ANALYSIS OF THE THIXOTROPIC BEHAVIOR AND THE DETERIORATION PROCESS OF BITUMEN IN FATIGUE TESTS

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ABSTRACT

The characterization of fatigue damage on bituminous materials under cyclic loading has been classically studied using tests and procedures previously developed for the characterization of metallic materials. However, these materials present important differences in their behavior in cyclic testing. For instance, the significant loss of modulus the bitumen exhibits at early stages of the test or its total recovery when loading is removed.

Comparison between two types of cyclic testing applied to bitumens, time and strain sweep tests has proven that this phenomenon is related with the nonlinear behavior of the bitumen, thixotropy and viscoelasticity, and that the amount of modulus loss during the initial part of cyclic testing is directly related with the strain applied.

Using the framework of the work potential theory, a new expression has been found for the damage law that describes the loss of modulus of bitumens during the linear phase of the fatigue tests. Additionally, a procedure is proposed to estimate the fatigue relation between the strain applied and the number of cycles to failure using only the data obtained in strain sweep tests. These relations fit reasonably well the experimental data obtained in more time consuming time sweep tests.

Applying this estimation procedure implies a great time savings in the characterization of the fatigue behavior of asphalt binders and the determination of their fatigue laws.

Key words: bitumen, asphalt, fatigue, thixotropy, strain sweep test.

1. INTRODUCTION

Fatigue in mechanics is associated with material damage caused by repeated loading. This property first became important in the design of metallic components used in the manufacture of early railway axles (Schutz, 1996). It has subsequently been applied to other materials which, like bitumen, undergo property deterioration under cyclic loading. However, significant differences are observed between metal and bitumen.

Loss in stiffness of metallic materials during repeated loading is mainly caused by the appearance of microcracks that grow into a macrocrack with the number of cycles, ultimately leading to material fracture in an irreversible process. In the case of bitumen, stiffness decreases without the appearance of macroscopic cracking or structural change. Moreover, if the material is allowed to rest, it can recover some, if not all, of its initial stiffness. Despite these differences, asphalt damage due to cyclic loading has typically been characterized using theory and concepts developed for the study of metallic materials.

The work potential theory has also been used to model asphalt materials behavior during fatigue failure (Schapery, 1993) (Daniel, et al., 2002) (Lundstrom & Isacsson, 2004) (Underwood & Kim, 2011) (Walubita, et al., 2012). This theory establishes a relationship of equality between available thermodynamic energy and energy required for damage to increase. This relationship is called the damage evolution law [1] :

$$\frac{\partial W}{\partial S_m} = -\frac{\partial W_S}{\partial S_m} \qquad [\ 1\ ]$$

where $W = W(\varepsilon_{ij}, S_m)$ = strain energy density function,

ε_{ij} = strain tensor,

S_m = internal state variable (or damage parameter), and

$W_S = W_S(S_m)$ = dissipated energy due to damage growth.

Equation [1] is only valid for elastic materials. For application to visco-elastic materials, such as bitumen, several authors have suggested the following modification (Park, et al., 1996):

$$\dot{S}_m = \left(-\frac{\partial W^R}{\partial S_m}\right)^{\alpha_m} \qquad [2]$$

where $W^R = W^R(\varepsilon^R, S_m)$ = pseudo-strain energy density function,

$\dot{S}_m$ = damage evolution rate with time or number of cycles,

α_m = material-dependent constant related to viscoelasticity, and

$\varepsilon^R = \frac{1}{E_R}\int_0^{\xi} E(\xi - \tau)\frac{\partial \varepsilon}{\partial \tau} d\tau =$ pseudo-strain.

Equation [2] was adapted from the Paris law (Paris, et al., 1961) for crack propagation calculation in quasi-elastic bodies by replacing strain with pseudo-strain using the elastic-viscoelastic correspondence principle (Schapery, 1984).

Traditionally, it is stated that the evolution of complex modulus during strain-controlled fatigue tests undergoes three different stages or phases .In phase I, a sudden drop in complex modulus is observed, which is often explained by an increase in the temperature of the material due to the energy released during the test, an initial adaptation and a time-dependent change in viscosity, also known as thixotropy. These factors can partially account for stiffness loss and subsequent recovery after a rest period during fatigue tests (Di Benedetto, et al., 2011) (Shan, et al., 2011) (Pérez Jiménez, et al., 2012) (Canestrari, et al., 2015). In phase II, the modulus remains constant or decreases linearly with the number of cycles. In phase III, the complex modulus drops suddenly, leading to complete failure of the specimen (Di Benedetto, et al., 1997).

This paper emphasizes the importance of thixotropy in asphalt fatigue characterization by comparing time and strain sweep test results. The comparison between those two procedures provided insight into the damage process in these materials under cyclic loading and the mechanisms leading to the fast initial stiffness loss in phase I. Results in this paper can be used to properly understand the work potential laws describing damage throughout the fatigue process, phase II. Moreover, from similarities between data of both tests, the authors propose an empirical model that provides an approximate relationship between applied strain and the number of cycles to failure using data obtained in a strain sweep test only. This method avoids repeating time sweep test to obtain the fatigue characterization of a material.

2. TEST METHODS

2.1 TIME SWEEP TEST

Time sweep test is the most common test procedure for asphalt fatigue characterization. It consists in monitoring the stiffness of a material while subjecting it to constant cyclic stress or strain amplitude. Once properties decrease to an arbitrarily established threshold value, the test stops and the number of cycles to failure is recorded. Regarding asphalt binders, complex modulus norm is typically analyzed. Variations of this parameter can be divided into three phases: rapid loss (phase I); slow linear loss with number of cycles (phase II); sharp reduction of property with cycles (phase III) (Di Benedetto, et al., 1997). It is commonly accepted that failure takes place in the third phase. Nonetheless, since this procedure requires long testing times, an arbitrary relative complex modulus value is fixed to define failure, i.e. half the initial value (Aenor, 2007). This failure criterion works reasonably well for conventional binders (the above percentage is typically reported near the beginning of phase III), but it often leads to errors when testing ductile or modified binders, Figure 1.

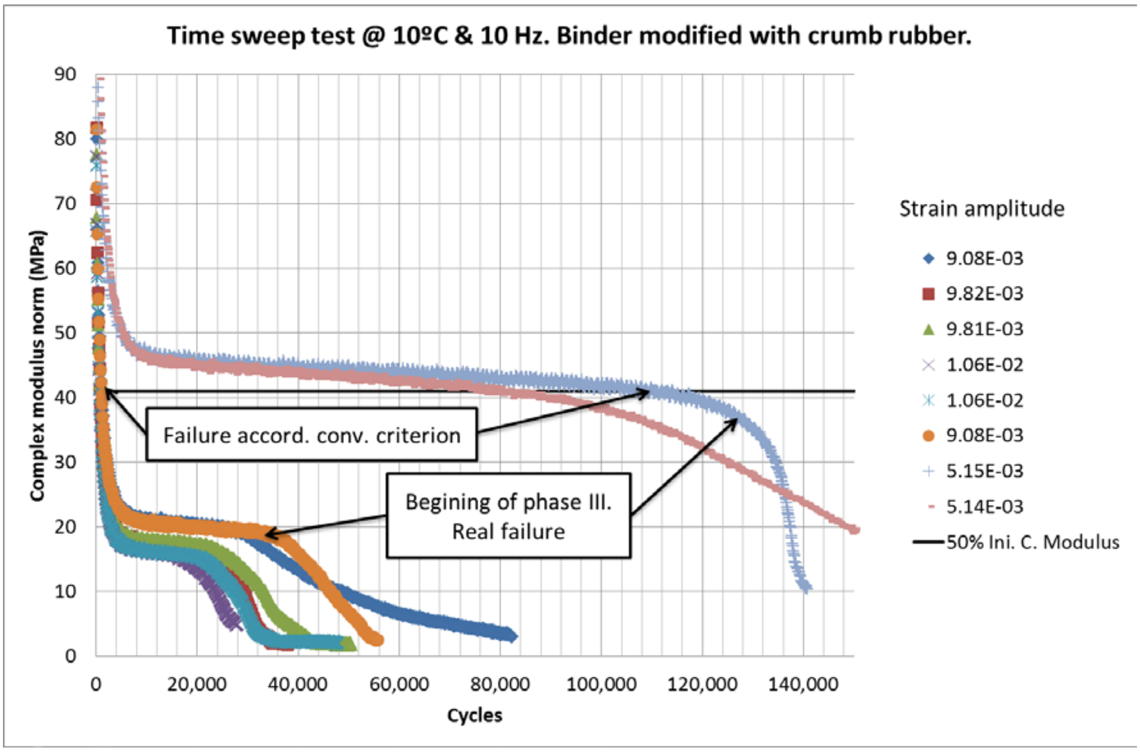

Figure 1. Time sweep tests performed in uniaxial cyclic tension-compression mode.

Time sweep tests are performed at different strain amplitudes to obtain a fatigue relationship between applied strain and number of cycles to failure. This relationship is assumed logarithmic (Boussad, et al., 1996) (Liang & Zhou, 1997) (Ambassa, et al., 2013) and is typically used to fit experimental values:

$$Log\ N_f = k_1 - k_2 Log\ \varepsilon \qquad [3]$$

where N_f = number of cycles to failure,

ε = applied strain, and

k_1, k_2 = experimental coefficients

In time sweep testing, uniaxial cyclic tension-compression tests were conducted on cylindrical specimens of 20 mm diameter and 39.5 mm in height, Figure 2. Testing temperature and frequency were 10°C and 10 Hz, respectively.

2.2 STRAIN SWEEP TEST

The same type of samples, loading configuration, test temperature and frequency was used to perform the strain sweep tests. This test starts with an initial strain amplitude of $7.6 \cdot 10^{-4}$, and this strain amplitude is increased the same value at a constant rate every 5,000 cycles, i.e. the second strain level is $1.51 \cdot 10^{-3}$, the third is $2.27 \cdot 10^{-3}$, and so on. This test configuration is called EBADE, which stands for the Spanish words for strain sweep test (Pérez Jiménez, et al., 2012).

Figure 2. Test configuration.

Stress amplitude, complex modulus norm ($|E^*|$) and dissipated energy density (W_D) were recorded every 100 cycles. $|E^*|$ decreases with strain amplitude and with every cycle, reaching very low values at the end of the test, Figure 3. The strain sweep test allows obtaining a realistic value for the initial complex modulus ($|E^*|_i$) since during the first 5,000 cycles the strain amplitude is very low, $7.6 \cdot 10^{-4}$. This ensures that the $|E^*|_i$ is measured in the linear viscoelastic domain. In addition, 50 values are recorded in the first 5,000 cycles, such that the $|E^*|_i$ is computed as an average of these values. This is one of the two main parameters provided by the strain sweep test (EBADE) to characterize the fatigue behavior of asphalt binders.

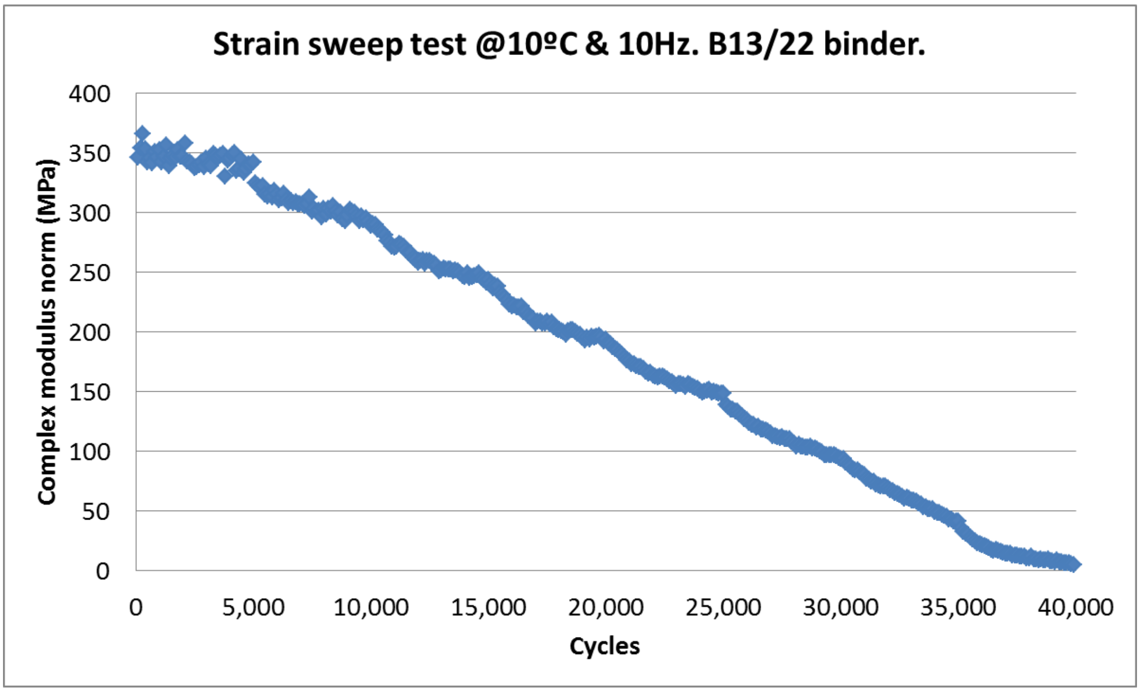

Figure 3. Evolution of complex modulus during a strain sweep test (EBADE).

The dissipated energy density (hysteresis cycle area), W_D, increases with applied strain but decreases with the number of cycles in each step, Figure 4.

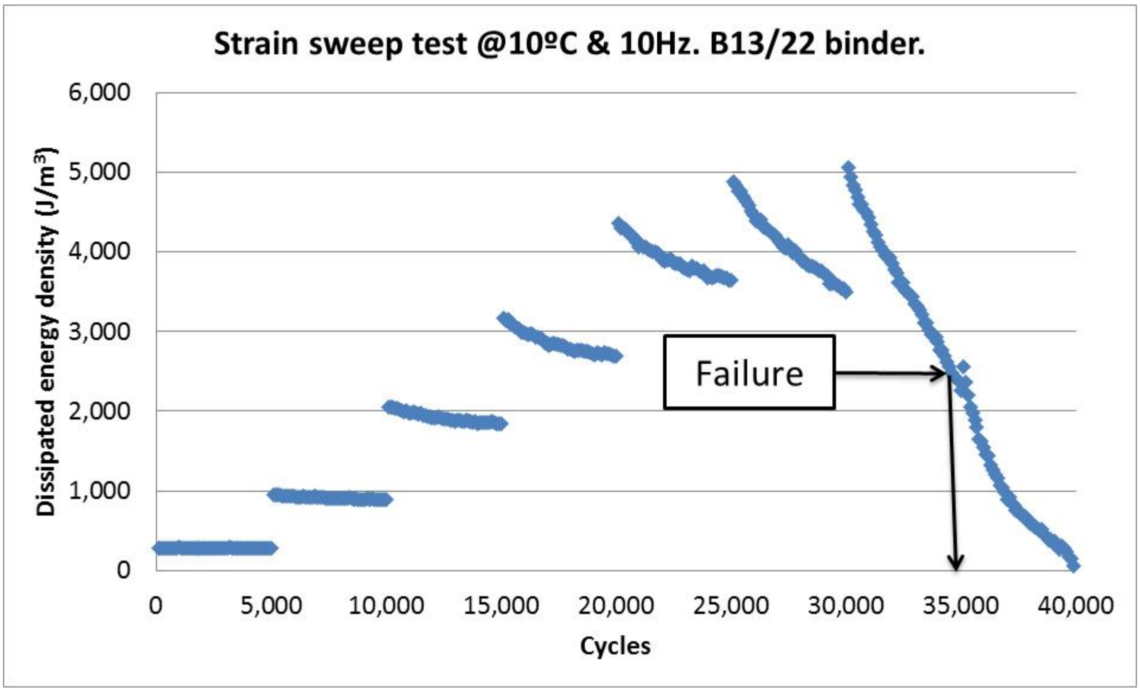

Figure 4. Evolution of dissipated energy density during a strain sweep test (EBADE).

When the W_D suddenly drops (50% maximum W_D) failure occurs. The corresponding strain level is called failure strain, ε_F, and is the second main parameter used to characterize the fatigue behavior of asphalt binders, Figure 4.

Fatigue behavior of asphalt binders can be characterized and compared using $|E^*|_i$ and ε_F. Hard and/or aged binders have high $|E^*|_i$ and low ε_F. For binders with similar penetration grades and stiffness, the higher ε_F (in EBADE tests), the higher ductility and fatigue cracking resistance.

3. TEST PLAN AND MATERIALS.

It is normal for time and strain sweep tests to have some clearly correlated parameters, such as the $|E^*|_i$ obtained in EBADE test and the initial modulus obtained in the time sweep test. Beyond that, The comparison made in this study between the two procedures provided insight into the damage process in these materials under cyclic loading and the mechanisms leading to the rapid decrease of |E*I. Comparison can also be used to properly understand the work potential laws describing damage throughout the fatigue process,, phase II. Moreover, the fatigue laws of tested bitumens were determined by time sweep tests and a new procedure to obtain them by strain sweep tests was developed.

Seven different bitumens divided into three categories were used in the tests:

- Three conventional binders from the same origin and of different penetration: B13/22, B40/50 and B60/70.
- Two conventional binders of same penetration (50/70- 1 and 50/70-2) and from different origin between them and the previous three.
- Two modified bitumens: one styrene-butadiene-styrene (SBS) polymer-modified bitumen (PMB 45/80-65) and one crumb rubber modified bitumen (BC 50/70), from now on referred to as PMB and BC, respectively.

The standard properties of the tested binders are presented in Table 1. It is observed that 50/70-2 is softer than 50/70-1 and that elastic recovery and penetration are higher for PMB than BC. These data were not available for the first group of three, and so results could not be compared with the characteristics of binders. However, this group of binders was used to compare time and strain sweep test results and see that relationships between both tests are valid independent of bitumen type.

Table 1. Asphalt binder standard properties.

Parameter	Units	Test method	50/70 - 1	50/70 - 2	PMB 45/80-65	BC 35/50
Penetration @ 25ºC	0,1mm	EN 1426	59	68	67	50
Softening point	°C	EN 1427	50.2	49.4	65.8	61.8
Fraass breaking point	°C	EN 12593	-11	-11	-17	-16
Elastic recovery @ 25˚C	%	EN 13398	-	-	88	59
After RTFOT						
Mass variation	%	EN 12607-1	0.02	0.07	0.04	0.07
Retained pen.	%	EN 1426	62	59	68	66
Softening point increment	°C	EN 1427	7.0	7.2	4.4	7.7

4. RESULTS

4.1 ANALYSIS OF PHASE I

Time and strain sweep tests apply 5,000 cycles at the same strain amplitude. The curves of variation in modulus, |E*|, or energy, W_D, with number of cycles almost overlap for the same applied strain. Figure 5 shows the overlap of both tests for the same strain levels. Figure 6 (a) compares the modulus value at 5,000 cycles in the time sweep test and at the end of each strain step in EBADE test for the same strain amplitude. Figure 6 (b) shows the same analysis with W_D. Regardless of the binder type or the strain level applied, there is nearly a 1:1 relationship between the |E*|and W_D results from time and strain sweep tests.

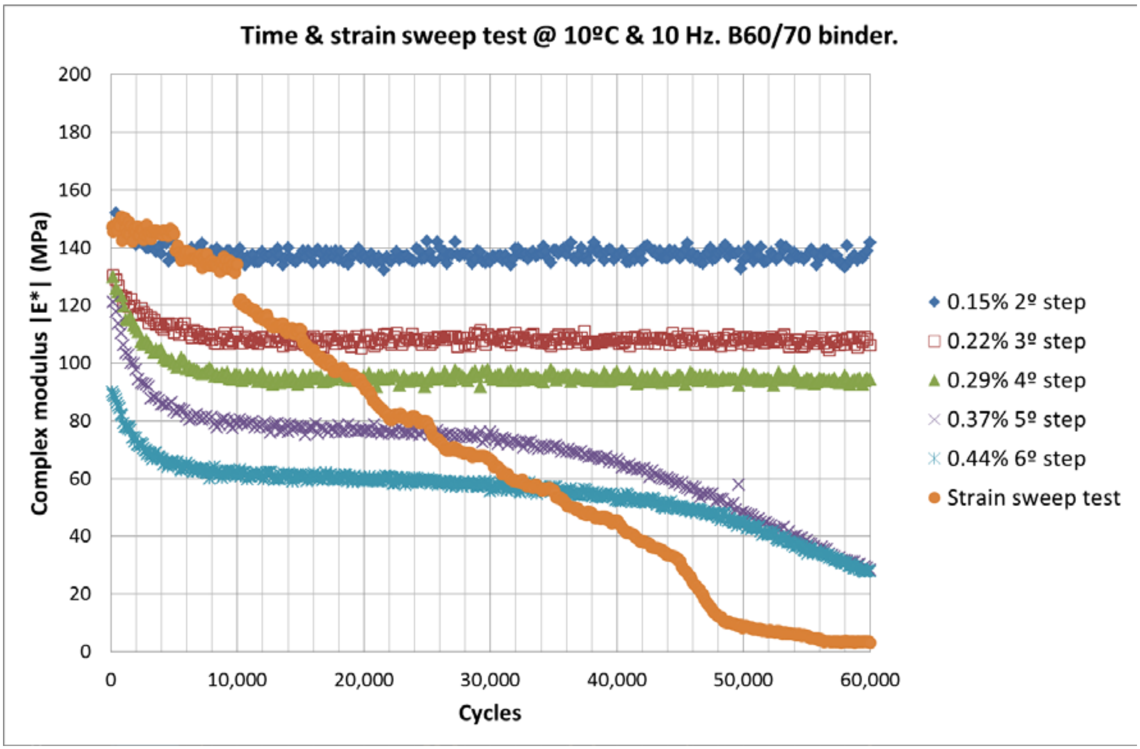

Figure 5. Overlap of modulus curve for time and strain sweep tests.

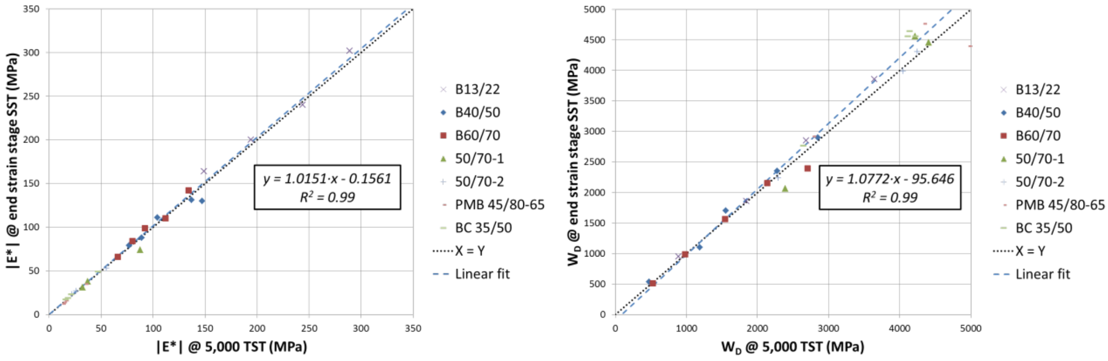

Figure 6. Comparison between |E*| and W_D at the end of each strain step in strain sweep test with |E*| and W_D after 5,000 cycles at the same strain amplitude in time sweep test.

These results demonstrate that |E*|loss during phase I of both tests is related to the applied strain amplitude. The modulus undergoes a rapid decrease when the strain is increased (EBADE) or a new strain is applied (time sweep test) until it reaches a steady value associated with that strain.

Moreover, in previous studies the strain sweep tests showed that by reverting the process, i.e. progressively reducing the strain amplitude, the modulus returns to initial levels without the need for a rest period (Pérez Jiménez, et al., 2012). No healing occurs as such. Variations in modulus depend mainly on strain: increasing strain results in modulus loss whereas reducing it or halting the test leads to recovery. This suggests that the stiffness loss in phase I is mainly due to the thixotropic response of bitumen.

The overlap of results from both tests for the same strain amplitude can be seen again in Figure 7. This figure plots the linear relationship between W_D and |E*| for the same strain amplitude up to 5,000 in EBADE test and until failure in time sweep test. This relationship remains constant throughout phases I and II for the same strain level. The slope of this relationship between W_D and |E*| varies with strain. It goes up with increasing strain amplitudes whereas at failure, the relationship changes (phase III).

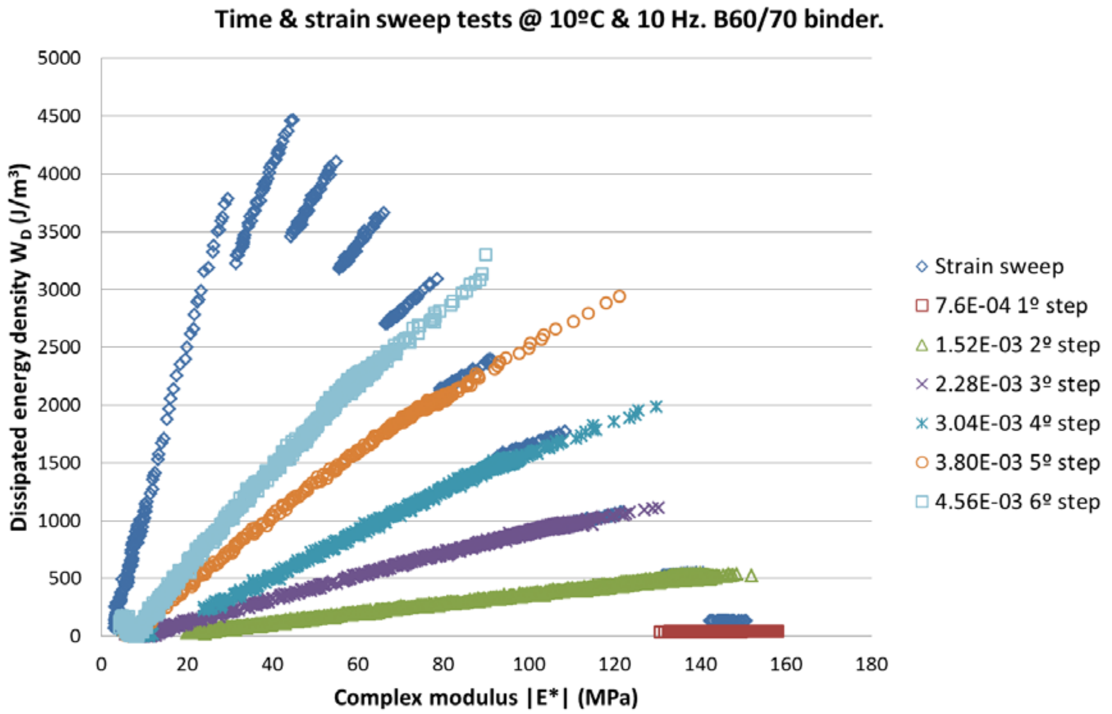

Figure 7. W_D vs. |E*| in time and strain sweep tests.

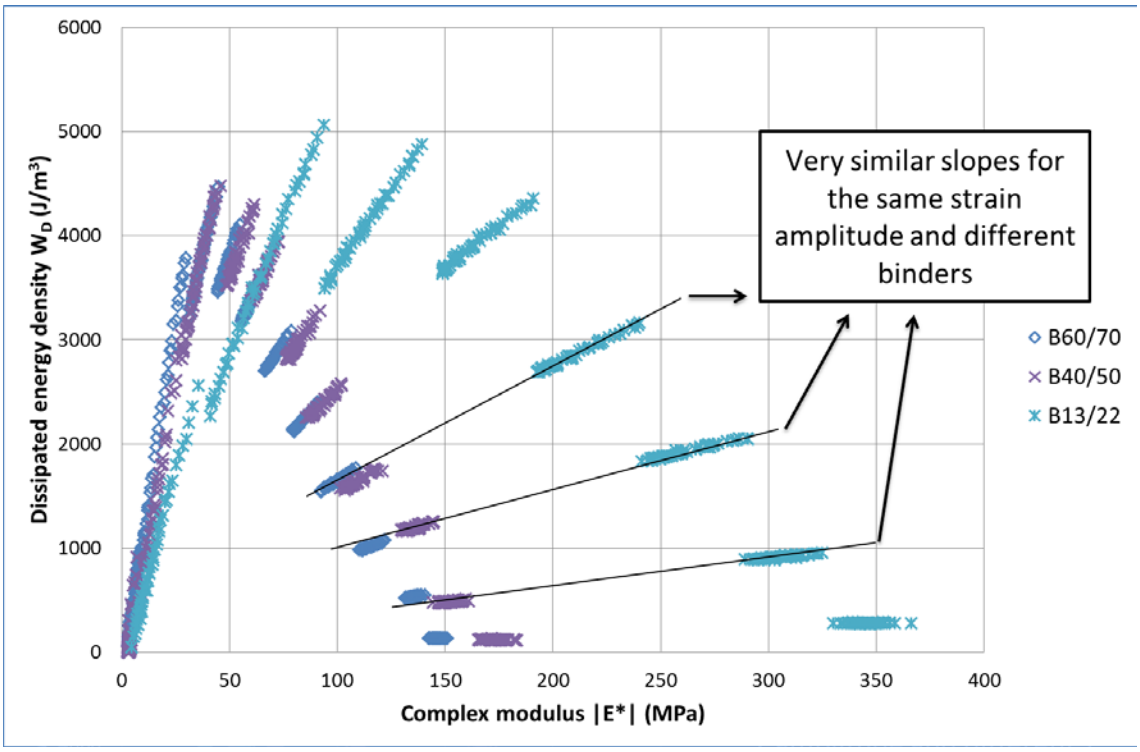

Figure 8. W_D vs. |E*| of three conventional binders in strain sweep test.

Figure 8 compares |E*| and W_D curves for three bitumens. The slopes are very similar for the same strain, especially at low strain levels. W_D was obtained by computing directly the area of the stress-strain loop (i.e., strain-stress hysteresis loop), but it can also be obtained using the following equation (Kim, et al., 2006):

$$W_D = \frac{1}{2}\pi\,.\,\varepsilon^2|E^*|\sin\phi \qquad [4]$$

where W_D = dissipated energy density

|E*| = (complex) dynamic modulus

ε = strain, and

ϕ = phase angle.

This equation predicts the linear relationship between |E*| and W_D. The overlap of all the curves, especially at low strain levels, indicates that phase angles are very similar for all binders.

4.2 ANALYSIS OF PHASE II- DAMAGE LAW.

Fatigue failure under cyclic loading of bituminous materials is determined based on their behavior in phase II. During this phase, a nearly linear relationship exists between modulus loss and loading cycles (N). The conventional failure criterion establishes that a material fails when its modulus decreases to half the initial value (Aenor, 2007).

However, this criterion can lead to significant differences between tested binders. With hard brittle bitumens, failure occurs near the 50% threshold. By contrast, in the case of soft, and in particular modified asphalt binders, the modulus can decreased more than 50% by the start of phase II, but many loading cycles (>> 1E5) are still required to reach failure, Figure 1. In this work, failure was defined as the number of cycles at which the transition from phase II to phase III takes place (N_f).

In phase II, the ratio between modulus loss and the number of cycles increases with applied strain. As seen before, the same is true of energy loss/modulus loss ratio (W_D/|E*|), which also increases with strain. The comparison of both slopes at different strain amplitudes for all bitumen types revealed a linear relationship, Figure 9.

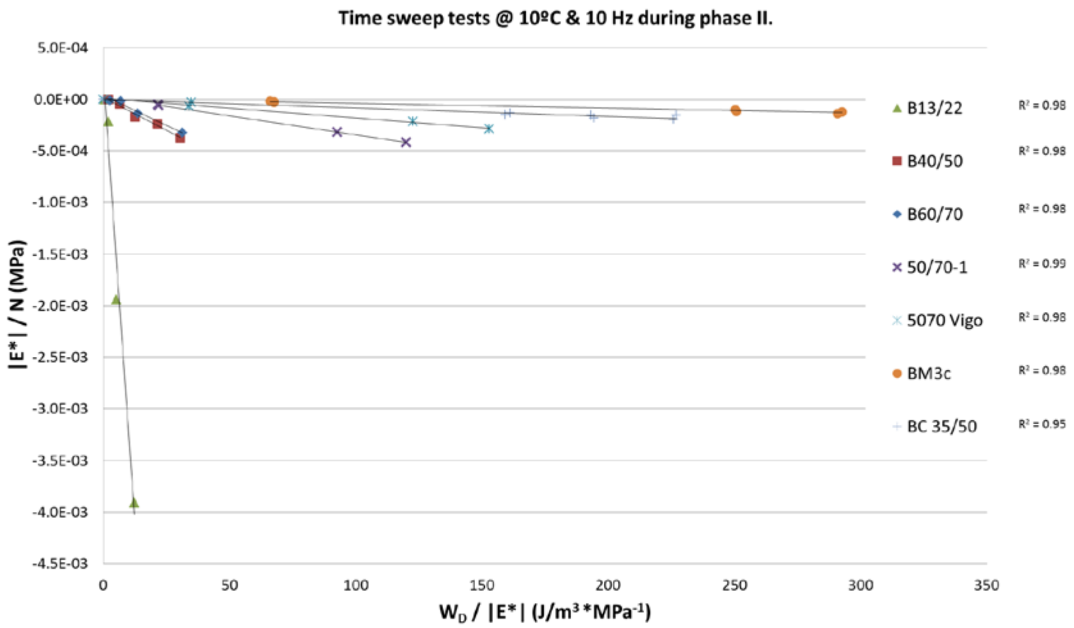

Figure 9. Linear relationship between Δ|E*|/ΔN and the ΔW_D/Δ|E*| slopes during phase II of time sweep tests.

Figure 9 shows that, whereas the W_D/|E*| slope changes very little with bitumen type for the same applied strain, the |E*|/N slope varies significantly with asphalt type at the same strain level. Thus, the coefficient relating both slopes changes accordingly. Its value is low for modified and ductile binders and high for hard binders, e.g. B40/50 and B13/22. Figure 9 trends can be described by equation [5]:

$$\dot{S}_m=\frac{\Delta|E^*|}{\Delta N}=-\varphi\left(\frac{\Delta W_D}{\Delta|E^*|}\right), \quad [5]$$

Equation [5] is very similar to the damage evolution law used in Viscoelastic Continuum Damage models (VECD) and described in [2] (Park, et al., 1996). In this case, the potential relationship with α_m, which accounts for the viscoelastic properties of the binder, is replaced by a linear relation with φ. This coefficient quantifies the influence of the change in the $\Delta W_D/\Delta|E^*|$ ratio on the damage rate of the material, and the sensitivity of the fatigue life of the binder with applied strain. It is important to note that the damage evolution law, $\dot{S}_m$, was obtained from the viscoelastic dissipated energy at every hysteresis loop (strain-stress hysteresis loop). Neither pseudo-deformation nor the elastic-viscoelastic correspondence principle was used.

The change in the applied strain produces strong variations on the evolution of |E*| with N of hard binders, those with high φ values. Whereas, at the same strain level, modified binders are less sensitive to the change in strain amplitude, low φ values. In hard binders, available energy results in severe damage with every cycle. By contrast, in modified binders with low φ values, only a small amount of available energy turns into dissipated energy, leading to hardly any damage

4.3. ESTIMATION OF THE FATIGUE LAW

Regarding bituminous mixtures fatigue tests, variations of $\pm log2$ are typically accepted for the distribution of 95% of the results for a given strain value, that is, between 0.5n and 2n, where n is the expected value. This is why calculation of the logarithmic relationship k2 slope yields very different results. Test accuracy can be improved by performing several repetitions at three different strain amplitudes (Aenor, 2007). However, any anomalous individual value can result in large variations of k2. Moreover, tests are conducted within a narrow range of strain amplitudes and loading cycles, and then logarithmically extrapolated to other very distant levels.

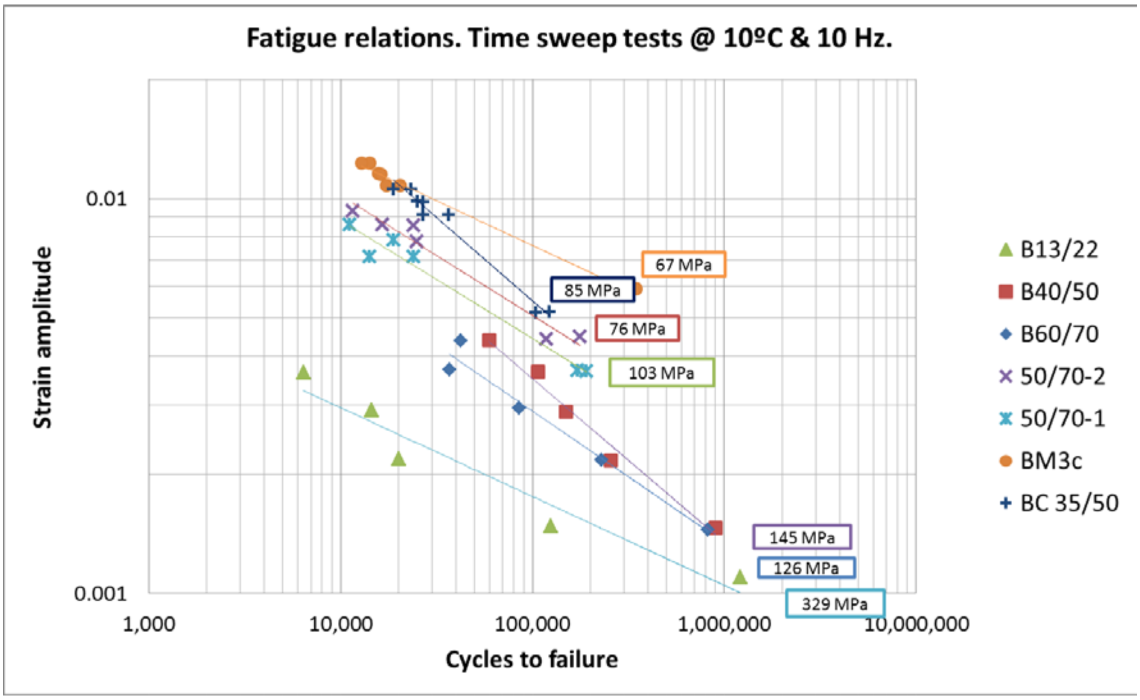

Figure 10. Fatigue laws obtained by time sweep tests at 10ºC and 10 Hz. Values in colored boxes indicate the |E*| value at the 100th cycle of the TST for each bitumen.

The fatigue laws obtained in time sweep tests of the seven bitumens at 10 °C and 10 Hz are plotted in Figure 10. Four were obtained using strain amplitudes leading to high and low failure cycles. In these cases, the points are located at very distant strain levels and the logarithmic correlation fits well. By contrast, the correlation is not as good for the remaining three binders because different strain amplitudes were used. In the case of B13/22, a parabolic law would fit better.

The results show that the modified bitumens, especially BM3c, have higher failure strains (ε_F) than penetration bitumens. Some differences were found between the latter, even between very similar ones. For example, 50/70-2 exhibits a more ductile behavior than 50/70-1. B60/70 and B40/50 behave very similarly and B13/22 is the most brittle.

The |E*| values obtained for the seven bitumens are given in Figure 10. They were calculated from the test results at cycle 100, that is, at the beginning of the fatigue process. The number for each bitumen is the average of all tested specimens. Binders that have the highest strain values in the fatigue tests have the lowest |E*|. It varies between 67 MPa for BM3c and 329 MPa for B13/22.

Fatigue laws are generally extrapolated beyond the experimental data range. This can lead to doubtful results. For example, the crumb rubber binder (BC) exhibit a poorer fatigue response than B50/70, or even than B40/50 and B60/70. This means a shorter life for the lowest strain values, below 0.003, which are those typically used in pavement design.

A procedure to obtain their fatigue law from the strain sweep test was implemented. Fatigue was characterized for a wide range of strain amplitudes, i.e. from low ones to those resulting in rapid failure of the material.

First, variation in stress amplitude during strain sweep tests was analyzed, Figure 11. Stress increased with strain during the initial loading steps and decreased with the number of cycles in each step. From a certain step, stress decreased with increasing strain and with the number of cycles in each step. This drop was faster for B13/22. For soft binders, especially modified ones, failure was more ductile.

Table 2 summarizes the strain amplitudes at which time sweep tests were conducted and the corresponding steps of the strain sweep test. The comparison of these values with those in Figure 11 reveal that the fatigue tests (time sweep procedure) were carried out after maximum stress, particularly for the more ductile, soft and modified binders.

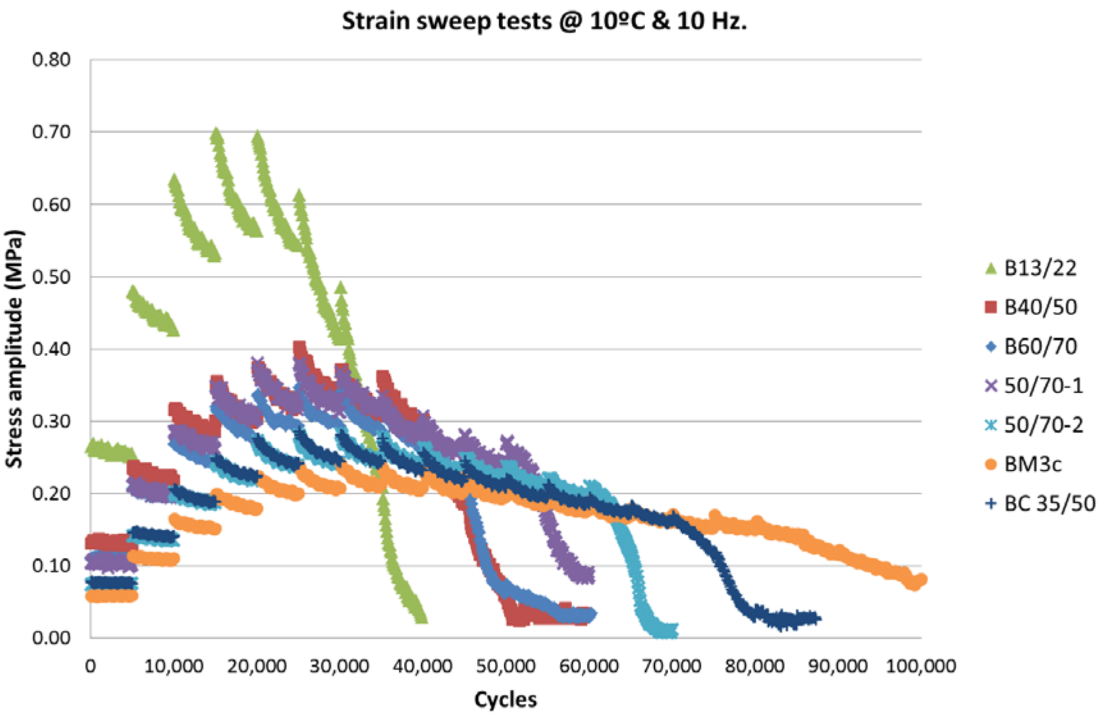

Figure 11. Stress variation with number of cycles in strain sweep tests.

			Minimum and maximum strains of time sweep test and corresponding strain steps of strain sweep test			
Bitumen	Strain at maximum stress		Minimum		Maximum	
	Step	Strain	Step	Strain	Step	Strain
BM3c	7	5.32E-3	8	6.08E-3	17-18	1.33E-2
BC 35/50	6	4.56E-3	6-7	4.94E-3	12-14	9.88E-3
50/70-2	6	4.56E-3	6	4.56E-3	10-12	8.36E-3
50/70-1	5	3.80E-3	5	3.80E-3	9-11	7.60E-3
B60/70	6	4.56E-3	2	1.52E-3	5-6	4.18E-3
B40/50	6	4.56E-3	2	1.52E-3	5-6	4.18E-3
B13/22	4	3.04E-3	1-2	1.14E-3	4-5	3.42E-3

Table 2. Strain amplitudes in time sweep tests and corresponding steps in strain sweep test.

These results lead to questioning the definition of asphalt fatigue failure. This concept is typically associated with a stress state before the failure stress. For example, cement concrete fatigue failure is characterized by specimen tensile strength obtained in a monotonic bending beam test. When the applied loading-failure relationship is below 0.5, the material is supposed to withstand infinite loading. Higher values mean less ability to withstand cyclic loading, but a stress state lower than maximum load is always assumed. In bitumen fatigue testing procedures, failure usually occurs after maximum load.

A new definition of fatigue failure of bituminous material can be established from failure strain, ε_F, during cyclic sweep testing. At this strain, failure occurs after a very small number of cycles. Lower ε_F mean greater ability of the material to withstand cyclic loading. $|E^*|$ was also found to be useful in this new approach. In strain sweep testing, this parameter decreases with each loading step and cycle until it reaches a step where a sudden drop occurs. Lower strain values mean a higher modulus, and thus failure occurs after a larger number of cycles.

As in the case of cement concrete, where the number of cycles is related to the applied stress/failure stress-ratio, in asphalt bitumens, the number of cycles can be related to the ratio between modulus for each strain and modulus at failure.

Comparison of time and strain sweep tests gave the following relationship between modulus and number of cycles:

- Failure $|E^*|$ ($|E^*|_F$): 10,000 cycles. For this modulus, corresponding to the previous step to the failure strain in the strain sweep test, the bitumen withstands between 10,000 and 20,000 cycles in the time sweep test.
- Double failure modulus ($2|E^*|_F$): 100,000 cycles. For the strain at which the bitumen has this modulus in the strain sweep test, the bitumen withstands between 100,000 and 200,000 cycles in the time sweep test.
- Triple failure modulus ($3|E^*|_F$): 1,000,000 cycles. For the strain at which the bitumen has this modulus in the strain sweep test, the bitumen withstands between 1,000,000 and 1,300,000 cycles in the time sweep test.

The determination of the strains corresponding to each failure $|E^*|$ is described in Figure 12, where W_D is plotted against $|E^*|$ for bitumen B60/70 in the strain sweep test.

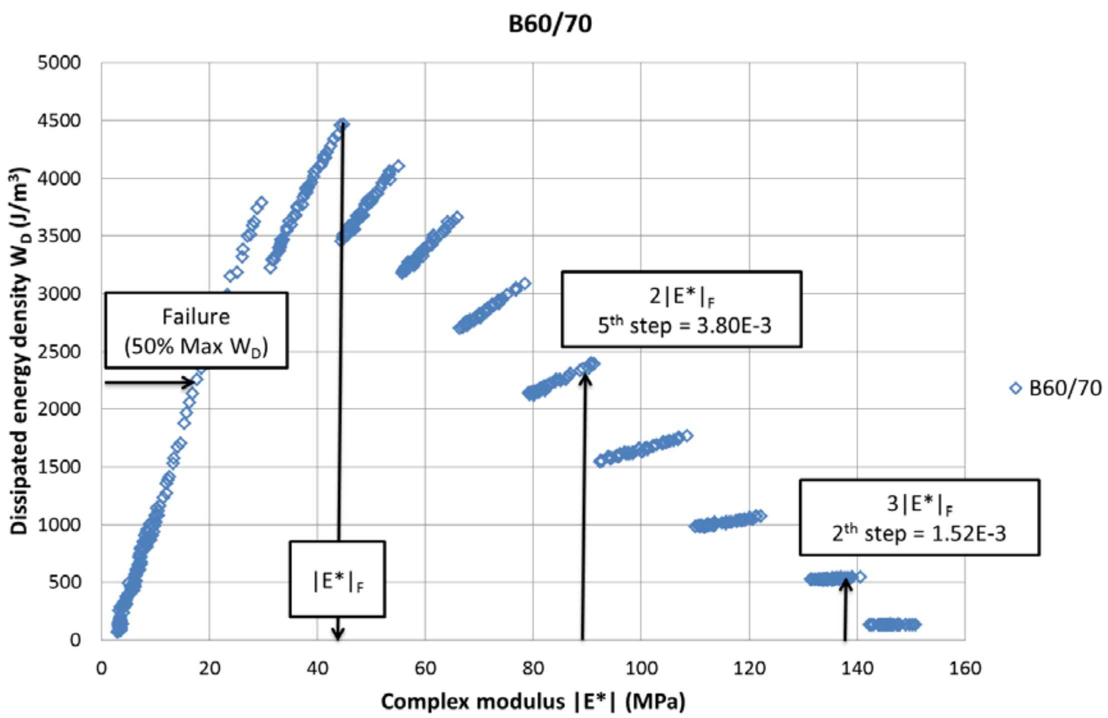

Figure 12. Failure strain and modulus in strain sweep test.

Figure 13 plots time sweep test results and the fatigue laws obtained by the above procedure from strain sweep tests. As can be seen, the fatigue laws fit the time sweep test values for all bitumens.

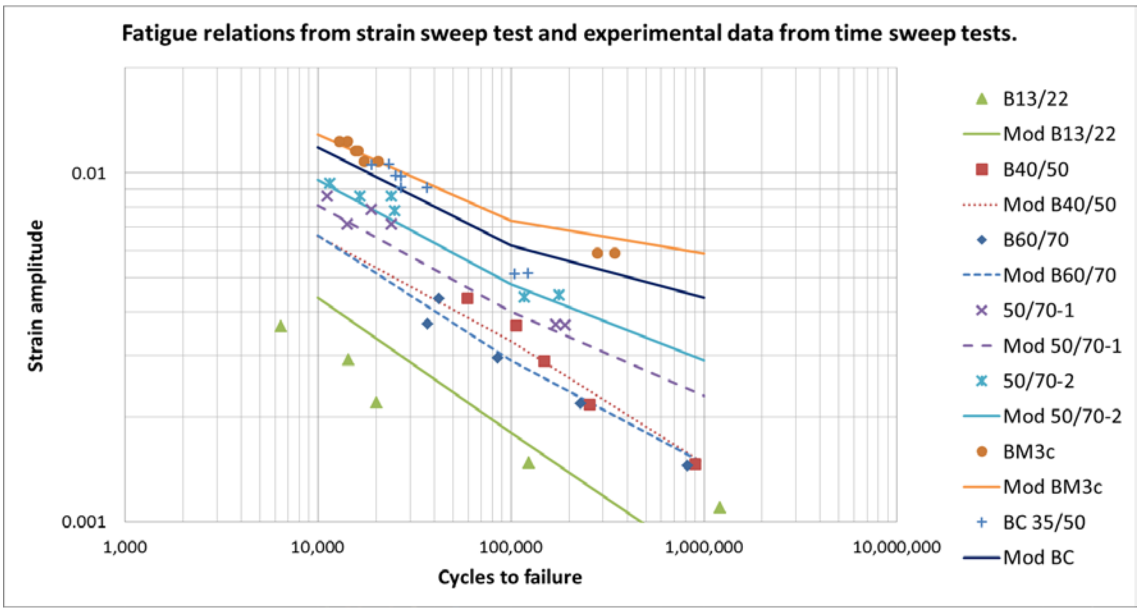

Figure 13. Fatigue relations obtained by the proposed procedure.

Agreement between failure strain and strain level applied in the time sweep test for 10,000-20,000 cycles was practically obtained. It shows the lack of creep in strain sweep tests, as also observed in laboratory testing.

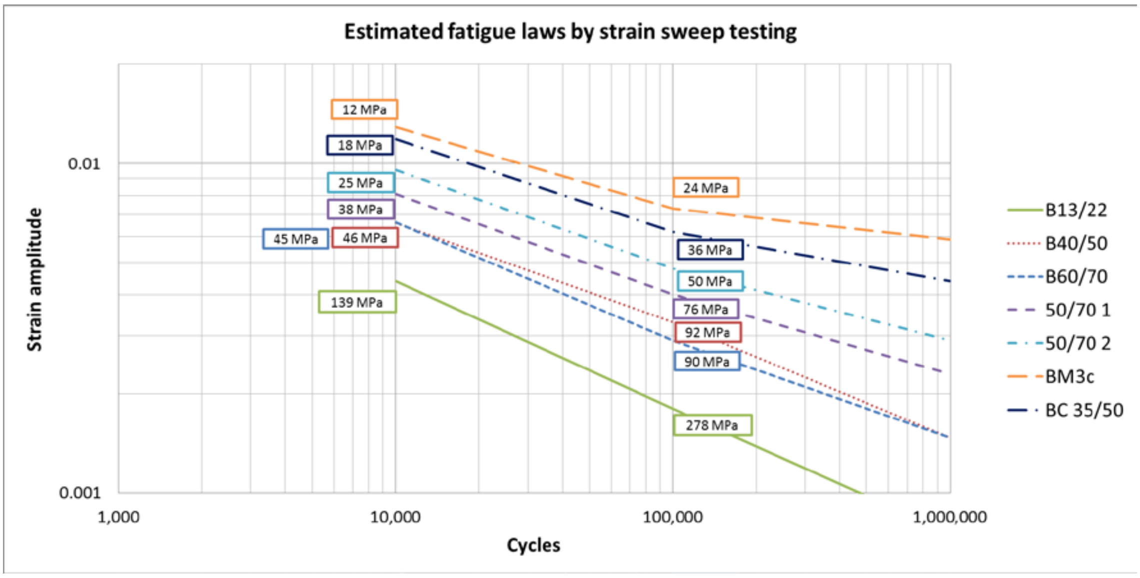

Figure 14. Strain and |E*| variation with the assigned number of cycles to failure.

Finally, in consistency with the observed modulus variation, the modulus at the beginning of phase II is plotted for each strain step during the fatigue process in Figure 14. This value is significantly lower, in the order of up to five times lower, than that used in current fatigue laws, which is highly associated with modulus for small strains.

5. CONCLUSIONS

The analysis and comparison of the results obtained in the time sweep (TTS) and strain sweep tests (EBADE) provided new insights into fatigue damage of asphalt binders, as summarized in the following points:

- Fast complex modulus norm loss during the first cycles of cyclic testing is directly related to the applied strain amplitude. Higher strain amplitudes result in greater complex modulus norm loss.
- This initial complex modulus norm loss is caused by nonlinear behavior, mainly thixotropy and viscoelasticity. Each applied strain amplitude causes the complex modulus to stabilize to a certain value at the end of phase I.
- Complex modulus loss during phase II is much slower and changes linearly with the number of cycles, $\dot{S_n}$.
- There is a linear relation between complex modulus loss and dissipated energy density loss during phases I and II in cyclic testing of asphalt binders. This relation is the same for time and strain sweep testing for same strain amplitude.
- In time sweep tests, this relation is constant during the initial and linear phases of the fatigue process, but changes at the end of the test. Complex modulus loss increases compared to dissipated energy density loss.
- The $W_D/|E^*|$ ratio depends mainly on the applied strain amplitude. It is hardly influenced by asphalt binder type, especially at low strain amplitudes.
- A linear relation was observed between the decrease of the complex modulus norm with the number of cycles and of the dissipated energy density with the complex modulus norm variation obtained in the time sweep tests performed at different strain amplitudes: $\frac{\Delta|E^*|}{\Delta n} = \varphi \frac{\Delta W_D}{\Delta|E^*|}$. This relation could be considered as a damage evolution law in the framework of the work potential theory.

- The φ parameter varies strongly with asphalt binder type. It has a small value for soft and ductile binders (modified binders) and a much higher one for hard and brittle binders.
- The strain sweep test (EBADE) allows observation of complex modulus variation of asphalt binders with applied strain. The failure strain value also provides information about material brittleness or ductility in much shorter tests.
- Failure strain and the graphic representation of dissipated energy density vs. complex modulus norm can be used to estimate the fatigue law (strain vs. cycles to failure) using a simple strain sweep test (EBADE).

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