Estimating the fatigue law of asphalt mixtures using a strain sweep test (EBADE test)

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ABSTRACT. *Fatigue characterization of asphalt mixtures is a very important issue. However, existing techniques to that end are expensive and time consuming. For that reason the asphalt technicians have been studying several different methods to reduce the testing time needed. Such is the case of the Visco-Elastic Continuum Damage models.*

In that regard, this paper presents the efforts carried out by the Road Research Laboratory at the UPC-BarcelonaTech to reduce that testing time, by implementing a strain sweep test and approximating the fatigue law of the material from the data obtained.

The EBADE test was applied to four mixtures for which the conventional fatigue laws were obtained using time sweep tests. The data collected was used to fit a fatigue model based on two strain values that can be directly computed from the EBADE test, namely Failure strain and No Damage strain. A good correlation was found between the model proposed and the experimental data.

KEYWORDS: *fatigue, strain sweep test, bituminous mixture, asphalt, EBADE.*

1. Introduction

One the most typical distresses in asphalt pavements is fatigue cracking and the calculation of the bituminous layers thickness is based on this mixture property. Fatigue failure takes place when the mixture is subjected to a repeated stress induced by the traffic loading. This stress, although lower than that at which pavement failure is produced, ends up causing cracking because of its repetition in time. This phenomenon it is called fatigue failure and it takes place in other materials, such as metals.

It is precisely in metallic materials where fatigue cracking was first analyzed (Schütz, 1996). During that study the engineer August Wöhler found that the number of cycles at which a metal axel failed was related with the stress amplitude applied to it, by a logarithmic relation, that later was called S-N curve. That finding has been applied since then to obtain the fatigue law of any kind of material, either by performing tests at constant stress amplitude or constant strain amplitude until failure. By plotting the number of cycles versus the controlled variable (stress or strain) for several tests the fatigue law of the material can be obtained, [1, 2]. Those kinds of tests are called time sweep tests.

$$\log N = a - b \cdot log\varepsilon \; (strain\ controlled\ tests) \qquad [1]$$

$$\log N = c - d \cdot log\sigma \; (stress\ controlled\ tests), \qquad [2]$$

where *N* is the number of cycles to failure, ε is the applied strain amplitude in strain controlled tests, σ is the applied stress amplitude in stress controlled test and *a, b, c* and *d* are the material related parameters determined by adjusting the data points to [1] and [2].

Later on, applying that potential relation between the number of cycles to failure and the loading amplitude, a relation was found between the ratio of crack growth and the stress state the material was undergoing. This relation is called the Paris law (Paris *et al.,*1961):

$$\frac{da}{dN} = C \cdot (\Delta K)^m, \qquad [3]$$

where d*a/dN* is the crack growth rate per cycle, $\Delta K = K_{max} - K_{min}$ is the stress intensity factor range during the cycle, and *A* and *m* are parameters experimentally determined that depend on the material, the environment, the frequency, temperature and stress ratio.

This law is applied to the analysis of cracking propagation in asphalt pavements, although viscous response of the material must be considered, since in the calculation of the stress intensity factor it is very important how the stress state is distributed in the tip of the crack. This calculation is easier in elastic materials such as metals but more difficult in the case of bituminous mixtures and visco-elasto-plastic materials.

The time sweep tests applied to obtain the fatigue law of the material, described, are expensive and laborious because they need special presses and equipment for a long period time. For that reason several researchers are trying to use simpler procedures and equipment based on the visco-elastic response of the materials and applying a modified version of the Paris law where the mixture damage is correlated with the energy applied to failure, which is called a damage evolution law (Kim *et al.,* 1996, Kutay *et al.,* 2009, Walubita *et al.,* 2012).

$$\frac{dD}{dt} = \left(-\frac{\partial W}{\partial D}\right)^{\alpha} \qquad [4]$$

where D is the amount of damage, W materials potential energy and α is a material constant related to the rate of damage growth.

The mixture damage is usually evaluated from the variation of one of its mechanical characteristics, like complex modulus, with the number of loading cycles. The initial modulus is usually assumed that corresponding to the testing value obtained at 100 or 200 load applications or it is determined using special tests that are carried out under very low strains (linear domain) to avoid mixture damage, since the mixture modulus decreases as imposed strain increases.

The loss of the material potential energy can be calculated in a cyclic fatigue test from the variation of the dissipated energy density, DED from now on, obtained by computation of the area enclosed by the stress-strain loop in each loading cycle. The DED decrease not always means mixture damage, but can also be caused by an initial rearrangement of the internal structure of the mixture, non-linear effects and/or thixotropy (Di Benedetto *et al.,* 2011, Pérez-Jiménez *et al.,* 2012, Nguyen *et al.,* 2012). In an undamaged material, after the initial loss attributed to these effects, the area of the stress-strain loop should remain constant. The shape of the loop changes as the mixture is deteriorating, increasing its area in controlled stress tests and decreasing it in controlled strain tests.

Summarizing, by fixing a damage evolution law and relating a measurable variable related to damage with the conditions applied to the mixture, for instance, obtain an expression for the DED as a function of the pseudostrain, it is possible to obtain a theoretical number of cycles to failure for a mixture under a certain strain amplitude by performing a few and short tests. That would be the main goal of what are called Visco-Elastic Continuum Damage (VECD) models (Luo *et al.,* 2008, Arambula *et al.* 2009, Luo *et al.,* 2010).

The aim of this research project is very similar, to sketch the fatigue law, in the form of equation (2), from the data obtained in a strain sweep test called EBADE (Pérez-Jiménez *et al.,* 2011). To do that, an interpretation of [4] was applied to approximate the fatigue law of the mixtures studied from the data provided by this kind of test. The validation of the procedure required the realization of time sweep tests to obtain the experimental fatigue law of the mixtures by the conventional procedure. With this data, the model was fitted to four mixtures, manufactured with four different binders.

2. Methods and Materials

2.1. EBADE test

The EBADE test (*Ensayo de BArrido de DEformaciones*) (Pérez-Jiménez *et al.*, 2011) consists of applying a number of tension-compression load cycles to a prismatic specimen at different strain levels.

A prismatic specimen is used in the test. Two notches are cut in its central area to reduce the specimen area and induce failure. The specimens are obtained from Marshall compacted cylindrical specimens by cutting of the round sides. In the developing of the research all specimens were 5 cm wide and thick, and 6 cm high. In two of the sides of the prismatic specimen two notches 6 mm deep and 4 mm wide are carved, to help the crack to propagate through the mid section.

Both ends of the specimen are bonded to a plate with an epoxy resin to allow clamping. Two extensometers are placed on the failure area of the specimen previously induced to control strain during testing, Figure 1.

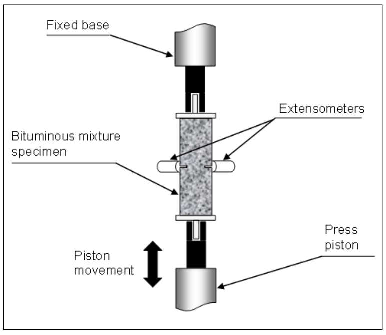

Figure 1. *EBADE test set up.*

The most important parameters that can be computed during the test are: maximum stress, σ_{max}, complex modulus, |E*|, and dissipated energy density, DED, during each cycle. Using the maximum stress and strain, ε_{max}, it is possible to obtain the complex modulus by [7]:

$$\varepsilon(t) = \varepsilon_{max} \sin(\omega t) \quad [5]$$

$$\sigma(t) = \sigma_{max} \sin(\omega t + \delta) \quad [6]$$

$$|E^*| = \frac{\sigma_{max}}{\varepsilon_{max}}, \quad [7]$$

where [5] and [6] represent the strain input signal and the stress output signal and δ is the delay between the two of them.

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 [8].

$$DED = \frac{g}{S} \cdot \frac{1}{2} |(\sigma_1 \varepsilon_2 + \sigma_2 \varepsilon_3 + \cdots + \sigma_{n-1} \varepsilon_n + \sigma_n \varepsilon_1) - (\sigma_2 \varepsilon_1 + \sigma_3 \varepsilon_3 + \cdots + \sigma_n \varepsilon_{n-1} + \sigma_1 \varepsilon_n)|, \quad [8]$$

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

The EBADE test protocol consist of applying several strain amplitudes in ascending order in stages of 5,000 loading cycles at a frequency of 10 Hz. The test finishes when the total failure of the specimen takes place. Each stage of 5,000 cycles at the same strain amplitude is called step. The strain amplitude applied in the first step is 2.5E-5, and every 5,000 cycles the strain increases in 2.5E-5. This way, the number of cycles and the strain amplitude are directly related.

2.2. Hypothesis

From the EBADE test, it is possible to obtain the behaviour of the mixture under different strain amplitudes. It is very straight forward to obtain the strain amplitude at which total breakage of the mixture takes place, just by plotting the DED evolution with the number of cycles. After reaching a maximum value, this parameter drops suddenly when failure takes place.

Furthermore, the EBADE test provides information regarding the DED evolution from very low strain levels to the Failure strain. In the first step the DED remains constant as the test progresses, in the second step the DED remains constant as well but at a higher value. That behaviour keeps showing until certain strain amplitude is reached and the DED starts to smoothly drop within the strain step. By recording the strain amplitude at which this phenomenon starts to happen, it is possible to obtain the maximum strain amplitude the material can endure without showing non-linear effects. Thus, the DED versus number of cycles curve provides two key values for the strain amplitude:

- The maximum strain amplitude at which DED remains constant within a strain step. That strain amplitude can be related with the strain level at which a specimen will not fail in a time sweep test, or will fail in a very large number of cycles (such as 5E6, for instance). The criterion to obtain that strain amplitude, from now on called No Damage strain or ND strain, is based on the DED loss during each step. The value of the ND strain was fixed as that of the last strain step in which the DED loss was less than 4%. That is based on the accuracy of DED measures; the average coefficient of variation of the DED during the first step, at which it is assumed to remain constant, is around 3.5%. Recalling [4], that would represent the extreme case in which no variation in energy with time (or number of cycles) implies an infinite number of cycles [9].

$$\Delta DED \rightarrow 0 \;\; => \;\; N \rightarrow \infty \qquad [9]$$

- Failure strain: That is the strain amplitude at which the material fails in the strain sweep tests. At that strain amplitude, a time sweep tests will finish in a small number of cycles, i.e., failure will take place in a few cycles. The criteria established to determine that strain amplitude is based on the DED evolution, 50% reduction of the maximum DED value reached during the test, figure 2.

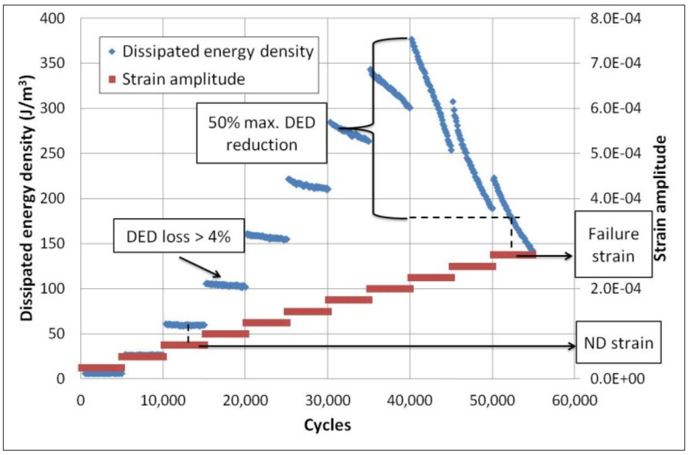

Figure 2. *Example of the determination of the failure strain and the LD strain from the DED data extracted from an EBADE test.*

For a given mixture, obtaining that two strain values, Failure strain and ND strain, and defining a reasonable number of cycles around which a time sweep test at these strain amplitudes will cause failure, two theoretical data points can be obtained. Those two points define a theoretical fatigue law that, results variability aside, should be close to the real fatigue law of the material.

To prove that theory four mixtures were tested using strain sweep tests (EBADE tests) and time sweep tests using the same loading configuration.

2.3. Test plan

In order to develop the model presented in the previous section, it was necessary to:

- Design different mixtures to obtain a broad spectrum of data.

- Perform strain sweep tests (EBADE tests) to obtain the two strain values to implement the model.

- Perform time sweep tests and obtain the fatigue law of the mixture to validate the model.

2.4. Mixtures

Four different mixtures were used in the development of this research project. The four of them had the same gradation, table 1, but were manufactured using four different binders, namely B50/70-1 and B50/70-2, two conventional binder of 50/70 dm penetration range at 25ºC from different factories, BM3c, an SBS modified binder, and BC-35/50, a binder of 35/50 dm penetration range at 25ºC modified with crumb rubber. All of them were fabricated using the same binder content, 5.26% in aggregate mass.

Table 1. *Mixtures gradation.*

Sieve (mm)	Passing (%)
22	100.0
16	95.0
8	75.5
4	60.5
2	43.5
0.5	20.0
0.25	9.5
0.063	3.0

2.5. Strain sweep tests

Following the test protocol described in section 2.1 the four mixtures were studied. The temperature to apply the model was chosen to be 20ºC, the most common temperature in Spain throughout the seasons. Three replicates were tested for each mixture.

2.6. Time sweep tests

Aiming to obtain the fatigue laws of all four mixtures, several time sweep tests were carried out using the same loading configuration, test temperature (20ºC), test frequency (10Hz) and sample size as the EBADE test, but maintaining a constant strain amplitude throughout the tests. Different tests at different strain amplitudes were carried out. The failure criterion was established as the number of cycles at which the complex modulus decreased below 25% the value at cycle 100. That value was chosen after analyzing different complex modulus curves and taking into account previous research studies that showed that the conventional criterion, 50% reduction of the initial modulus, is not appropriate for ductile mixtures (Pérez-Jiménez *et al.,*2009) .

The tests were planned as follow: three replicates at the failure strain amplitude obtained in the previous EBADE tests, three at failure strain plus 2.5E-5 strain, three at failure strain less 2.5E-5 strain and three at half the Failure strain, giving a total of 12 data points to obtain the fatigue law of each mixture.

However, due to the long time duration of these tests, some of them did not reach the failure criterion in a reasonable time, and others experienced anomalous breakage and, therefore, were discarded in the final computation of the fatigue laws.

3. Results

3.1. Strain sweep tests

In this section the results obtained in the strain sweep tests (EBADE tests) are presented. As an example one replicate from each mixture tested at 20ºC have been plotted together to show the difference between mixtures behaviour, figure 3.

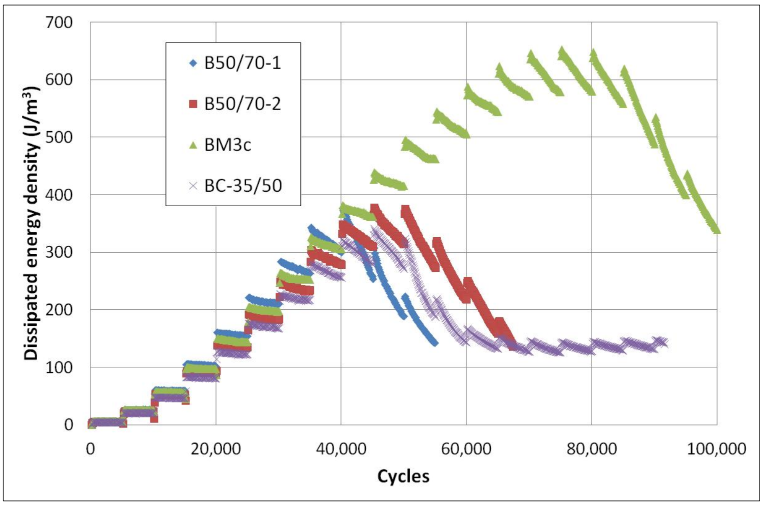

Figure 3. *DED evolution with the number of cycles in the EBADE test for the four mixtures tested.*

It is clear from figure 3 that the mixture manufactured with the polymer modified binder (BM3c) had an extremely higher Failure strain than the two mixtures with the conventional binders and the mixture manufactured with the crumb rubber binder. In addition, there were no significant differences between the B50/70-2 mixture and the BC-35/50, while the B50/70-1 had a slightly lower Failure strain. The differences in the ND strain were not as clear as those on failure strain. The average values are showed in table 2.

Table 2. *Average values obtained in the EBADE tests.*

	20ºC		
Mixture	Initial Modulus (MPa)	Failure strain	No Damage strain
B50/70-1	6176	2.33E-04	7.50E-05
B50/70-2	5322	3.25E-04	1.08E-04
BM3c	5108	4.92E-04	1.75E-04
BC-35/50	5621	3.25E-04	1.00E-04

3.2. *Time sweep tests*

In this section, the results obtained in the time sweep tests using the EBADE test configuration are presented. Figure 4 shows the fatigue curves of the B50/70-2 mixture as an example. Each one of these curves represents a dot in the fatigue law, figure 5.

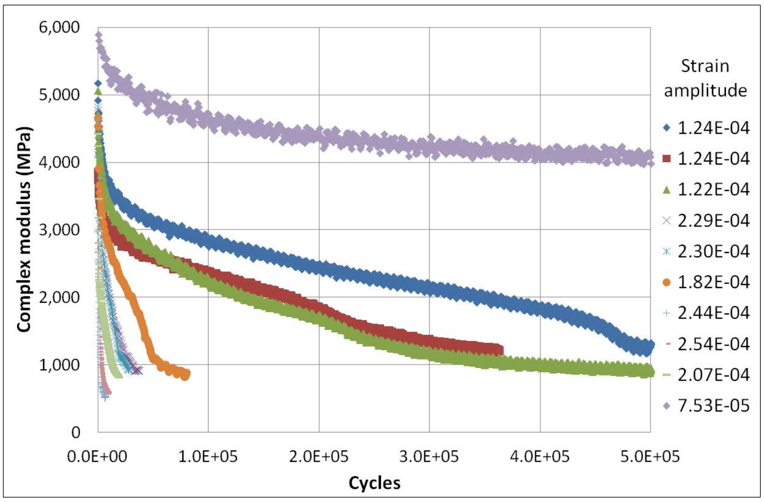

Figure 4. *Complex modulus evolution with the number of cycles in the time sweep tests performed on the B50/70-2 mixture.*

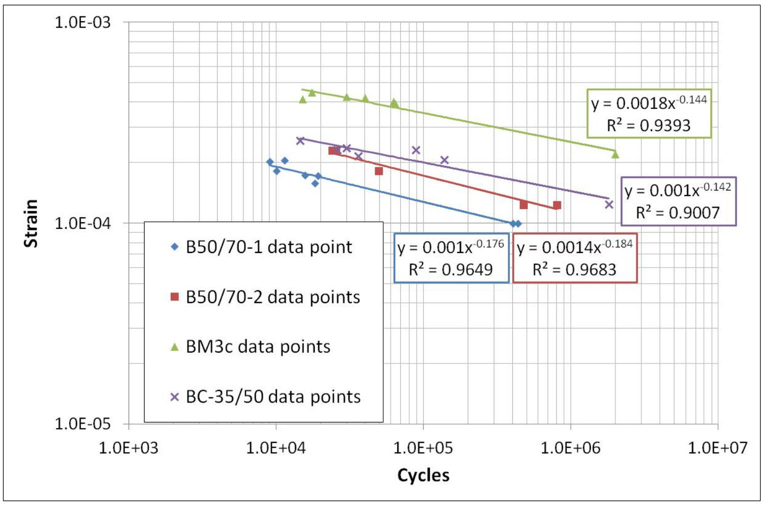

Figure 5. *Fatigue laws obtained for the four mixtures using the time sweep tests at 20ºC.*

Comparing the fatigue laws obtained using the time sweep tests, the BM3c mixture was the one with the better fatigue behaviour followed by the BC-35/50 and the B50/70-2, these two very close to each other, and the worst one was the B50/70-1 mixture. The ranking followed the same order as it did when the failure strain obtained in the EBADE tests was taken into account. Therefore, a relation must exist between the strain at which mixtures fail in the strain sweep tests and the fatigue law.

3.3. Validation of the hypothesis

To compare the results from strain and time sweep tests the specimens that fail between 10,000 and 20,000 cycles in the time sweep tests were selected. Those strain values are assumed to cause a very fast fatigue process. For each mixture, the average strain amplitude from all tests comprising between those two number of cycles to failure was calculated, table 3. Those values were plotted together with the Failure strain obtained in the EBADE tests, figure 6a. There is a good correlation between the strain values and the data points are very close to the equality line (X = Y).

Table 3. *Average values for the strain amplitudes obtained in strain and time sweep tests.*

	Time sweep tests		Strain sweep tests	
	Strain at 10,000<N<20,000	Strain at N>5.0E+5	Failure strain	ND strain
B50/70-1	1.78E-04	1.00E-04	2.33E-04	7.50E-05
B50/70-2	2.30E-04	1.24E-04	3.25E-04	1.08E-04
BM3c	4.26E-04	2.30E-04	4.92E-04	1.75E-04
BC-35/50	2.57E-04	1.20E-04	3.25E-04	1.00E-04

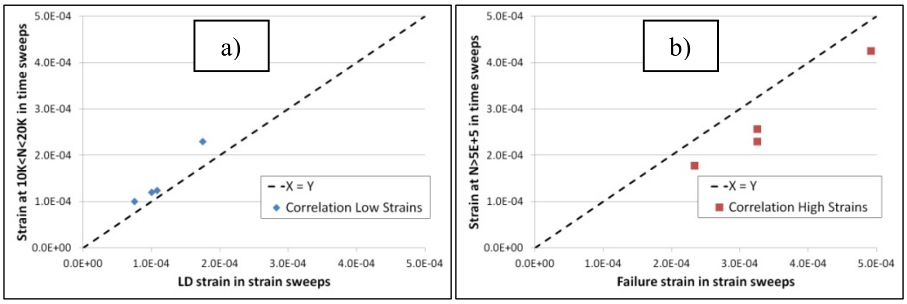

Figure 6. *Correlation between strains determined in the EBADE tests and in the time sweep tests. a) High number of cycles versus no DED loss. b) Low number of cycles versus Failure strain.*

In figure 6b, the strain amplitude of those time sweep tests that lasted between 5E+5 and 2E+6 was plotted versus the maximum strain amplitude at which the DED loss within a step was less than 4%.

Again, a good correlation was found between these strain values, although in this case the ND strain showed lower values than the strain amplitudes from time sweep tests. That was expected, since the later values came from tests that reach failure, while the ND strain corresponds to a strain level at which failure should not take place at all.

These results agree with the hypothesis presented in section 2.2, no variation in DED lead to an infinite number of cycles and an important loss of that parameter leads to failure in a few number of loading cycles.

Finally, using the two strain values obtained in the EBADE test, Failure strain and ND strain, a theoretical fatigue law was plotted over the data points obtained in the time sweep tests, figure 7. The values for the number of cycles to failure were chosen as 5,000 for the Failure strain and 5 million cycles for the ND strain.

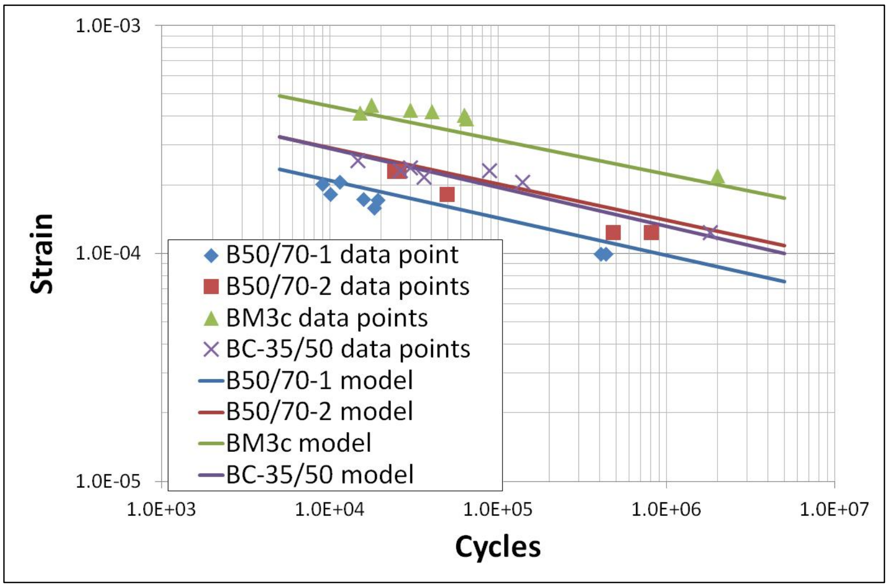

Figure 7. *Data points from the time sweep tests together with the theoretical model implemented using the EBADE tests data*

The BM3c and the B50/70-1 both data points and fatigue law were very close to the predicted by the model, while there was some discrepancy for the application of the model to the B50/70-2 and the BC-35/50 mixtures. Nevertheless, those two mixtures presented very similar results in failure strain, ND strain and fatigue law.

3. Conclusions

The main goal of this research project was to be able to characterize fatigue behaviour of asphalt mixtures using a simple and quick procedure, such as the EBADE test, a strain sweep test.

From the EBADE tests carried out, it was found that the strain at which failure took place was characteristic of each mixture, and ranked them in the same order as the conventional fatigue laws did, the ones based on the time sweep test.

Therefore using this parameter and the level of strain at which the mixture was still behaving linearly, a model was proposed. Two values of the number of cycles to failure were assigned to each strain level: 5,000 to the failure strain and 5 million to the ND strain.

The fatigue laws obtained by means of these models also ranked the mixtures in the same order as the conventional ones, and were very close to both the data points and the actual fatigue laws.

As a final conclusion, the results obtained show that it is possible to use a strain sweep test, such as the EBADE test, to study the fatigue behaviour of bituminous materials and to approximate their fatigue law, by analysing the dissipated energy density variation.

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