OBTAINING THE FATIGUE LAWS OF BITUMINOUS MIXTURES FROM A STRAIN SWEEP TEST: EFFECT OF TEMPERATURE AND AGING

Teresa López-Montero, Corresponding Author

Department of Civil and Environmental Engineering

Universitat Politécnica de Catalunya - BarcelonaTech

Jordi Girona 1-3, Módulo B-1. Barcelona, Spain, 08034

Tel: +34934017271; Email: teresa.lopez@upc.edu

Rodrigo Miró

Department of Civil and Environmental Engineering

Universitat Politécnica de Catalunya - BarcelonaTech

Jordi Girona 1-3, Módulo B-1. Barcelona, Spain, 08034

Tel: +34934017085; Fax: +34934017264; Email: r.miro@upc.edu

Ramón Botella

Department of Civil and Environmental Engineering

Universitat Politécnica de Catalunya - BarcelonaTech

Jordi Girona 1-3, Módulo B-1. Barcelona, Spain, 08034

Tel: +34934017342; Email: ramon.botella@upc.edu

Félix E. Pérez-Jiménez
Department of Civil and Environmental Engineering
Universitat Politécnica de Catalunya - BarcelonaTech
Jordi Girona 1-3, Módulo B-1. Barcelona, Spain, 08034
Tel: +34934017085; Email: edmundo.perez@upc.edu

ABSTRACT

Fatigue is associated with the deterioration caused by applying repeated loads, and is affected by temperature or aging. Generally, time sweep tests are used to simulate fatigue, in order to obtain the fatigue laws. However, this requires too much time, often preventing its use. A method to estimate the fatigue laws from a strain sweep test is presented. The test was performed on a semi-dense mixture with different types of binder (unconditioned or aged) tested at different temperatures. This test is able to estimate fatigue laws more quickly, allowing the effect of different factors on the mixtures' fatigue life to be studied.

Keywords: fatigue; EBADE; strain sweep test; aging; temperature.

1. INTRODUCTION

Fatigue cracking by applying repeated loads due to traffic is one of the major failure modes in asphalt mixtures and contributes to the degradation of pavements [1]. Fatigue failure is one of the main factors considered in the design of asphalt pavements [2]. Furthermore, due to the complex behavior of mixtures, fatigue failure not only will depend on traffic loads, but also on the duration of those loads [3] and on the environmental conditions, temperature being one of the most important factors to take into account [4]. The asphalt mixtures' properties will vary according to the temperature they are subjected to, behaving in a more rigid and elastic way at low temperatures, and in a softer and viscous form at high temperatures [5]. Furthermore, it must be added that because of environmental conditions, mixtures undergo an aging process during their service life. This process produces changes in the physical and/or chemical properties of the binder of asphalt mixtures. These changes are manifested in an increase in stiffness and brittleness [6]. In addition, temperature can play a very important role in the effect of aging on the mechanical response of the bitumen that forms asphalt mixtures [7], it being advisable to study their combined effect on the fatigue of mixtures. It is therefore important to evaluate the effect of phenomena such as aging or temperature variation, as well as the combination of different phenomena that may produce variations in the fatigue behavior of a mixture during its service life.

To analyze the fatigue behavior of the mixture layers, the fatigue laws of the material are used. Their determination is essential for the design of asphalt pavements by analytical methods. These laws are usually obtained experimentally in the laboratory from the results of standardized fatigue tests. These tests are based on subjecting the samples to a series of cyclic loads. The applied stress, strain or displacement remains constant until the failure of the mixture occurs [8]. Such tests are called time sweep tests. In the literature, there are different methods to evaluate the fatigue resistance, which are difficult to perform. According to the European standard, fatigue can be characterized using five methods [9]. They are two-point bending on trapezoidal specimens, two, three and four point bending on prismatic specimens, and an indirect tensile test on cylindrical samples.

The fatigue laws allow the level of strain or stress to which the mixture is subjected to be related to the number of cycles the mixture can withstand before failure. They have the following expression (1):

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

where N is the number of applications to produce the fatigue failure of the material, a and b are the regression parameters which are adjusted by experimental data, and ε is the strain the material is subjected to in each load application. Thus, this law allows the lifespan of the mixture to be determined.

The prediction and proper assessment of the fatigue process is a difficult task [10]. This is not only because of the complex nature of the phenomenon itself, but also because the time sweep tests to determine the material fatigue law are time consuming and often very expensive. The study of the fatigue behavior of the materials is even more complicated if the evaluation of the effect of different variables such as temperature or moisture, or the state of the mixture (aged or not, different degrees of aging, etc.) is expected, making it an almost impossible task to carry out. For this reason, researchers try to use other procedures simpler than the standard.

In this context, recently strain sweep tests have appeared. Their main advantage is the speed in assessing fatigue compared to other tests. The LAS (Linear Sweep Amplitude) test is an accelerated fatigue test for bitumens, the intention of which is to replace the time sweep tests. It is based on the application of a cyclic loading at a strain which increases linearly [11]. In the case of bituminous mixtures, the UPC Road Research Laboratory has developed the EBADE test (from the Spanish acronym of strain sweep test). This test applies a cyclic tension-compression loading to an asphalt mixture specimen at a constant strain which increases progressively every certain number of cycles [12]. These tests are based on Schapery's viscoelastic theory [13]. This theory states that changes in the dissipated energy are an indicator of cummulated damage. Schapery found that the damage is defined by Paris' law, equation (2).

$$dD/dt = (-\partial W/\partial D)^{\alpha} \tag{2}$$

where D is the damage, W is the energy and α is a constant of the material related to the damage growth ratio.

The decision of the failure criterion used in determining the fatigue law is a critical element in the fatigue behavior characterization of asphalt materials. The classical failure criterion defines the failure as the moment at which the relative reduction of 50% of the initial modulus occurs [14]. However, this failure criterion has been refuted by different authors [15, 16] based on its arbitrariness. Di Benedetto, *et al.* [17] divided the fatigue process into three stages depending on the evolution of the complex modulus. They defined the failure criterion as the point at which the transition between the second stage and the third stage occurs. This is the point where damage spreads rapidly until total failure [18]. Other failure criteria are defined from the dissipated energy. Throughout the literature, different failure criteria have been proposed based on the concept of dissipated energy, such as the cumulative dissipated energy (CDE) approach, the dissipated energy ratio (DER) approach, the energy ratio (ER) approach, or the ratio of dissipated energy change (RDEC) approach [19]. The advantage of these criteria based on dissipated energy versus that calculated from the reduction of the initial modulus to 50% resides in that the former are based on mechanical principles and depend on the material [20]. Furthermore, by comparing the energy ratio (ER) approach with the classical one, Tarefder, *et al.* [21] found that fatigue life using the first approach was longer than that found using the classical failure criterion, indicating its conservative position.

Although the determination of asphalt mixture fatigue laws is not possible from the strain sweep tests, this paper shows a method to estimate them from the EBADE test results. The test was performed on a semi-dense mixture, manufactured with different types of binder, subjected or not to a laboratory aging process, and performed at different temperatures. Results show that it is possible to evaluate the variation of an asphalt mixture fatigue life which depends on its conditioning (unconditioned or aged) and temperature in a simpler and faster way. This study would be impossible by standard time sweep tests due to the cost it would entail.

2. MATERIALS AND METHODS

The aim of this work is to study the effect of temperature and aging on the fatigue behavior of a mixture from an EBADE test. For this reason, a methodology to estimate the classic fatigue laws of the material is proposed.

Tests on aged specimens were performed and then compared with tests carried out on unconditioned samples. Two types of bitumen were used. Tests were performed at different temperatures (-5, 5 and 20ºC). At least 3 replicates of the test were performed for each condition.

2.1. Materials

A semi-dense asphalt mixture manufactured with a maximum limestone aggregate of 16 mm maximum size (AC16S) and aggregate gradation at the center of the grading envelope (Figure 1) was selected to study the effect of temperature and aging on the fatigue behavior. This mixture was prepared with two types of bitumen, one conventional (50/70) and one polymer modified (PMB 45/80-65), with the characteristics shown in Table 1. The PMB 45/80-65 bitumen was chemically modified with Styrene-Butadiene-Styrene (SBS) polymer. The content of the SBS modifier was 4% by weight of the asphalt binder. The bitumen content was 4.5% by mixture weight.

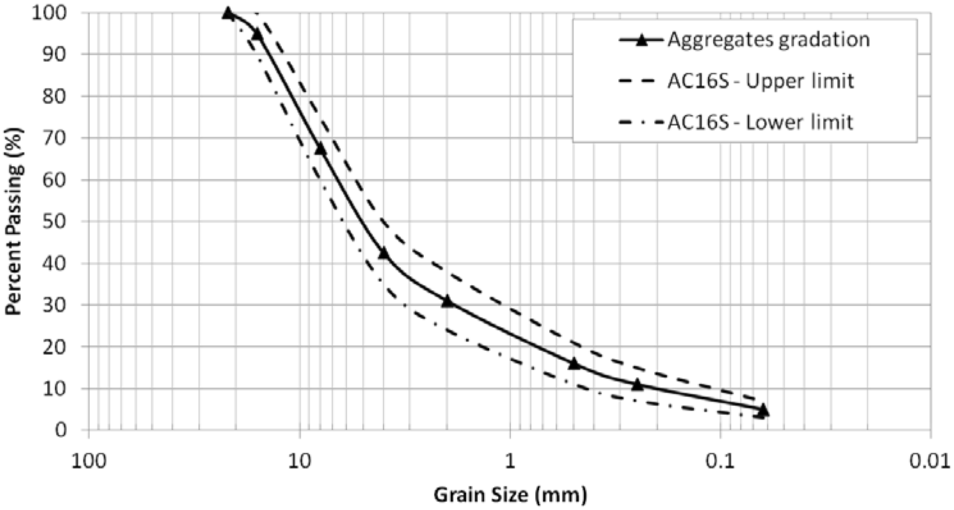

FIGURE 1. Aggregate gradation (AC16S).

TABLE 1. Characteristics of Asphalt Binders.

Characteristics	Unit	Standard	50/70	PMB 45/80-65
Original Bitumen				
Penetration at 25°C	(0.1 mm)	EN 1426	61	57
Softening Point R&B	(ºC)	EN 1427	50.9	65.3
Fraass breaking point	(ºC)	EN 12593	-14	-15
Flash Point	(ºC)	EN 2592	280	290
Residue after RTFOT				
Mass variation	(%)	EN 12607-1	0.1	0.29
Penetration at 25°C	(% p.o.)	EN 1426	66	64
∆ Softening Point	(ºC)	EN 1427	7.6	10

2.2. Aging Protocol

The protocol followed in the laboratory to simulate the effect of aging on asphalt mixtures is based on the one established by the RILEM ATB-TG5 committee [22]. This protocol considers two aging levels: the short- and the long-term. Short-term aging consists of maintaining the loose mixture in a convection oven at 135ºC for 4 hours. Long-term aging consists of maintaining the mixture, also loose, in the oven at 85ºC for 9 days.

However, to simulate the long term aging in this study the loose mixture was maintained in the oven at 85ºC for only 7 days. The reduction of the aging period is because, according to the results of De La Roche, *et al.* [22], 7 days of aging provides similar results to 9 days, and it can reduce the time for the aging effect study [23]. During the period of aging, the mixture was stirred three times. The mixture was compacted, once aged.

2.3. EBADE test

The EBADE test (from the Spanish acronym of Strain Sweep test) is a tension-compression cyclic test, where a number of load cycles is applied with a constant strain amplitude. This amplitude is gradually increased in successive steps until the mixture fails. The number of cycles in each step is 5,000, 25 µm/m is the strain amplitude in the first step which is increased by 25 µm/m in each step (Figure 2). The test frequency in this study, and in the EBADE test, is 10 Hz. The frequency selected in these tests, which is defined as the number of loading cycles applied to the material per unit time, is given by the loading speed. Thus, in an asphalt pavement, higher speeds of load application are related to higher frequencies. Both entail higher values of the mixture's stiffness, which involves minor deformations of the pavement. The work of Barksdale [24] showed that high speeds are related to short load application times. The load application time is related to the frequency, so that short load application times correspond to higher frequencies. According to the NCHRP [25] report, for a speed of 96 km/h on a highway, the estimated load frequency for an asphalt mixture layer with a thickness within the 7.6 and 30.5 cm range is between 10 and 25 Hz. For a speed of 80 km/h, Mollenhauer, *et al.* [26] found a frequency between 8 Hz and 22 Hz, depending on the thickness of the asphalt mixture layer. This is the reason why a frequency of 10 Hz has been chosen, since it is between these ranges. A different test frequency would result in a different fatigue behavior of the mixture [27]. However, maintaining the frequency constant allows the effect of temperature and aging on the fatigue behavior of the mixture to be analyzed. Specimens can be tested at different temperatures and aging conditions.

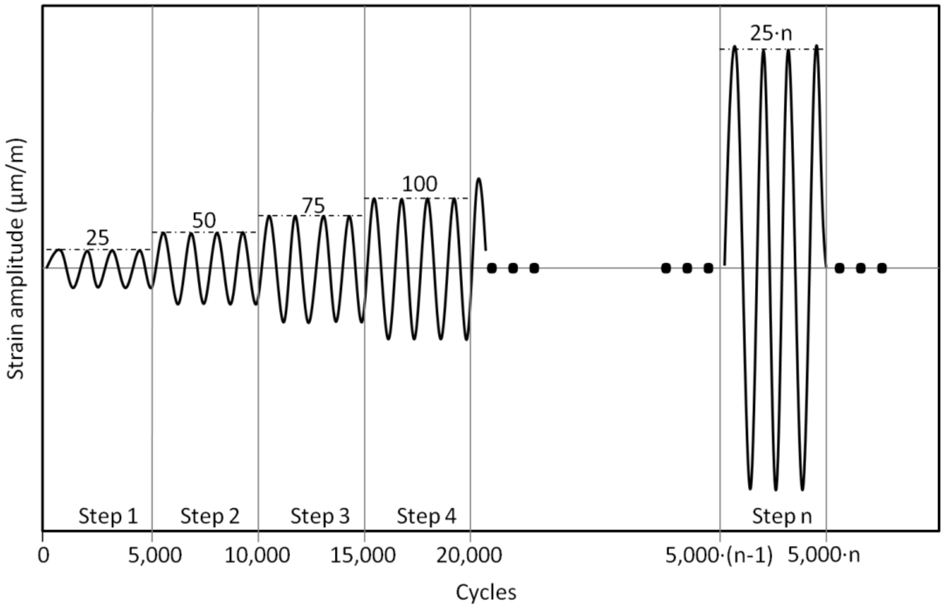

FIGURE 2. Representative scheme of the EBADE test.

A prismatic specimen with two notches in the center to reduce its area is used to perform the test. These notches allow the stress concentration area where the fatigue crack will start to be predefined. Though specimen dimensions are not fixed, they are usually 5-6 cm wide, a similar thickness and 6-9 cm in height. The size of the specimen is intended to simplify the complexity of the test, since it is easy to obtain from both laboratory specimens and in-situ samples from the pavement. The specimens are glued to steel plates using an epoxy resin. The plates are fixed to the press clamp. Two extensometers are placed in the induced failure area, one on each side of the specimen. They measure the strain during the test (Figure 3).

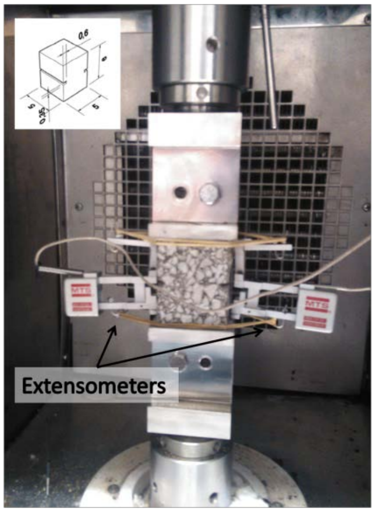

FIGURE 3. EBADE test configuration (units in cm) [6].

Maximum stress and strain in each cycle, σ_{max} and ε_{max}, can be obtained from the EBADE test. For each cycle, the complex modulus, $|E^*|$, is obtained from equation (4):

$$\sigma_{max}=F/S \qquad (3)$$

$$|E^*|=\sigma_{max}/\varepsilon_{max} \qquad (4)$$

where F is the maximum load recorded by the load cell and S, the cross section of the specimen. The cross section of the specimen is where the start of the crack has been predefined (Figure 4).

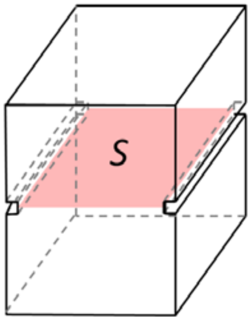

FIGURE 4. Prismatic specimen for the EBADE test. *S:* cross section.

The strain and the stress input signals, ε and σ, are represented by equations (5) and (6). δ is the phase difference between both signals that forms an ellipse in the stress-strain representation (Figure 5). The dissipated energy density, *DED* (7), is obtained directly from the ellipse from equation (8).

$$\varepsilon = \varepsilon_{max}\sin\,(\omega t) \tag{5}$$

$$\sigma = \sigma_{max}\sin\,(\omega t+\delta) \tag{6}$$

$$DED\ =\ \sum_{i=1}^{n}\pi\ \varepsilon_i\ \sigma_i\sin\delta_i \tag{7}$$

$$DED\ = 1/2\left|(\sigma_1\varepsilon_2+\sigma_2\varepsilon_3+\cdots+\sigma_{n-1}\varepsilon_n+\sigma_n\varepsilon_1)-(\sigma_2\varepsilon_1+\sigma_3\varepsilon_3+\cdots+\sigma_n\varepsilon_{n-1}+\sigma_1\varepsilon_n)\right| \tag{8}$$

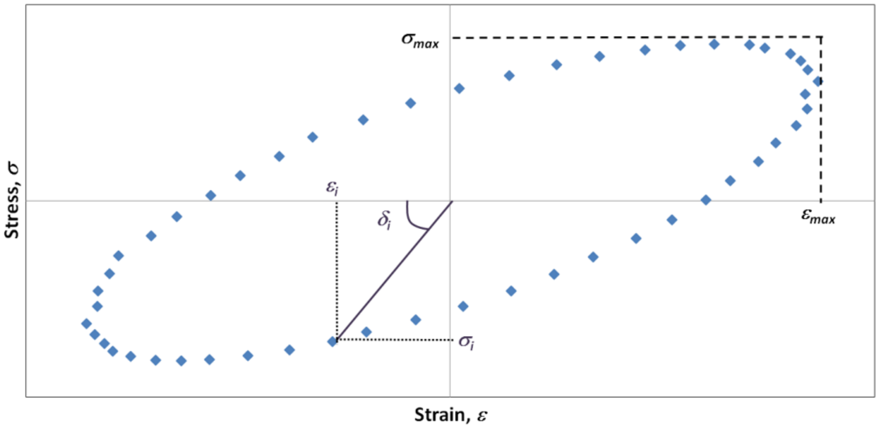

FIGURE 5. Ellipse formed by the stress-strain signals in a cycle.

2.4. Fatigue laws estimation

The behavior of the mixture under different strain levels can be analyzed using the EBADE test. This test can specify the strain level below which a mixture is not fatigued, and the strain at which a mixture fails in few cycles. These two strain levels are obtained from the analysis of the dissipated energy density with the number of cycles (Figure 6):

- The DED tends to remain constant on the same strain step at the first strain levels. It is not until a certain strain level that the DED decreases with the number of cycles on the same step.
- After reaching the maximum value of the DED, this parameter drops dramatically once the failure occurs.

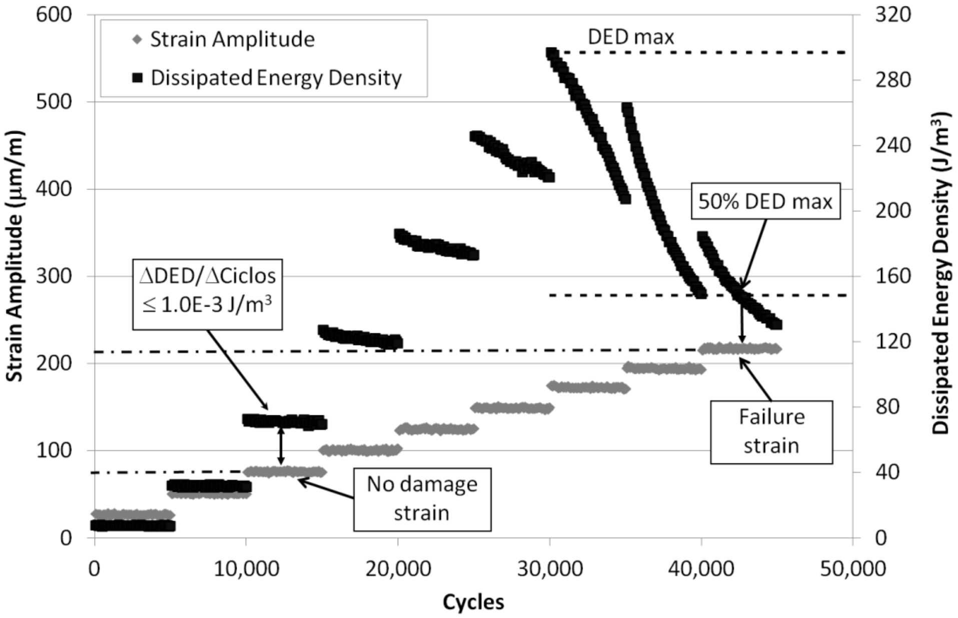

FIGURE 6. Evolution of the strain amplitude and the dissipated energy density with the number of cycles.

The strain level below which the mixture is not fatigued and, therefore, the specimen will not fail in a time sweep test, or the failure will occur for a high number of cycles, is related to the maximum strain level at which the DED remains constant. This value is called the "no damage strain". It is obtained as the strain level at which the DED starts to decrease with the number of cycles on the same strain step.

In practice, the determination of the step from which the DED begins to decrease is complex, since the calculation of the variable itself has an associated error. However, the determination of the no damage strain is based on the calculations of the slope of a linear regression between the DED and the number of cycles every 5,000 cycles (the duration of each strain step). For the first steps, this gradient should be zero and, as the strain increases, so does the slope.

The analysis of the results of the dissipated energy density gradient variation with the number of cycles (ΔDED/Δcycles) for each strain step for different types of mixtures has provided a limit value of the slope ΔDED/Δcycles to define the beginning of the DED loss with cycles. This limit was established at 1.0E-3 J/m^3. Therefore, the no damage strain is defined as the maximum strain amplitude in the EBADE test for which the slope ΔDED/Δcycles is less than 1.0E-3 J/m^3. As an example, Figure 7 shows the evolution of this slope with the strain steps for an unconditioned AC16S mixture manufactured with a conventional bitumen, 50/70, and a polymer modified bitumen, PMB 45/80-65. Both were tested at 20ºC.

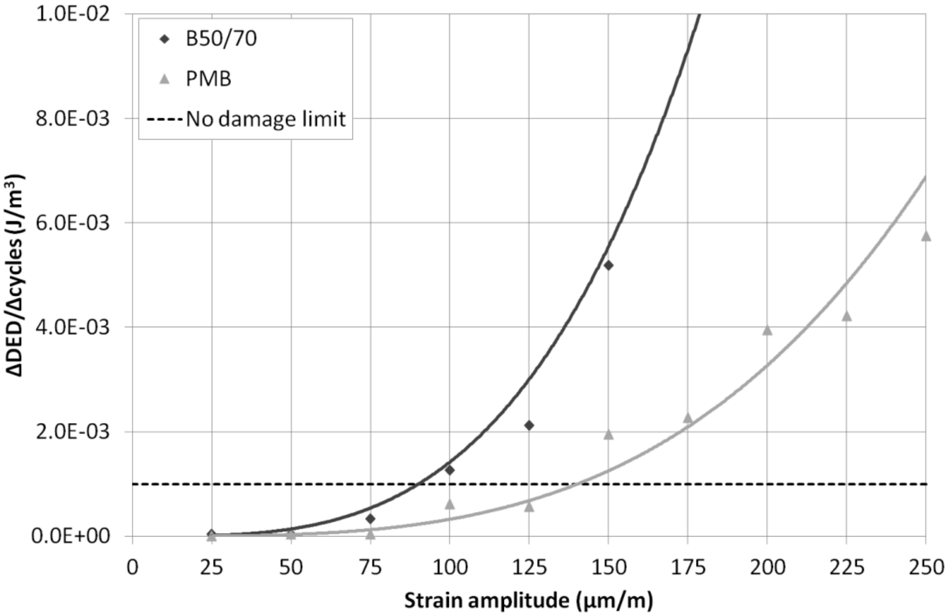

FIGURE 7. Dissipated energy density variation with the number of cycles for different strain steps in the EBADE test at 20ºC. AC16S mixture. 50/70 and PMB 45/80-65 bitumens.

The criterion established to obtain the failure strain is the strain level at which the maximum DED is reduced to half (Figure 6).

The no damage strain and the failure strain values for a mixture can be used to estimate a theoretical fatigue law. In previous research, the comparison of the EBADE test with the time sweep tests (strain amplitude constant until failure) has shown a correlation between no damage strain and failure strain with the duration of the classic fatigue tests. Specifically, it has been observed that time sweep tests performed at a failure strain lasted between 5,000 and 20,000 cycles [28], whereas the tests performed at the no damage strain lasted more than 2,000,000 cycles without failing [29].

Taking into account these results, two values of number of cycles associated with the failure strain and no damage strain have been set to estimate a theoretical fatigue law of the material. The number of cycles associated with the failure strain has been estimated at 10,000 cycles whereas, for no damage strain, a value of 10 million cycles has been selected as the necessary cycles for the mixture to fail.

For example, the mixture fatigue laws estimated from the EBADE test at 20ºC are shown in Figure 8. Furthermore, they are compared with the fatigue laws obtained by a tension-compression time sweep test with the same specimen geometry as the EBADE test. Both fatigue laws are very close. Consequently, the match of the fatigue laws estimated from the EBADE test with the fatigue laws from a classic fatigue test is acceptable.

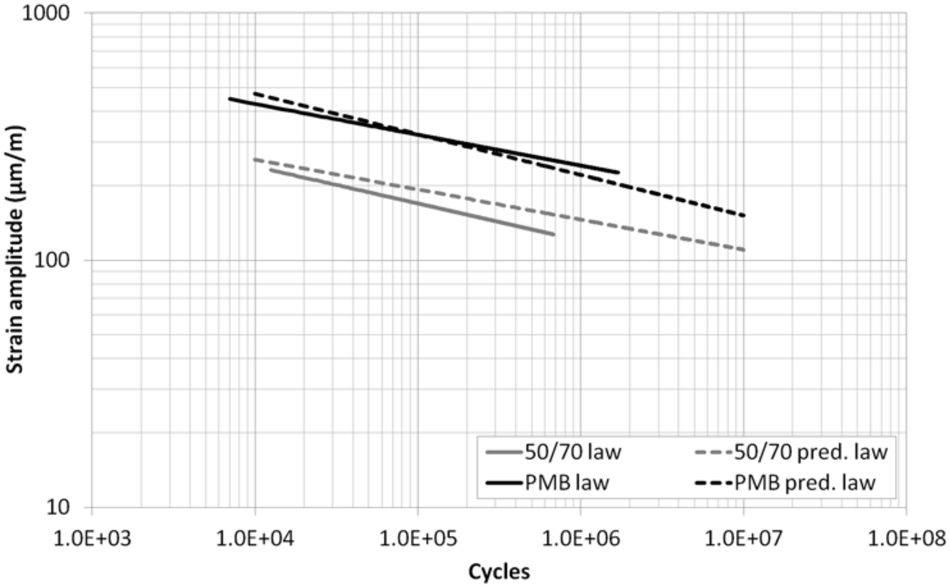

FIGURE 8. Fatigue laws obtained from a time sweep test together with the estimated laws from the EBADE test. AC16S mixture. 50/70 and PMB 45/80-65 bitumens.

The failure criterion used in the time sweep test is based on the distinction of the complex modulus evolution in three stages. In Phase I, a sharp decrease in the modulus takes place. In phase II, the modulus decreases linearly and its slope depends on the applied strain amplitude. Finally, in Phase III a sudden drop of the modulus occurs. This decrease is associated with the interconnection of macrocracks which rapidly progress until total failure [30]. The failure of the specimen has been set for the number of cycles in which the modulus behavior changes from linear to a sharp fall, Phase III (Figure 9). This criterion is much more reliable than the classical one based on the relative reduction of the initial modulus to half.

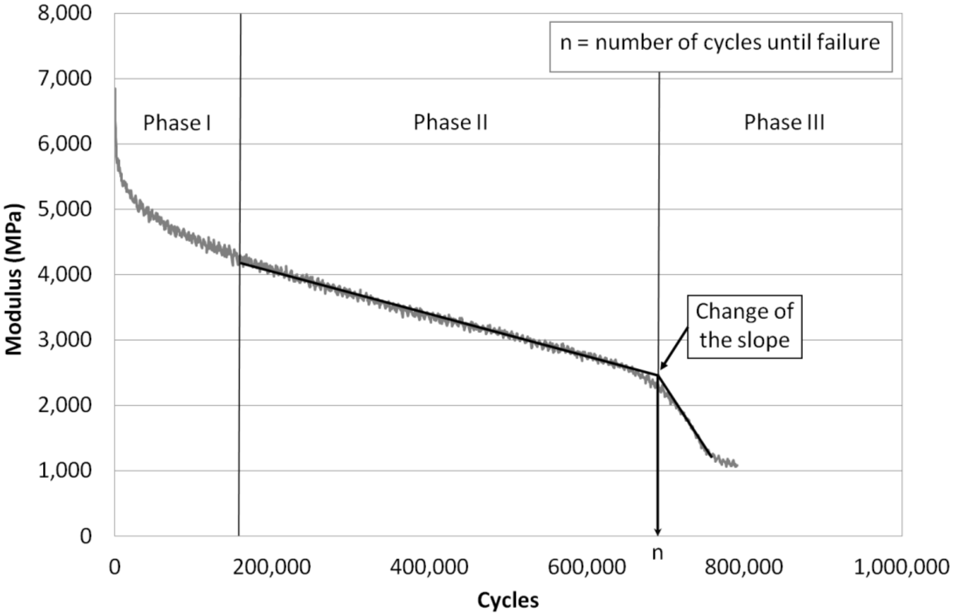

FIGURE 9. Distinction of the modulus evolution in three phases and failure criterion adopted for the time sweep test.

3. RESULTS AND DISCUSSION

Figure 10 shows the evolution of the DED values with the number of cycles for the different cases studied: unconditioned and aged mixture manufactured with conventional bitumen, 50/70, and modified bitumen, PMB 45/80-65, and tested at different temperatures (-5, 5 and 20ºC). The differences observed in the DED indicate variations in the mixture fatigue life. Thus, the maximum DED decreases on lowering the temperature. The maximum value of the curve tends to move towards the left, i.e. the mixture is able to endure fewer cycles before failure. In addition, the DED tends to fall faster once the mixture fails. This behavior is similar to that observed in the aged mixture. It is indicating that both low temperatures and aging produce a change in the mixture behavior to a more rigid and brittle one. On comparing the behavior of the mixture depending on the type of binder, the modified bitumen mixture has a better performance. This is denoted by a higher value of the maximum DED and a larger number of cycles, and therefore a higher strain level until failure. Muniandy, *et al.* [31] stated that the better fatigue behavior of modified bitumen mixtures is due to the fact that the polymer acts as a barrier which blocks the crack propagation in the material.

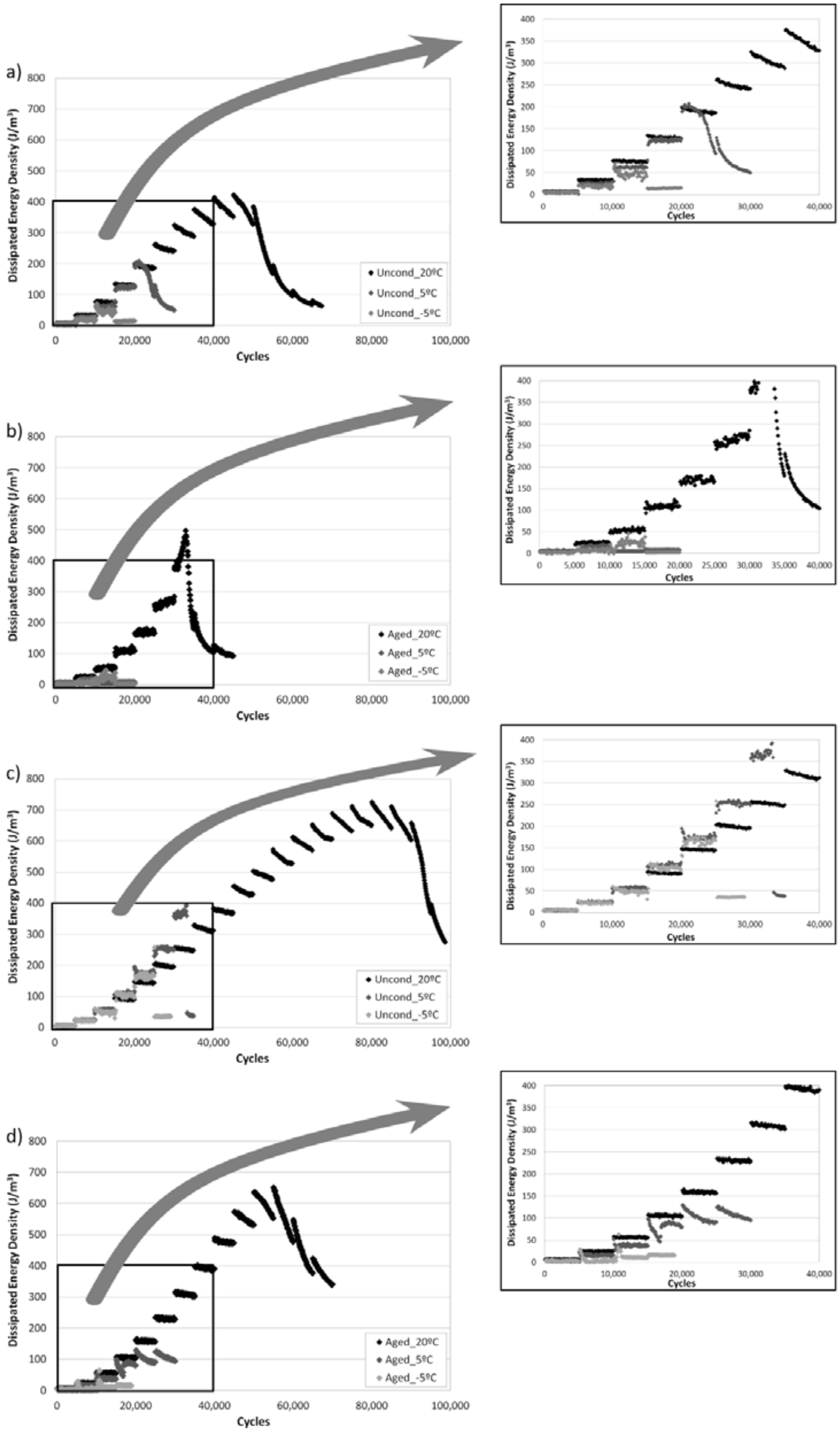

FIGURE 10. Evolution of the DED with the number of cycles for the different cases. a) Conventional bitumen unconditioned mixture, b) Conventional bitumen aged mixture, c) Modified bitumen unconditioned mixture, and d) Modified bitumen aged mixture. Test temperatures: -5, 5 and 20ºC.

The no damage strain and failure strain can be obtained from the DED curves. These values are presented in Table 2.

TABLE 2. No damage strain and failure strain values obtained from EBADE test results.

Bitumen	**Conditioning**	**T (°C)**	**$\varepsilon_{no\ damage}$ (μm/m)**	**$\varepsilon_{failure}$ (μm/m)**
50/70	Unconditioned	-5	54	86
		5	65	132
		20	119	264
	Aged	-5	55	77
		5	63	87
		20	123	156
PMB 45/80-65	Unconditioned	-5	60	135
		5	84	179
		20	152	471
	Aged	-5	43	70
		5	51	87
		20	163	289

Besides, a theoretical fatigue law can be estimated using the values of the two strain values obtained. This law allows the classic analysis of the mixture fatigue behavior under the different conditions studied.

Figure 11.a) shows the estimated fatigue laws for the conventional bitumen unconditioned mixture at the different test temperatures. Analyzing the slopes of the three laws, it is possible to predict the behavior of the mixture in the different cases studied. A slight slope in the fatigue law is observed at -5ºC. This result indicates that the mixture is rigid and it will fail in a brittle way. The DED values already indicated the same conclusions. As the test temperature increases, so does the slope of the fatigue law, a sign of the more flexible behavior of the mixture. Therefore, the failure will be less brittle.

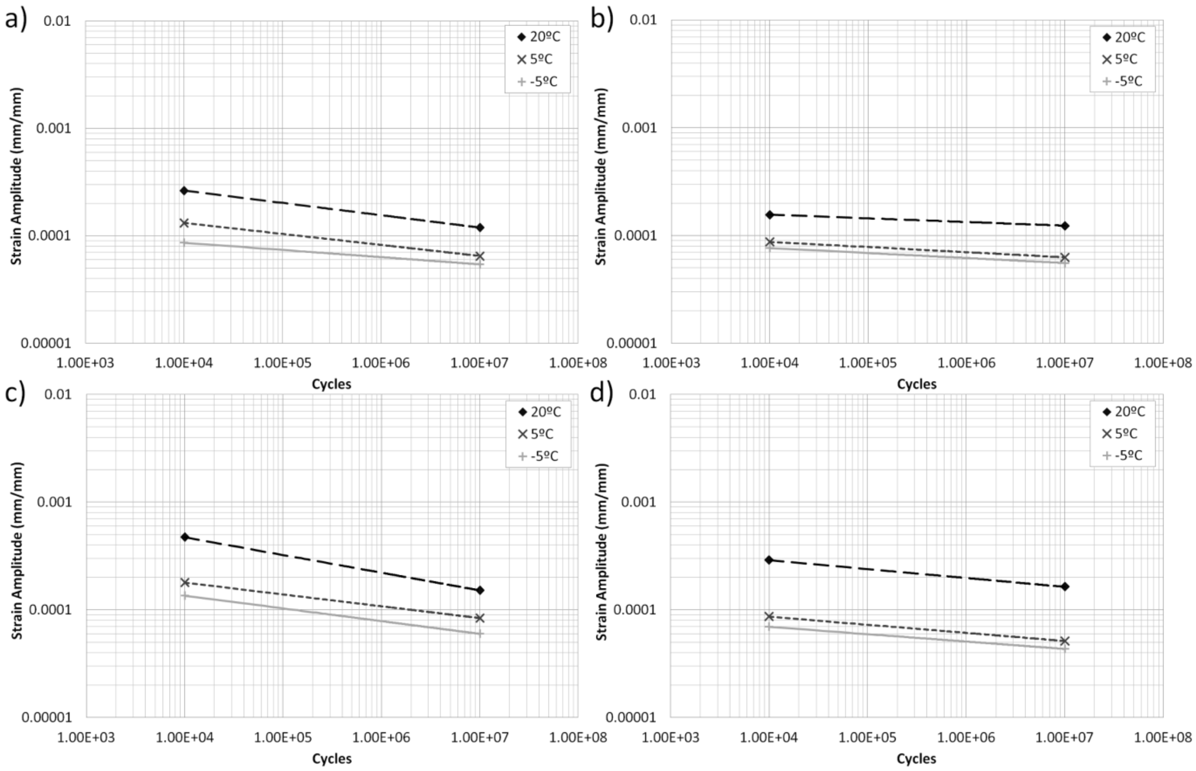

FIGURE 11. Estimated fatigue laws. Test temperatures: -5, 5 and 20ºC. a) Conventional bitumen unconditioned mixture, b) Conventional bitumen aged mixture, c) Modified bitumen unconditioned mixture and d) Modified bitumen aged mixture.

Likewise, fatigue laws for the modified bitumen unconditioned mixture have been obtained, Figure 11.c). The behavior of this type of bitumen indicates a similar pattern to the conventional bitumen at the different temperatures. However, if the fatigue laws for both types of bitumen are compared, it is observed that the modified bitumen mixture is able to withstand greater strains and at the different test temperatures. This indicates a better fatigue behavior.

When the mixture is aged, the slope of the fatigue laws tends to decrease. Likewise, the strain the mixture can withstand decreases, Figure 11.b) and 8.d). This behavior is similar to that observed in the unconditioned mixture when it is tested at low temperatures. Both the mixtures tested at low temperatures and the aged ones increase their stiffness and, thus, their brittleness. For the aged mixtures tested at medium temperatures (20°C), the modified bitumen mixture exhibits better fatigue behavior than the conventional bitumen mixture. However, the behavior of the mixture at low temperatures is very close regardless of the type of bitumen. The differences between 5 and -5°C are minimal.

Table 3 contains the fatigue laws estimated from the EBADE test for the different cases studied. In addition, the parameter ε_6 has been calculated for every law. ε_6 is defined as the strain amplitude in which the material withstands exactly one million cycles. It is considered a very important parameter for the fatigue laws of mixtures. This parameter corroborates numerically the conclusions drawn from the estimated fatigue laws, i.e., the fatigue behavior of the material is better with the modified bitumen, and it allows the quantification of how the mixture fatigue behavior worsens as it is aged and/or tested at low temperatures.

TABLE 3. Fatigue law equations for different case studies.

Bitumen	**Conditioning**	**T (ºC)**	**Fatigue Law**	**ε_6 (10^{-6})**
50/70	Unconditioned	-5	$N = 3 \cdot 10^{-57} \cdot \varepsilon^{-14.89}$	72
		5	$N = 2 \cdot 10^{-34} \cdot \varepsilon^{-9.719}$	79
		20	$N = 8 \cdot 10^{-28} \cdot \varepsilon^{-8.697}$	163
	Aged	-5	$N = 4 \cdot 10^{-85} \cdot \varepsilon^{-21.47}$	52
		5	$N = 2 \cdot 10^{-81} \cdot \varepsilon^{-20.87}$	52
		20	$N = 7 \cdot 10^{-108} \cdot \varepsilon^{-29.2}$	125
PMB 45/80-65	Unconditioned	-5	$N = 2 \cdot 10^{-29} \cdot \varepsilon^{-8.467}$	78
		5	$N = 9 \cdot 10^{-31} \cdot \varepsilon^{-9.09}$	109
		20	$N = 6 \cdot 10^{-17} \cdot \varepsilon^{-6.087}$	218
	Aged	-5	$N = 2 \cdot 10^{-57} \cdot \varepsilon^{-14.6}$	39
		5	$N = 2 \cdot 10^{-50} \cdot \varepsilon^{-13.22}$	70
		20	$N = 1 \cdot 10^{-39} \cdot \varepsilon^{-12.11}$	190

Below, two pavement sections are considered, one with a high thickness layer of bituminous mixture (section 031, according to the Spanish Standard), and another with a thin layer of bituminous mixture (section 4131), Figure 12. Assuming that both sections consist of a system of horizontal layers with uniform thickness based on a semi-infinite basis (Burmister hypothesis), it is possible to determine the stress/strain state in the pavement structure caused by a load type (13t single axle, with twin wheels).

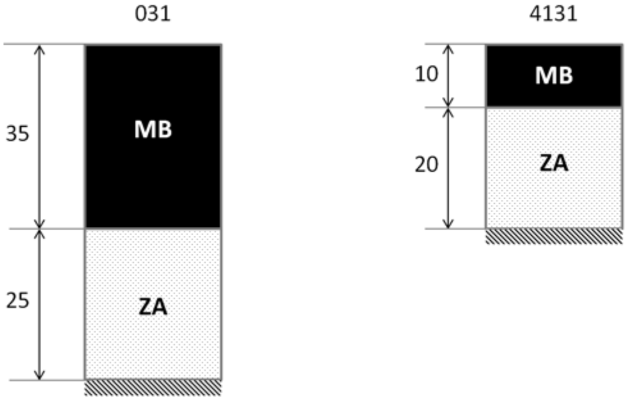

FIGURE 12. Pavement sections considered (dimensions in cm). MB: bituminous mixture and ZA: granular base.

Table 4 shows the results of the horizontal strain below the conventional bitumen mixture layer. It is assumed that the modulus of the layer is the initial one obtained from the EBADE test (the average of the first 5,000 cycles). The determination of the mixture fatigue life is possible from the strain value obtained and its fatigue law. Thus, fatigue life for the higher thickness section increases with the decrease in temperature and when the mixture is aged. This is because the initial modulus is higher under these conditions and its effect predominates over other factors. Nevertheless, fatigue life for a thin section tends to decrease with the decrease in temperature and when the mixture is aged. In this case, the effect of the modulus is much smaller.

TABLE 4. Horizontal strains and fatigue lives calculated from the estimated fatigue laws.

Bitumen	**Conditioning**	**T (°C)**	**Initial Modulus (MPa)**	**Section 031**		**Section 4131**	
				ε (µm/m)	**N**	**ε (µm/m)**	**N**
50/70	Unconditioned	-5	26645	21.8	7.72E+12	89.5	5682
		5	18983	28.7	2.79E+10	113	45831
		20	8013	57.1	6.42E+9	194	154197
	Aged	-5	24992	23	1.53E+15	93.5	128
		5	21769	25.7	1.25E+15	103	326
		20	14192	36.3	3.13E+22	136	556880

In the calculation of the fatigue life carried out, it is assumed that the modulus remains constant throughout the fatigue process. However, the modulus values decrease as the mixture is deteriorated for both the time sweep test and the strain sweep test. Therefore, the fatigue life will depend on the value of this modulus over the mixture deterioration.

The EBADE test allows the variation of the modulus to be obtained according to the strain the mixture will be subjected to. Thus, an iterative procedure could be considered where the value of the modulus would be changing for each strain. This would reveal whether a specific section may be critical depending on its temperature and its degree of aging.

Figure 13 shows a visual example of the iterative process considered. If this figure is followed, from the value of the initial modulus, it is possible to determine the horizontal strain on the lower fibre of the mixture layer (ε_1) by analytical procedures. This value depends on the mixture modulus and the pavement structure. The obtained horizontal strain, ε_1, corresponds to a certain strain step in the EBADE test. Considering the modulus at the end of that strain step (E_2), it is possible to calculate again the horizontal strain that would occur in the section, ε_2. The previous process is repeated again with the new value of horizontal strain. This process will be repeated until the value of the modulus between two consecutive iterations remains constant. And, therefore, the horizontal strain is similar between both iterations. With the value of horizontal strain, and considering the fatigue law of the mixture, it is possible to obtain the fatigue life of the section. Thus, considering the modulus value related to each value of strain instead of a single initial modulus value, the degradation of the mixture during its service life is taken into account. If the section of the mixture is critical, the modulus values will decrease rapidly and the fatigue life of the mixture will be almost zero.

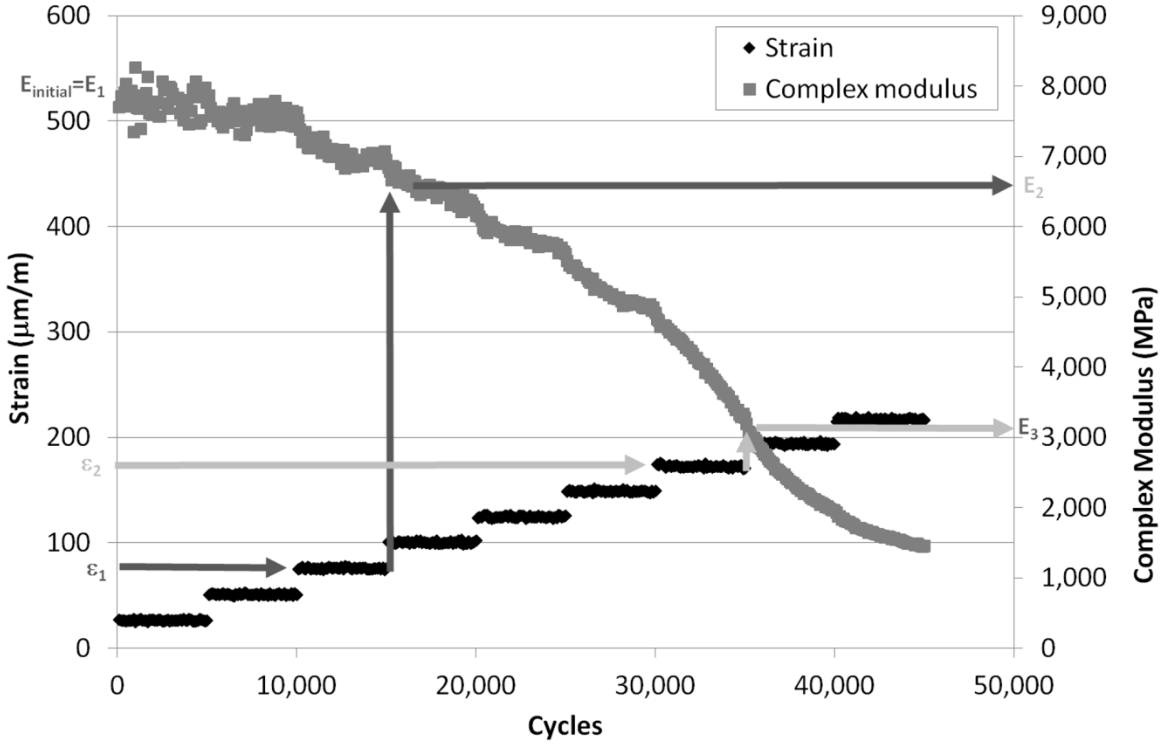

Figure 13. Illustration of the iterative process.

Table 5 shows the results obtained when applying the iterative procedure on the conventional bitumen mixture. The iterative process finishes when the value of the horizontal strain obtained in an iteration and that obtained in the next is similar. Likewise, the value of the stiffness modulus will be the same. The value "n" is defined as the total number of iterations to obtain similar values of horizontal strain and stiffness modulus between two consecutive iterations. Two different behaviors are observed depending on the value of the initial modulus and the modulus for the last iteration “n”. For the thin layer section of bituminous mixture (4131) the value of the modulus decreases drastically throughout the iterative process. This is an indicator that the section is critical and it will break in a few cycles. In contrast, the behavior of the thicker section (031) is more stable. The values of the modulus vary little and the mixture layer will be able to withstand a large number of cycles until failure.

TABLE 5. Values of horizontal strain and fatigue life obtained from the iterative process for the unconventional bitumen mixture.

Section	Conditioning	T (ºC)	Initial Modulus (MPa)	Modulus_n (MPa)	ε_1 (μm/m)	ε_n (μm/m)	N_1	N_n
031	Unconditioned	-5	26645	24868	21.8	23.1	7.72E+12	3.26E+12
		5	18983	18237	28.7	28.4	2.79E+10	3.09E+10
		20	8013	7022	57.1	63.3	6.42E+9	2.62E+9
	Aged	-5	24992	24493	23	23.4	1.53E+15	1.06E+15
		5	21769	21415	25.7	23.9	1.25E+15	5.67E+15
		20	14192	13206	36.6	38.5	3.13E+22	5.62E+21
4131	Unconditioned	-5	26645	1364	89.5	517	5682	0
		5	18983	1101	113	580	45831	0
		20	8013	102	194	2830	154197	0
	Aged	-5	24992	3062	93.5	336	128	0
		5	21769	4513	103	271	326	0
		20	14192	953	136	627	556880	0

4. CONCLUSIONS

This paper studies the fatigue behavior of an AC16S asphalt mixture, estimating its fatigue laws from a strain sweep test, the EBADE. In particular, the effect of test temperature (-5, 5 and 20ºC) and the conditioning of the mixture (unconditioned or aged) using two types of binder (conventional and modified) is studied. This research shows the advantages of the EBADE test in the analysis of the mixtures' fatigue as compared with classic time sweep tests.

The estimation of the fatigue laws from the no damage strain and failure strain established from the EBADE test allows the assessment of the fatigue life of a mixture to be made quickly and easily. The match of the fatigue laws estimated from the EBADE test with the fatigue laws from a classic fatigue test is acceptable. This highlights the usefulness of this method when the behavior of mixtures is characterized, taking into account the effect of the conditioning of the mixture in the field and its different components.

The ε_6 parameter obtained from the fatigue laws allows the effect of temperature and aging on the mixture fatigue life to be quantified. At low temperatures, the origin ordinate of the law is lower and so is its slope, therefore ε_6 decreases. The aging has an effect on the mixture behavior similar to that due to the decrease of temperature. In addition, the modified bitumen mixture has a greater fatigue behavior compared to the conventional bitumen mixture. Nevertheless, when the mixture is aged and tested at low temperatures, no significant changes are observed in the behavior of the mixture depending on the bitumen type.

However, when the fatigue laws are applied in the mixture lifespan calculation for different sections, the thickness effect of the mixture layer is shown. For a high thickness layer, fatigue life is greater as the temperature decreases and the mixture is aged. The opposite is shown for a thin layer. This is due to the large effect of the modulus on the behavior of thick layers. Besides, a constant modulus is assumed throughout the fatigue process. Nevertheless, the EBADE test allows an iterative process to be conducted where the modulus value changes according to the strain.

ACKNOWLEDGEMENTS

The authors would like to thank the Ministerio de Economía y Competitividad (Spain) for its assistance in the project PROFIS (BIA2012-36508), established within the framework of the VI Plan Nacional de Investigación Científica, Desarrollo e Innovación Tecnológica, co-financied with funds from the European Regional Development Fund (ERDF) of the European Union. The work of the first author was partially funded by the Ministerio de Economía y Competitividad, Spain (Research Grant BES-2013-065678). The authors would also like to acknowledge the company CEPSA for supplying and characterizing the bitumens used in this study.

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