the EBADE procedure, which is described in the following lines.

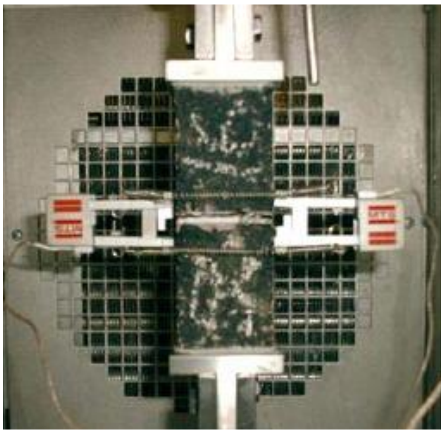
2.1 Four-point bending beam fatigue test

The Four point bending beam machine, as described in UNE-EN 12697-24, Annex D [14], is composed of two inner and two outer clamps symmetrically placed. The two outer clamps keep the beam fixed and the two inner clamps are loaded to create a constant movement. The software records the stiffness modulus, the strain applied and the number of cycles, among other parameters. The tests were performed at 20ºC and 10 Hz.

2.2 EBADE test

This test procedure consists of subjecting a specimen to a sinusoidal displacement signal (tension-compression) at a frequency of 10 Hz. A certain strain amplitude is applied for a specified number of cycles, in our case 5,000. Then, the amplitude increases a certain value for the same number of cycles, and so on. In each cycle the resultant load is recorded and the test ends when load drops to zero.

A 5 cm wide and thick, 6 cm high prismatic samples are carved from a cylindrical Marshall specimen and two notches are cut in their middle section to reduce the specimen area and induce failure. Both ends of the specimens are bonded to a plate with an epoxy resin to allow clamping. Two extensometers are placed on the failure area of the specimens to measure and control strain during testing, Figure 3. The test temperature was 20ºC, the test frequency was 10 Hz, the initial strain amplitude was $2.5 \cdot 10^{-5}$, and the strain amplitude increase between steps was $2.5 \cdot 10^{-5}$ [17].



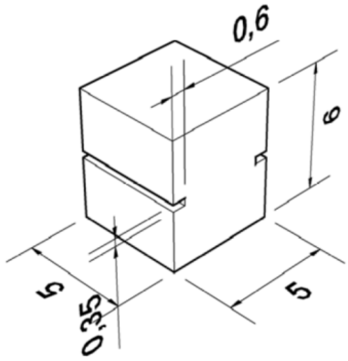


Figure 3 : EBADE test set up for prismatic asphalt mixture specimens (in cm).

The most important parameters that can be computed during the test are: maximum stress, σ_{max}, complex modulus, $|E^*|$, and dissipated energy density, E_D, during each cycle. Using the maximum stress and strain, ε_{max}, it is possible to obtain the complex modulus by equation 3:

$$E^* = \frac{\sigma_{\max}}{\varepsilon_{\max}}. \tag{3}$$

Due to the delay between stress and strain, an ellipse is formed in the stress vs. strain plot and the dissipated energy density is proportional to its area. To compute this area from the test data, Gauss area formula is employed (equation 4).

$$E_D = \frac{g}{S} \cdot \frac{1}{2} \left| (\sigma_1\varepsilon_2 + \sigma_2\varepsilon_3 + \ldots + \sigma_{n-1}\varepsilon_n + \sigma_n\varepsilon_1) - (\sigma_2\varepsilon_1 + \sigma_3\varepsilon_2 + \ldots + \sigma_n\varepsilon_{n-1} + \sigma_1\varepsilon_n) \right|, \tag{4}$$

where g is gravity, S is the fracture surface, and $\sigma_i\varepsilon_i$ are the n values obtained for the stess and strain during a cycle arranged clockwise or counterclockwise.

3. TEST MATERIALS

Four Mixtures manufactured with four different asphalt binders were studied. Two of them were conventional binders coming from different sources that were named B 50/70 1 and B 50/70 2. The two remaining were a polymer modified binder BM3c and a crumb rubber modified bitumen BC 35/50. The mixtures contained limestone aggregate with the gradation showed in table 1.

Table 1 : **Mixture gradation.**

Sieve (mm)	Passing (%)
22	100
16	95
8	75.5
4	60.5
2	43.5
0.5	20
0.25	9.5
0.063	3

4. RESULTS

Due to the high amount of data obtained in the time and strain sweep tests, only relevant results are graphically represented.

4.1. Time sweep tests

In the time sweep tests the response expected from a bituminous mixture is a three-stage behavior on the complex modulus evolution with the number of cycles [18]. In the first cycles the complex modulus drops quickly, normally due to thixotropy, then it stabilizes slowly linearly decreasing, and finally a complete loss of the complex modulus takes places. Failure is assumed to happen in the third stage. However the conventional failure criterion disregards this behavior by relating failure with a 50% loss of the complex modulus during the test.

In the four points bending beam tests carried out, in the majority of the cases the 50% initial complex modulus was reached before the third stage of the fatigue process took place, figure 5.

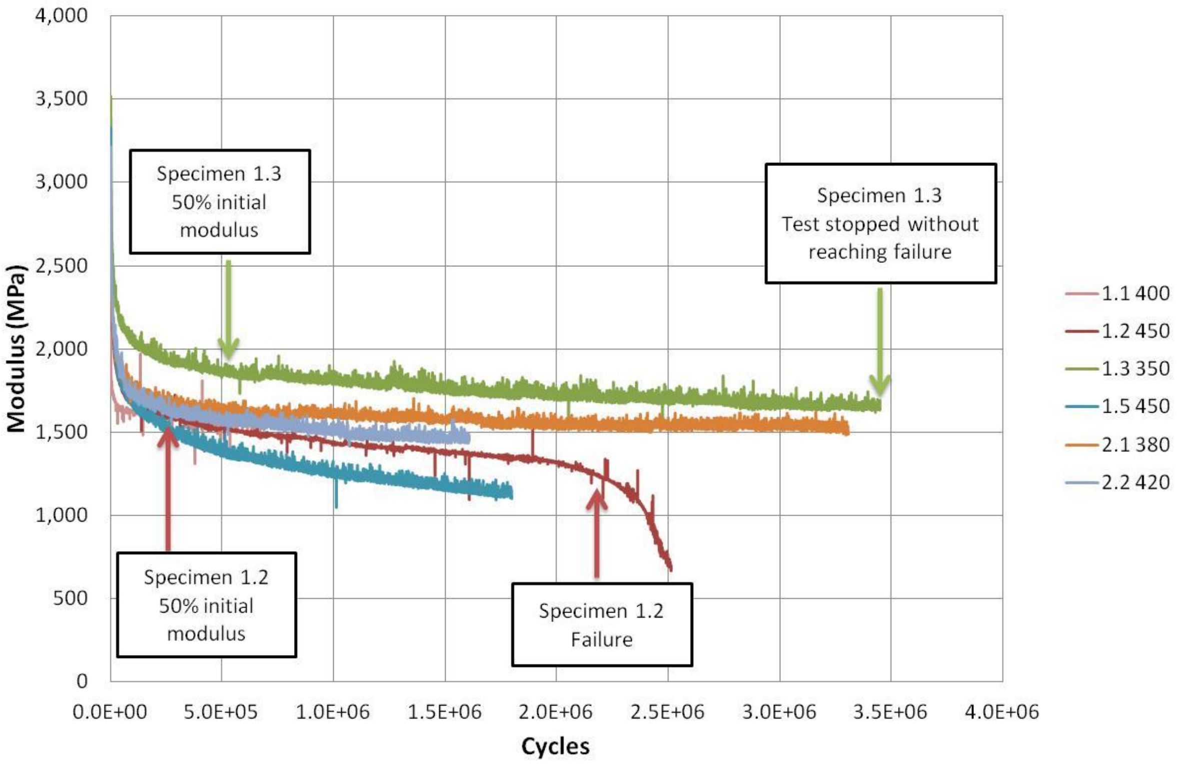


Figure 5 : Modulus vs. cycles curves for the BM3c mixture obtained in the 4PB tests. Each curve has the number of specimen and the strain applied in microstrains.

The specimen 1.2 and 1.3 are noted as two examples of the inconvenience of the conventional criterion. The 1.2 specimen, tested at 350 microstrains, lasted over 2,000,000 cycles before experience a complete loss of the complex modulus, i.e. the third stage. However, the conventional criterion established failure for this specimen at 68,000 cycles. The same happened with the 1.3 specimen, which reached the 50% modulus loss at 500,000 cycles but lasted more than 3,000,000 cycles without showing the third stage behavior. No sign of fatigue failure was observed in this specimen.

Polymer modified binders tend to show that kind of behavior, but the same phenomenon was observed when testing conventional binders, figure 6.

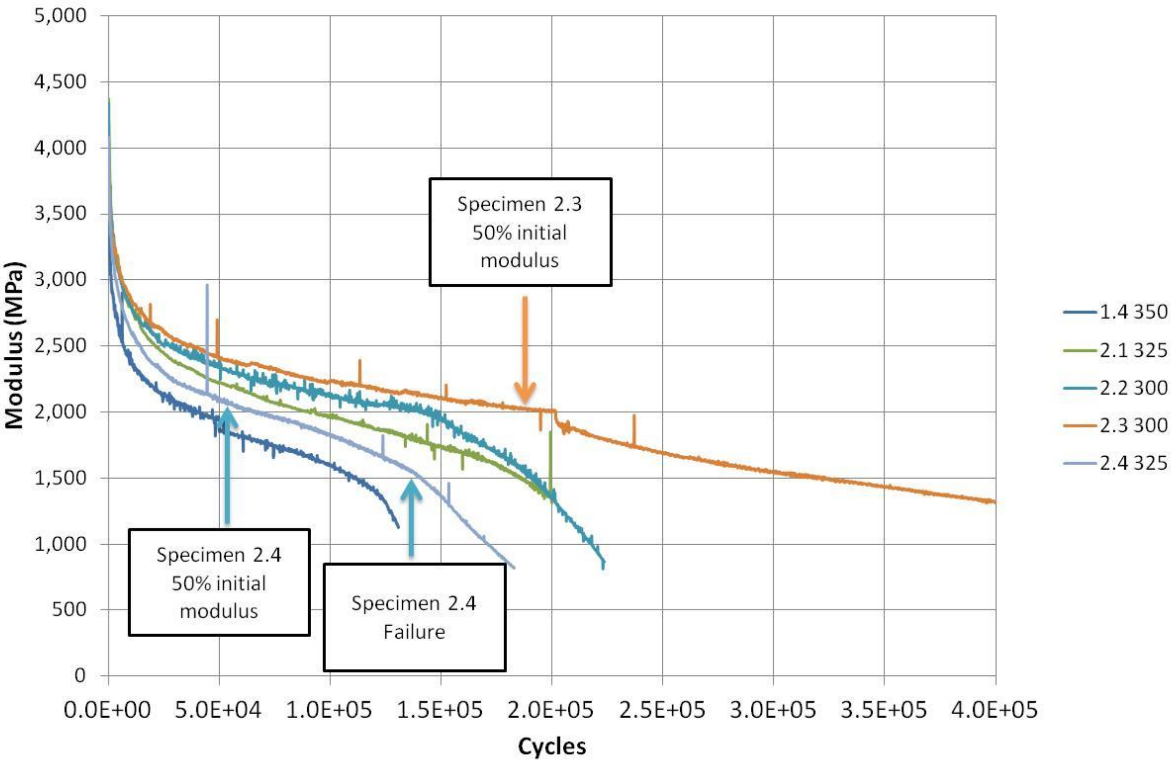


Figure 6 : Modulus vs. cycles curves for the B 50/70 2 mixture obtained in the 4PB tests. Each curve has the number of specimen and the strain applied in microstrains.

The conventional binders showed a higher slope on the modulus vs. cycles curves during the second stage of the fatigue process. However, the 50% modulus loss took place an important number of cycles before the third stage began.

The fatigue laws obtained by applying the conventional criterion are shown in figure 7. The results obtained showed that the mixture manufactured with the BM3c binder had a more ductile behavior, i.e. it needed higher strain levels to reach failure. The B 50/70 1 and BC 35/50 mixtures presented a more fragile behavior, failing at lower strain levels while the B 50/70 2 was able to sustain slightly higher strain levels than the former two.

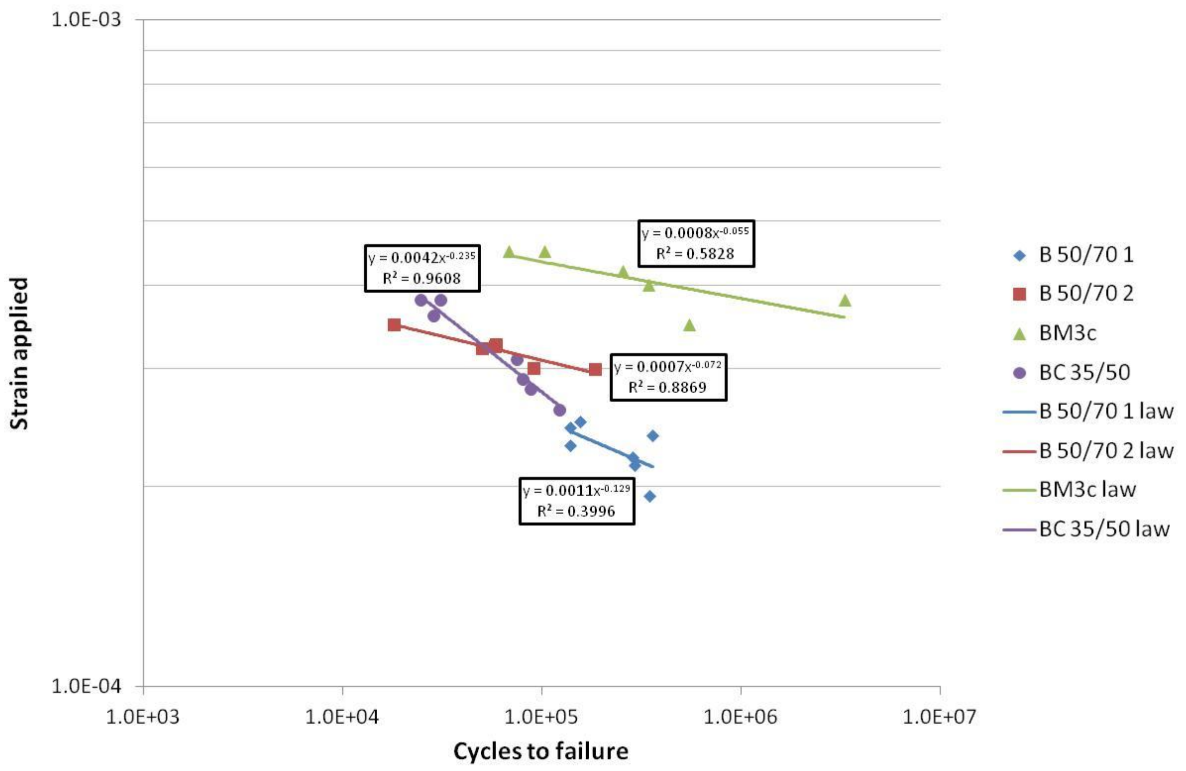


Figure 7 : Fatigue laws obtained for the four mixtures.

As it has been shown in figure 1, when the EBADE test is applied with increasing and decreasing strain levels, the complex modulus loss is mostly due to thixotropy instead of damage. That questions the reliability of the fatigue laws, computed by applying a complex modulus relative loss related criterion. A 50% loss of complex modulus does not imply failure, because the modulus loss due to thixotropy is completely recoverable and in some cases this effect can cause that kind of drops recovering more than 90% of the initial value when the strain applied is decreased [16]. Therefore, a fatigue law elaborated with the conventional criterion can mix data from specimen that had failed with specimens that had experienced thixotropic effects.

4.2. Strain sweep tests

The most important parameters analyzed were the maximum stress, the complex modulus and the dissipated energy density measured at each cycle. The graphical representations of those three parameters with the number of cycles are showed in figures 8, 9 and 10. Every 5,000 cycles the strain applied increased in $2.5 \cdot 10^{-5}$, thus the superior axis of figures 8, 9 and 10 represents the strain applied during each step.

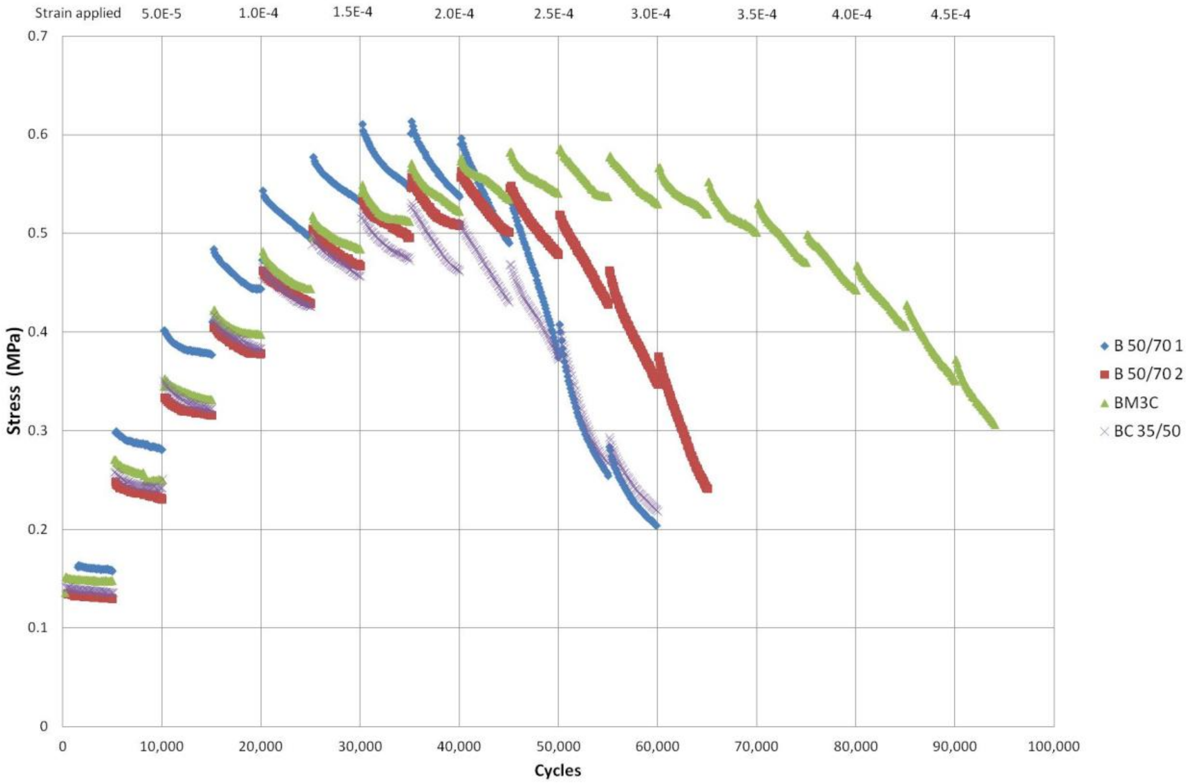


Figure 8 : Maximum stress vs. cycles curves obtained in the strain sweep tests.

The maximum stress recorded each cycle, figure 8, increased with the strain applied until it reached a maximum value and it started to decrease. However, within each step (section at constant strain during 5,000 cycles) the maximum stress decreased continuously.

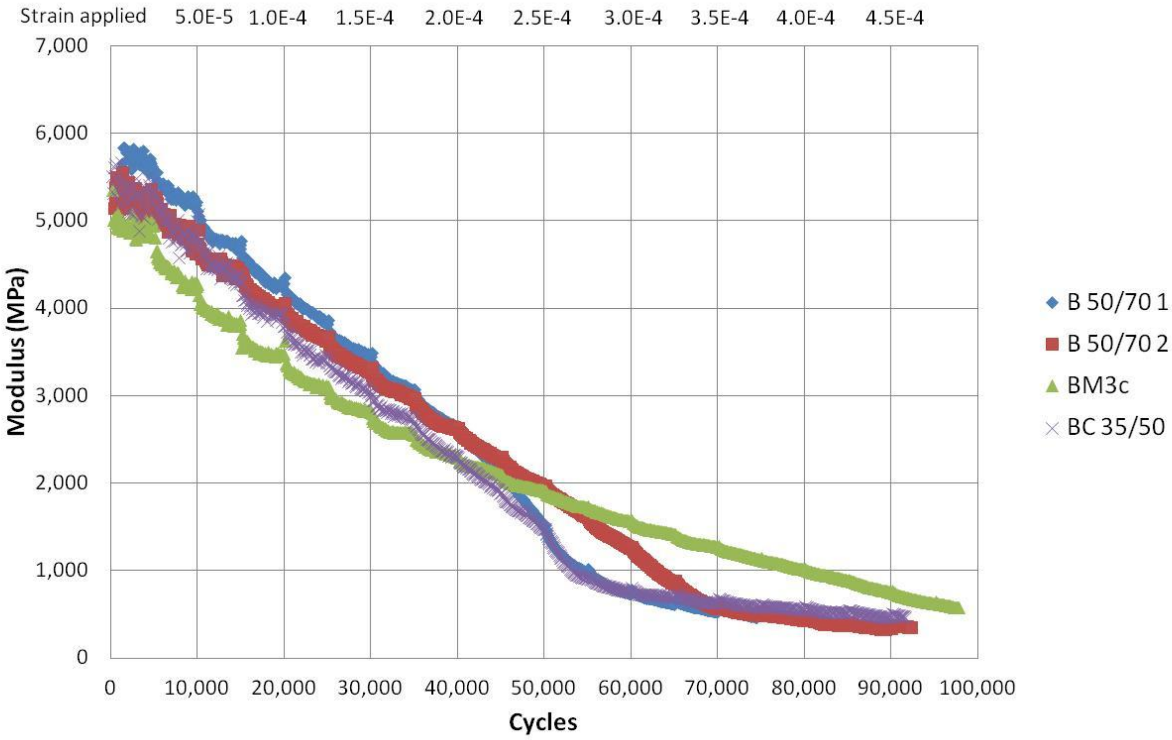


Figure 9 : Modulus vs. cycles curves obtained in the strain sweep tests.

The complex modulus showed the same behavior within each strain step, but unlike the maximum stress, its maximum value was obtained in the first cycles of the test, decreasing as the test progressed.

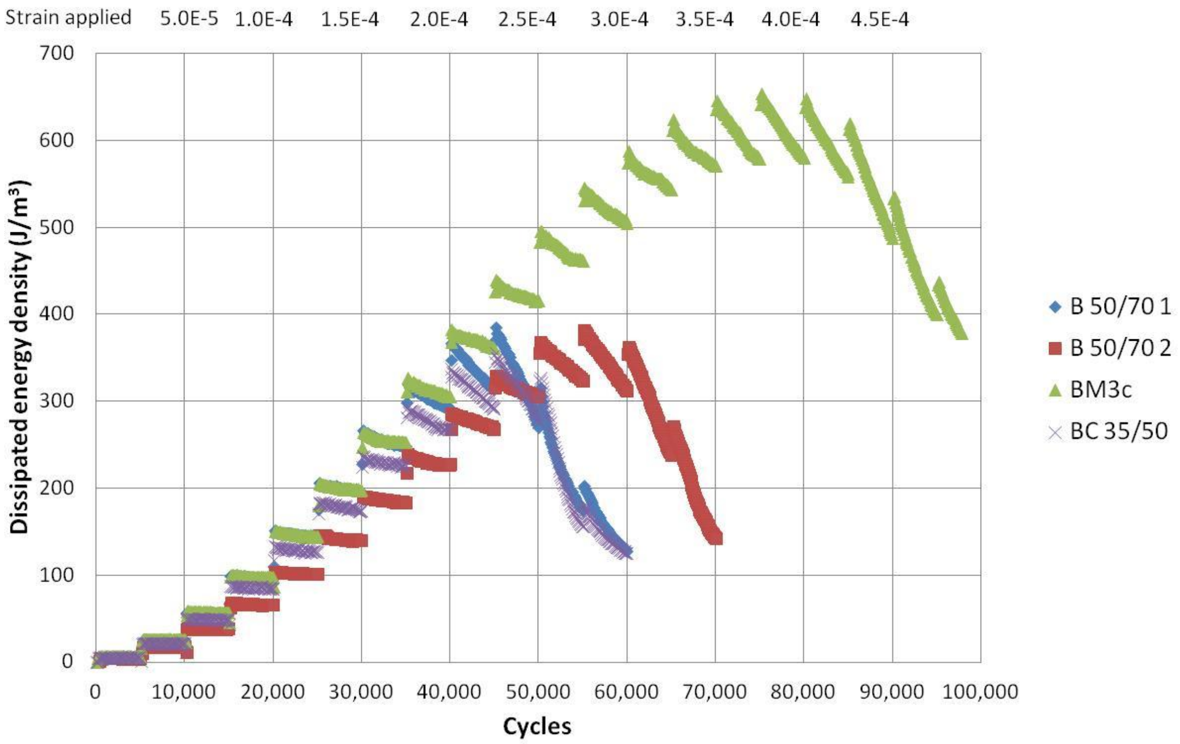


Figure 10 : Dissipated energy density vs. cycles curves obtained in the strain sweep tests.

Finally, the dissipated energy density increased with the strain applied and dropped suddenly when failure occurred. Thus, the strain at which the mixture fails can be determine using figure 10. To compare between mixtures, a failure strain was defined as the strain level at which the dissipated energy density dropped below 50% the maximum value reached during the test. Within each cycle it also showed a continuous decrease, being higher when the strain applied was higher as well

Analyzing these results, the B 50/70 1 and BC 35/50 mixtures failed at the same strain levels, while the B 50/70 2 failed at a higher strain. Looking at figure 10, it is clear that the B 50/70 2 sustained, at least, three more strain steps than the B 50/70 1 and the BC 35/50. At the same time, figure 9 shows that the B 50/70 2 mixture presented a similar modulus than the BC 35/50 and slightly lower than the B 50/70 1. Clearly, the mixture with better fatigue behavior from those three is the one manufactured with the B 50/70 2 binder, having a similar modulus it failed at higher strains. This is the same conclusion obtained in section 4.1. by means of the fatigue laws. However, in this case, the time employed to obtain the results was considerably lower.

Regarding the BM3c mixture, the results obtained in the strain sweep tests provided the same information. It showed the best performance, with a slightly lower modulus and a much higher failure strain.

In figure 11, the strain at which the mixture sustains only 100,000 given by the fatigue laws obtained in the 4PB tests is plotted against the strain at which the mixture failed in the EBADE tests. There is a good correlation between both parameters.

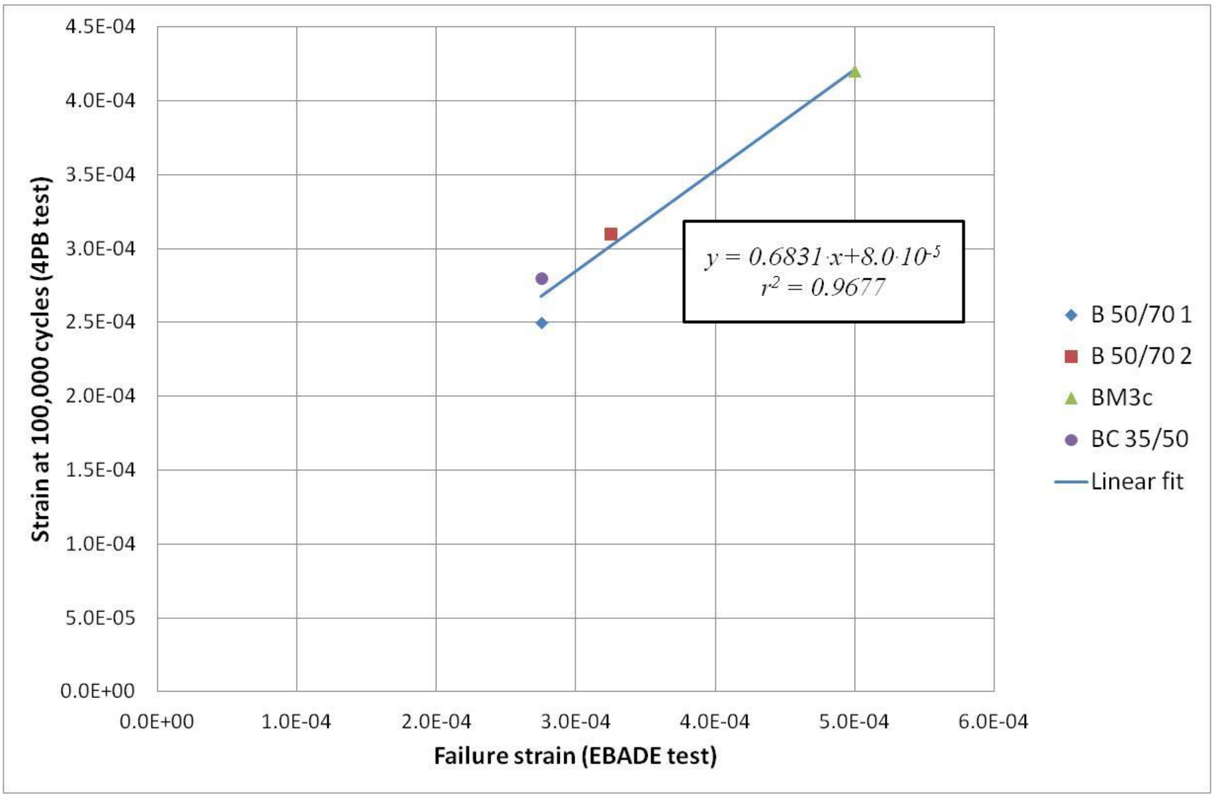


Figure 11 : Strain at 100,000 in the fatigue law vs. failure strain in EBADE test.

There is also a good correlation between the initial modulus recorded on the four point bending beam test and the initial modulus obtained in the first steps of the EBADE test, figure 12.

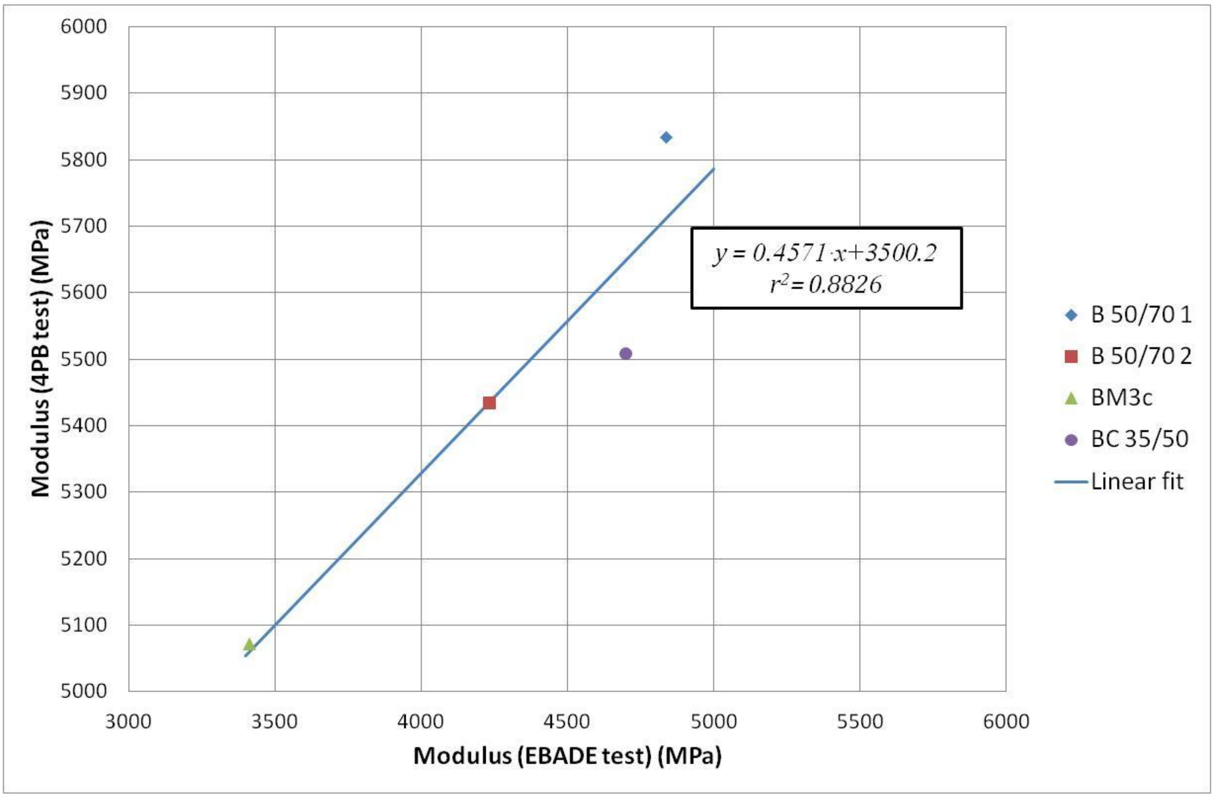


Figure 12 : Initial modulus in 4PB tests vs. failure strain in EBADE test.

According to these results, the EBADE test allows to obtain two important parameters to characterize the fatigue behavior of bituminous mixtures, the modulus and the strain at which the mixture fails. Those are the same parameters one can obtained from the fatigue laws delivered by the four point bending beam fatigue test, which also provides a life prediction for the material which is not accurate since the failure criterion employed mixes data from specimen that had failed with specimens that had experienced thixotropic effects.

5. CONCLUSIONS

The application of the time and strain sweep tests to the four mixtures studied showed a series of advantages and disadvantages of both procedures, that have to be taken into account when analyzing the results.

- It is needed a profound analysis regarding the failure criterion employed in fatigue tests. It is necessary differentiate between modulus loss due to material damage and modulus loss due to increase in the flow rate, i.e. thixotropy.
- The conventional failure criterion (50% loss of modulus) employed in the four point bending beam fatigue test can underestimate the fatigue life of the mixture in some cases, especially when ductile mixtures are tested. As a consequence, the fatigue laws, obtained using this criterion, are not reliable.
- The four point bending beam fatigue test only provides reliable information about the strain level at which the mixture fails. It is also possible to obtain this information by applying a strain sweep test, such as the EBADE test, which is a much quicker and simpler procedure.

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