COMPLEXITY OF THE BEHAVIOR OF ASPHALT MATERIALS IN CYCLIC TESTING

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ABSTRACT

This paper compares the results obtained in two types of cyclic tension-compression tests, a time sweep test, constant strain amplitude, and a strain sweep test, increasing strain amplitude every 5,000 cycles, called EBADE (standing for the Spanish words for strain sweep test). This comparison has shown that the rapid loss of stiffness during the initial part of cyclic testing is recoverable in bituminous materials. It has been found that reversible phenomena dominate in asphalt binders, while in mixtures are as important as damage. A damage equation has been proposed to describe the evolution of the material distress during the phase II in time sweep tests. In addition, a new methodology to estimate the fatigue law of bituminous mixtures is proposed.

Key words: fatigue, asphalt, cracking, strain sweep test, bituminous mixture

1. Introduction

One of the most frequent current failures of bituminous mixtures and which is prioritised when designing flexible pavements is the cracking of the asphalt layers. This can be due to various deterioration mechanisms, especially the failure of bituminous mixtures at low temperatures due to thermal stresses and their failure due to fatigue cracking as a result of load repetition over the lifetime of the pavement. The latter type of failure has to be especially considered during the design of the pavement, and this property of the mixture has been studied for many years. Until now, the laws and models that govern the cracking of the pavement over time and passing of loads have not been clearly defined. There are many factors that have an impact on this failure that must be taken into consideration, in addition to traffic loads. Firstly, there is the viscoelastic or thixotropic behaviour of the mixture and the variation of its mechanical properties with temperature. These properties also undergo changes with the passage of time and aging of the binder.

Given the complexity of the problem due to the amount of the variables involved, failure due to fatigue cracking has been analysed at the intermediate temperature of the pavement. Not at the lowest temperature with which the most fragile response of the bitumen and mixture is associated, nor at the highest temperatures when the fracture mechanisms are associated with the settling and plastic deformations of the mixtures and granular layers and subgrade. Thus, the average temperature of the location of the mixture and the response of the bitumen to fatigue at this temperature is one of the criteria used in the Superpave [1] for the selection of the type of bitumen.

The tests for the evaluation of resistance to fatigue failure of the bituminous mixtures are also usually carried out in the average temperature range, normally between 10 and 20°C, and most frequently at 20°C. The variation of the properties of the mixture over time is not normally taken into consideration, and the tests are usually made on unaged mixtures.

The conventionally employed tests are the flexural tests on beams with 2, 3 or 4 support points, or tension-compression tests on cylindrical or prismatic specimens, Fig. 1. In these tests, either the cyclic force applied (testing at constant stress) or the applied strain (testing at constant strain) is kept constant. From these tests, the number of cycles (N) is obtained that the mixture can withstand for a given stress or strain (ε, σ).

Also, the dynamic modulus of the mixture is determined at the start of each test. The procedure is repeated with different stresses or strains and, based on these results which require several days to obtain, the fatigue law of the mixture and its average dynamic modulus are determined for the range of tested loads.

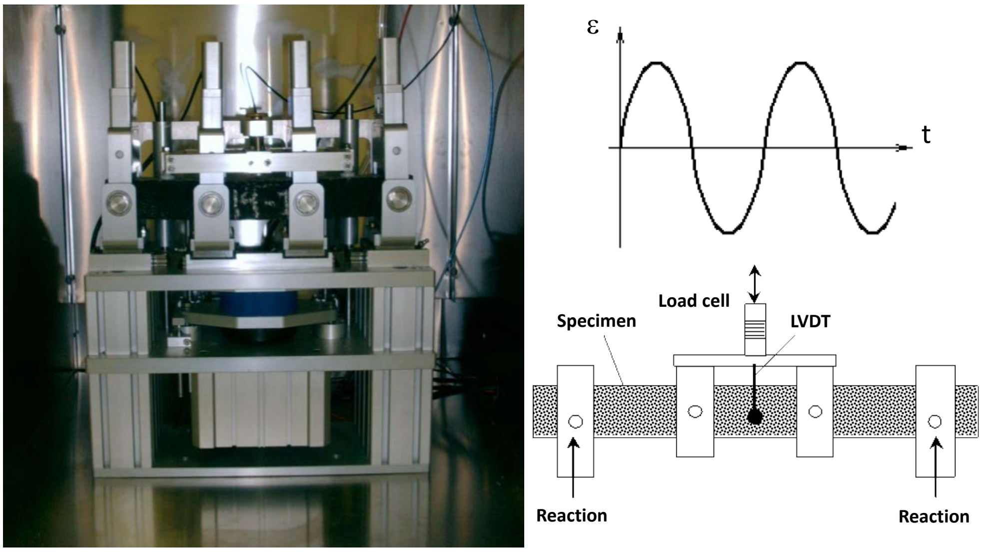


Fig. 1. Four points bending beam fatigue test.

However, it should be borne in mind that the conducting of these tests is not a simple and straightforward task given the complex behaviour of the bituminous mixtures. When fatigue tests are carried out on metals and concrete, a more or less continuous loss of the mechanical properties of the materials is observed until the failure occurs. There is very little difficulty in defining the mechanical characteristics of the material at the start of the test and when the failure occurs. In the case of bituminous mixtures, Fig. 2, there is a first phase in which there is a rapid loss of stiffness (phase I), then the trend changes and there is a linear and more moderate loss (phase II), and finally there is again a more rapid and continuous deterioration (phase III). For the evaluation and quantification of these results, guidelines have been established that associate the initial properties of the mixture with those that are present at cycle 100, and its failure with the cycle in which the property that is being measured (normally the load or the modulus) is reduced to 50% of the value measured at cycle 100. This does not correspond to a defined and specific state of the specimen (initial/failure); it is totally arbitrary and can lead to errors when the fatigue laws obtained in this way are applied to the design of pavements by analytical methods. Fig. 2 shows how the failure of the specimens would be associated to a smaller number of cycles, and the actual number when failure occurs (phase III). This fact has been highlighted by a number of authors [2 – 4].

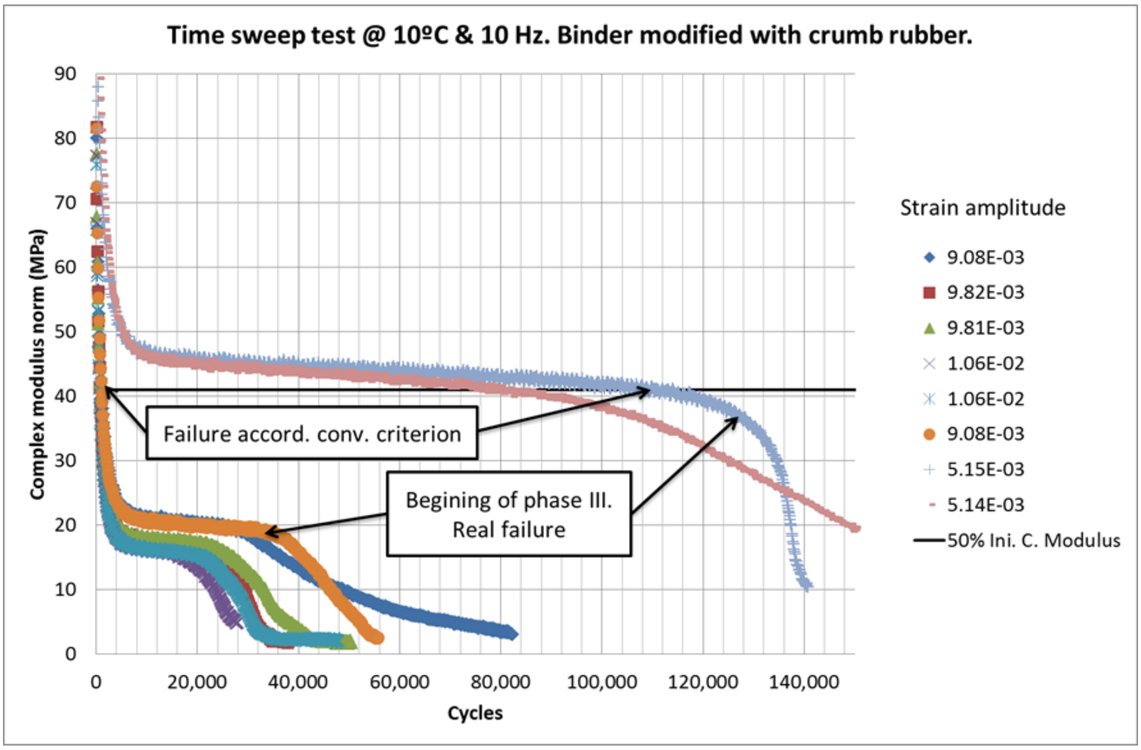


Fig 2. Time sweep test (tension-compression) on asphalt binder. Conventional criterion of fatigue failure.

The response of bituminous mixtures during the deterioration processes due to load repetition has also been analysed based on the application of thermodynamic principles, which relate the deterioration of the material with the dissipated energy. For bituminous materials, Schapery and Park [*5*] propose the following expression for the deterioration equation:

$$\dot{S}_m = \left(-{}^{\partial W^R}/_{\partial S_m}\right)^{\alpha} \tag{1}$$

where $\dot{S}_m$ is the change of the variable that represents the material damage, W^R is the pseudo-energy dissipated in each load application and α is a coefficient related to the viscoelastic response.

This equation assumes that it is a characteristic of each material and it is maintained independently of the deterioration or fatigue process to which the material is subjected.

Different authors have applied this correlation to characterise the fatigue response of bituminous binders with the use of DSR equipment [6]. In this procedure, the deterioration equation is determined based on a strain sweep test (continuous increase of the strain imposed on the DSR) and, assuming a viscoelastic and linear response of the bitumen, this deterioration equation is equated with the evolution of the energy dissipated in the time sweep test (where the applied strain is maintained). This allows the number of cycles for a given strain and the fatigue law of the bitumen to be obtained.

This procedure has the great advantage of reducing the number of tests, as only one strain sweep test (of limited duration) is carried out compared with several time sweep tests (of variable duration and, sometimes, unlimited), although another additional test is required for the determination of the α parameter. Normally a creep test is used, where the slope of the relaxation curve of the material, m, is determined. Although there is no fixed criterion for establishing the relationship between α and m, some authors associate the value α with m, and others with 1/(1+m) [*6*].

In this article, the use of a new strain sweep test is presented, the EBADE test (standing for the Spanish words for strain sweep test), for assessing the resistance to fatigue of the bituminous mixtures. The results obtained by this procedure have been compared with those obtained with the same equipment and loading process, but applying a constant strain, which is commonly known as time sweep test.

The comparison of both test modes has allowed us to examine, during the fatigue deterioration process under cyclic loads, the rapid modulus loss in phase I during the conventional fatigue time sweep tests; the relationship between phase I and phase II in these tests; the observed self-healing phenomenon and, lastly, to be able to estimate that the fatigue law based on the use of the more efficient and simple EBADE test.

2. EBADE Test

The EBADE test consists of applying a tension–compression sinusoidal strain, increasing its amplitude every 5000 cycles, Fig. 3. This test mode is known, as previously mentioned, as the strain sweep test, from which comes the test name (EBADE, Ensayo de BArrido de DEformaciones) [*7*].

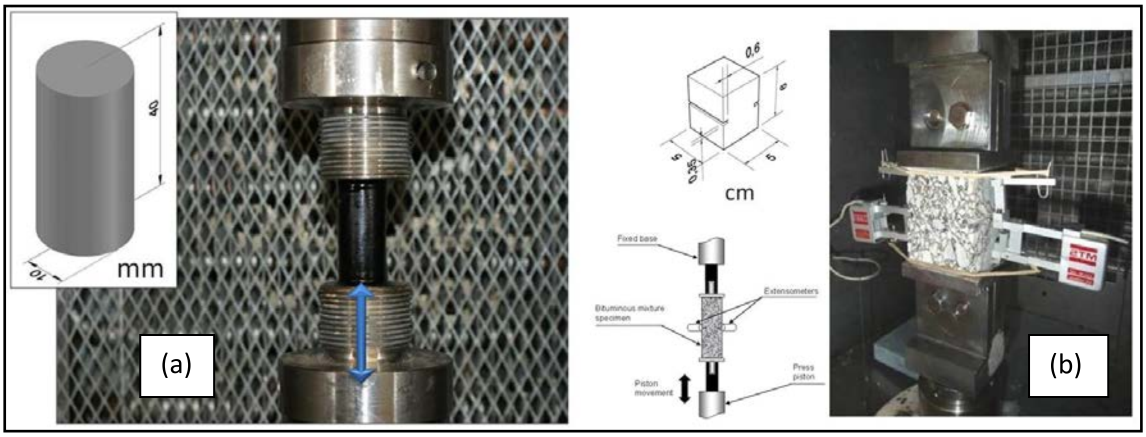


Fig. 3. The EBADE test in bitumen, (a), and mixture, (b) [*7*,*8*].

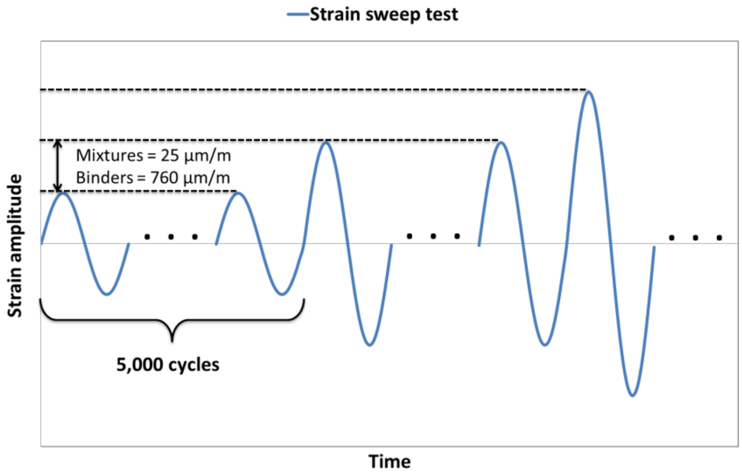
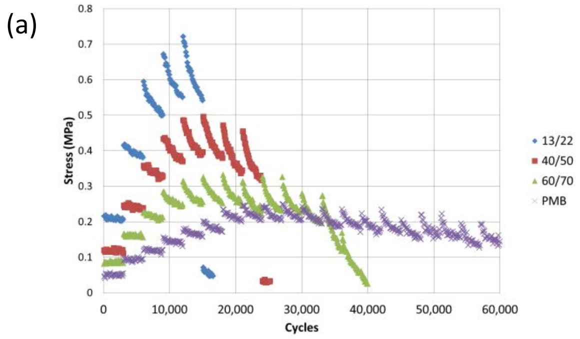


Fig. 4. Example of the strain signal applied during the EBADE test.

In this test, the evolution of the stress with each load cycle is measured and the evolution of the complex modulus of the mixture and the energy dissipated in each cycle is calculated. This energy is calculated based on the hysteresis cycle area exhibited by the viscous materials in each load cycle. Fig. 5 shows the results obtained in four different asphalt binders, the penetration range of three of them is stated in the legend in 0.1 mm, the fourth one is an SBS polymer modified binder. Fig. 5(a) shows the evolution of the stress with the loading cycles, and it can be seen that there is a maximum load and a slow fall of this load as the strain of the load steps increases. Within each load step, a loss of stress is always observed, as well. The variation of the modulus is shown in Fig. 5(b). This variable continues to decrease throughout the entire test. This occurs more quickly in the first cycles corresponding to each increase of the level of the imposed strain. It tends to be maintained at the end of each step, especially at the lowest strain levels.

Fig. 5(c) shows the increase of the dissipated energy density with the strain amplitude, until it reaches a strain amplitude at which a pronounced decrease occurs. This step is the one considered for establishing the failure strain. If this strain level was used in a conventional fatigue test (time sweep), it would result in the rapid failure of the specimen, about 10,000 to 20,000 load applications.



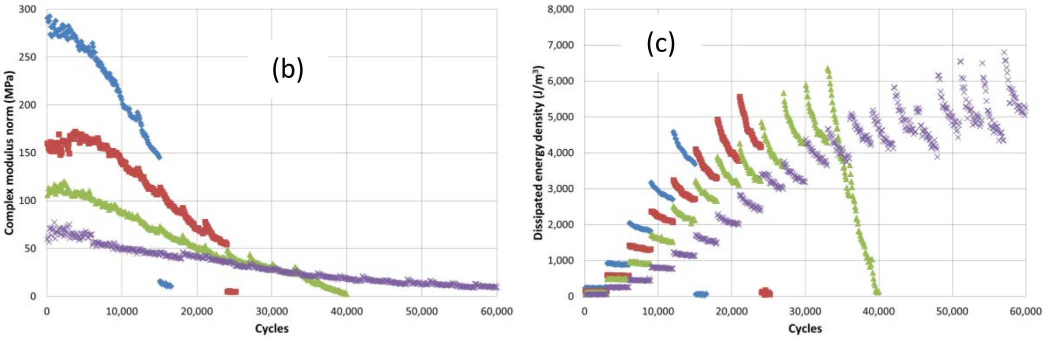


Fig. 5. EBADE test results: (a) evolution of the stress, (b) evolution of the complex modulus, (c) evolution of the dissipated energy.

Therefore, in the EBADE test, it is very easy to define the initial modulus of the mixture for small strain and the step at which the failure occurs. These two parameters are used to characterize and define the fatigue response of the mixtures. It is clear that for the same modulus, the greater the failure strain the more ductile the response of the mixture will be, and its failure on the pavement will occur at a higher strain.

In this article, emphasis will be put on the results that have been obtained during a test under tension-compression cyclic loads, using time and strain sweep test modes, and thus provide more detail on the response of the bituminous mixtures in the fatigue tests.

3. Asphalt binders in phase I

When a time sweep test is applied, a rapid and sharp fall of the modulus is observed at the beginning of the test. If this test is carried out in the strain sweep mode, the modulus drop is progressive as the strain is increased. However, if we overlap both tests, it can be seen that the curves obtained for the same strain level clearly tend to overlap, Fig. 6. That is to say, that the sharp drop that the modulus exhibits in phase I in the time sweep tests, until it stabilises in phase II, is because the mixture has to adapt itself as quickly as possible to the modulus that corresponds to the applied strain.

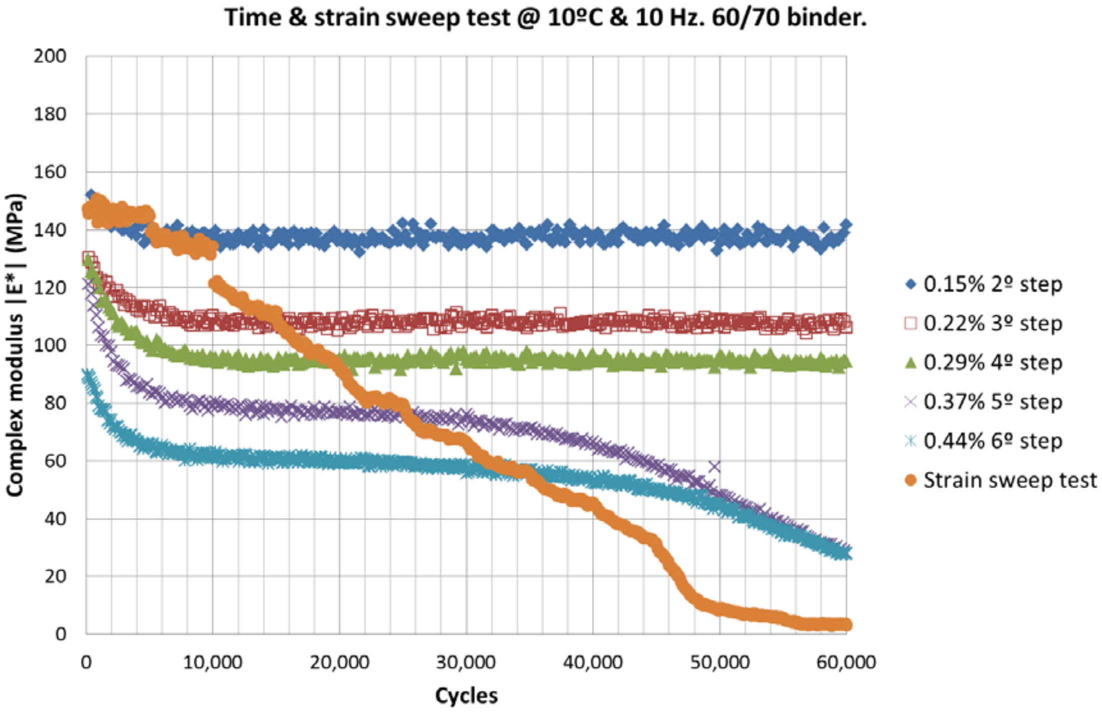


Fig. 6. Overlaying of the modulus evolution curves in the time and strain sweep tests [8].

There is a correlation between the stabilization complex modulus and strain amplitude applied. The response of the mixture is not linear; its modulus drops as the applied strain level increases. This loss of modulus with the strain can be associated with a non-linear viscoelastic response, which is the model normally used in the characterization of bitumen and bituminous mixtures. However, thixotropy may describe better the behaviour observed in bitumens. This phenomenon can be described as an increase of viscosity in a state of rest and a decrease of viscosity when submitted to a constant shearing stress, Fig. 7 [9]. Normally, in increasing strain sweep tests a loss of modulus over time and strain is observed. But when the strain amplitude is decreased, an increase in the modulus is observed. Furthermore, this recovery takes place as predicted by the thixotropic model and not as predicted by the viscoelastic model. In thixotropic materials, when the strain rate is reduced, the stress drops suddenly and later tends to recover, while in the viscoelastic materials there is a progressive drop.

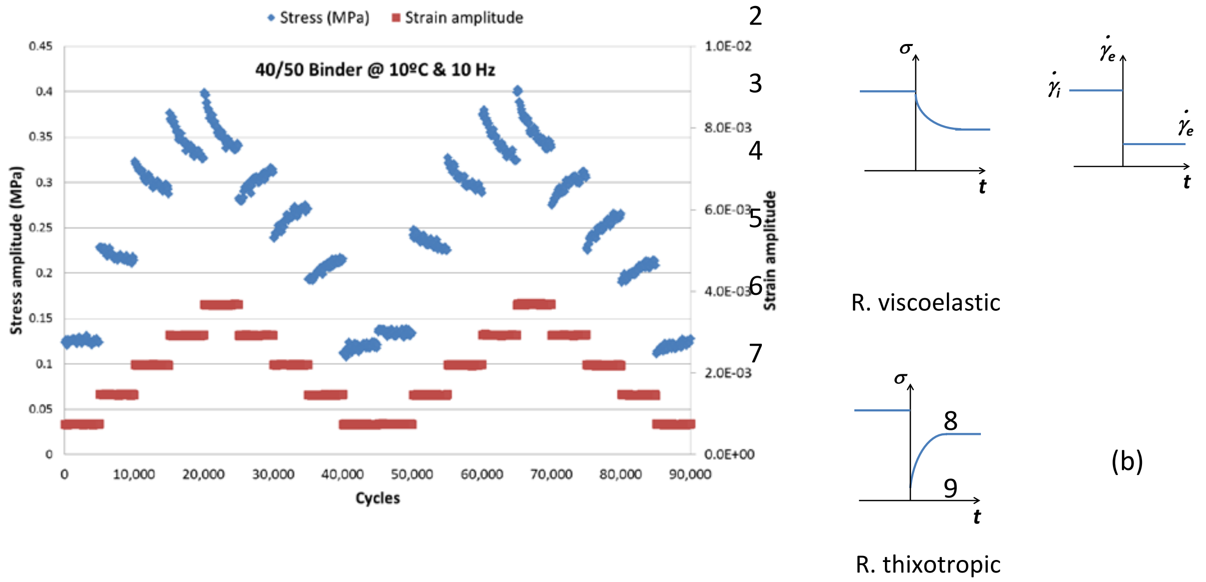


Fig. 7. Behaviour of an asphalt binder with a penetration range between 40 and 50 0.1 mm [10] (a). Differences in theoretical response to a decrease in strain rate of a viscoelastic and a thixotropic material [9] (b).

4. Asphalt binders in phase II

After the rapid loss of the mechanical properties in phase I, the deterioration of the mechanical properties of the bituminous mixtures may or may not continue. When the applied load is small, i.e. a low stress or strain level, the modulus tends to stabilise and a large number of load applications can be reached without a failure or change in behaviour being observed. If the strain level is increased a linear loss of modulus is observed until failure. The greater the strain or stress applied, the faster the loss of modulus is.

When plotting together the results of the time and strain sweep tests, an overlap of the modulus and dissipated energy is observed, i.e., the stabilisation value after the initial decrease for both variables is the same in time and strain sweep tests. Data from both types of tests have been represented in Fig. 8. There is a linear relationship between the complex modulus norm and the dissipated energy density, which is expected, since both are related by the phase angle, Eq. (2). What is more important is that this relationship is the same in time and strain sweep tests when the same strain amplitudes are compared. That means that the relationship between modulus and energy depends only in the strain amplitude applied. The slope of this relationship increases as the strain increases. For low strain values, the modulus reduces but the dissipated energy is maintained. As the strain increases, both the modulus and the dissipated energy decrease.

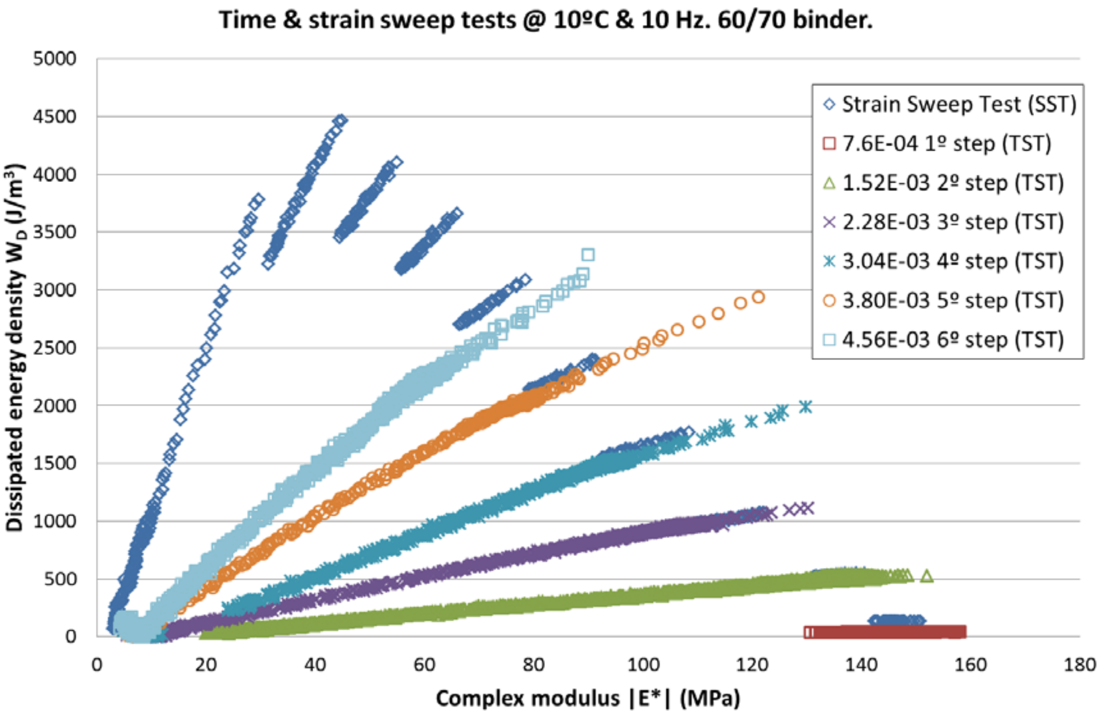


Fig. 8. Relationship between the evolution of the modulus and the dissipated energy in the time and strain sweep tests (bitumen of 60/70 0.1 mm penetration range at 25ºC) [11].

Comparing relationships obtained in the strain sweep tests with those of the time sweep tests, it can be seen that these practically coincide over their straight section for the same strain level. The relationships obtained for the time sweep test have a curve in the final section that tends to the zero modulus and energy point. This curved section corresponds to phase III of the test, i.e. the area where the failure of the specimen occurs. The values corresponding to phases I and II are found on the linear section of the relationship. For the same strain, a constant relationship is maintained between the modulus and the dissipated energy in phases I and II.

This graph also shows that the maximum strain that is reached in the strain sweep test corresponds to that which quickly results in the sample failure in the time sweep test, and that the strain that a horizontal energy-modulus relationship exhibit would correspond to a very high level of cycles in the time sweep test.

Fig. 9 shows the results of the EBADE test for different types of bitumens. It can be seen that for the same level of strain, the slope of the line that relates the variation between the modulus and the energy ($\Delta W_D/(\Delta(E))$) is similar for all the bitumens. This is in part explained by the equation that is used to calculate the dissipated energy, W_D.

$$W_D = \pi\sigma\varepsilon E sen\varphi = \pi\varepsilon^2 E sen\varphi \qquad (2)$$

If *E* and *ε* are the same, the difference would only obey to variations of the phase angle, φ, of the bitumens. This parameter has similar values for the tested bitumens, especially at low strain levels.

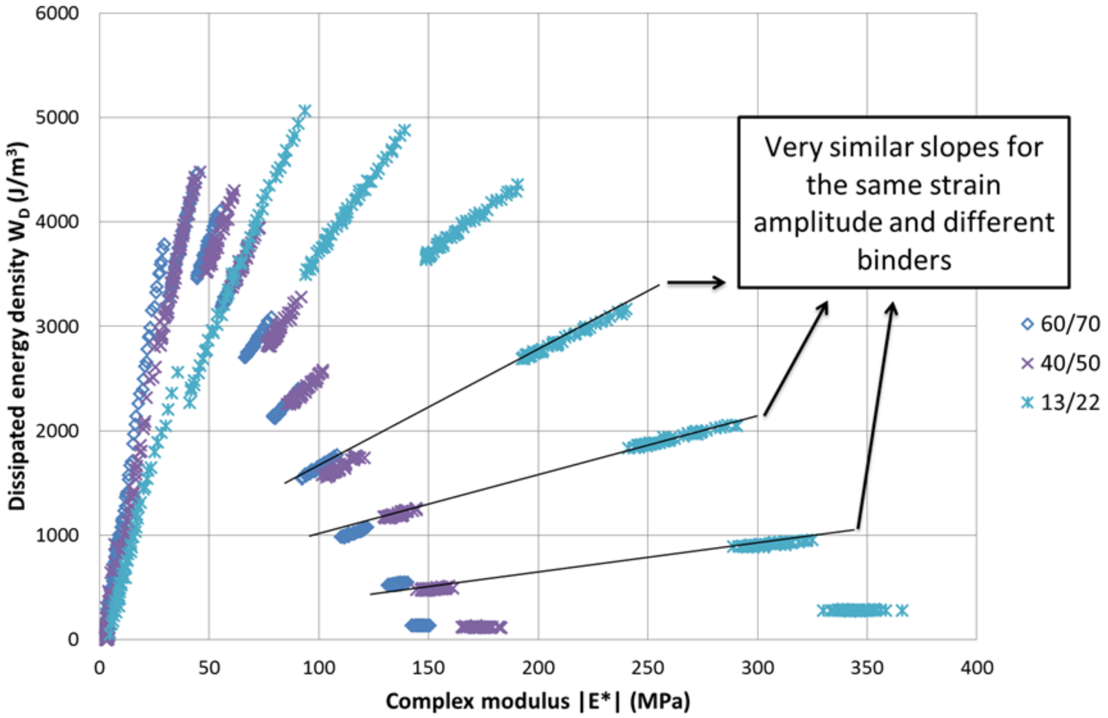


Fig. 9. Effect of the type of bitumen on the modulus-dissipated energy relationship in the cyclic tests [11].

Furthermore and based on these results, the relationship that exists (in the time sweep tests) between the loss of modulus during each cycle (Δ| E* |/Δn) in its phase II, slope of the complex modulus vs. cycles, has been compared with the loss of energy with respect to the loss of modulus (ΔW/Δ| E* |), slope of the straight lines in fig. 8 and 9. These values are shown in Fig. 10 for each type of bitumen for the strain amplitudes in which both results are available in the time sweep tests. In this figure it can be seen that there is a linear relationship between both variables.

$$\Delta|E^*|/_{\Delta n} = \dot{S}n = \varphi.\,^{\Delta W_D}/_{\Delta|E^*|} \tag{3}$$

In this case, the factor that relates both variations is very sensitive to the type of bitumen. The harder the binder the higher the slope between Δ| E* |/Δn and ΔW/Δ| E* |, i.e. the more sensitive is the modulus loss during time sweep test with the ratio between the dissipated energy and the modulus.

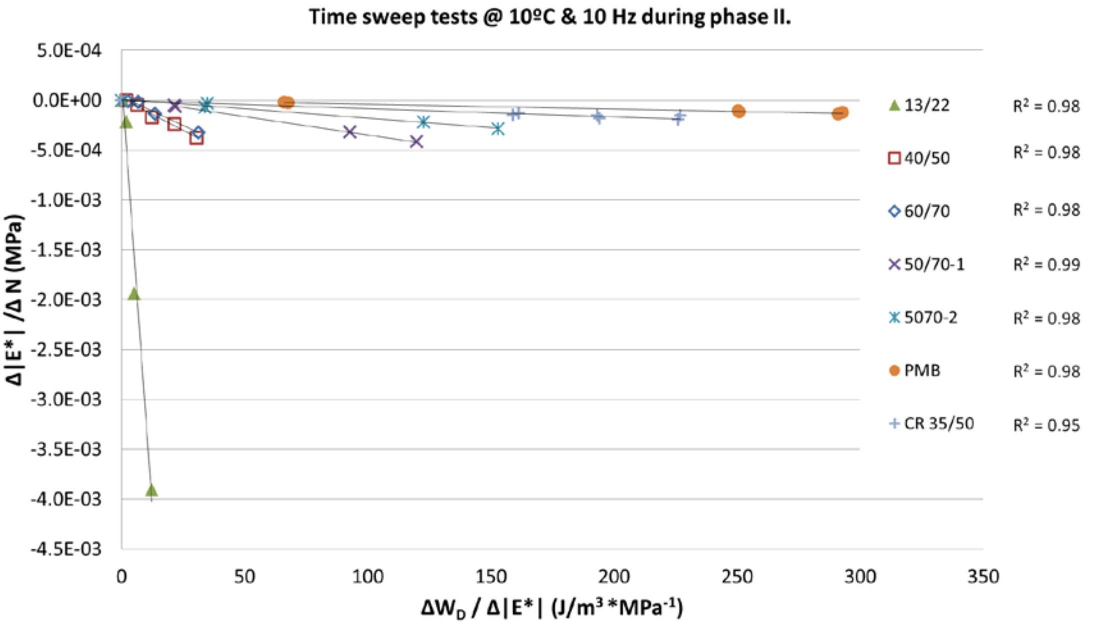


Fig. 10. Effect of the type of bitumen on the deterioration relationship [11], 5 conventional binder of different penetration ranges, 1 SBS polymer modified binder and 1 crumb rubber modified binder with penetration between 35 and 50 0.1 mm at 25ºC.

This equation is of the same type as that proposed by Schapery and Park as a deterioration Eq. (*5*). However, this expression has a simpler form if we only consider phase II, which is the phase normally associated with the deterioration process under repeated loads. Furthermore, it allows the differences of response of the bitumens and bituminous mixtures to be assessed against their deterioration by continuous application of cyclic loads. In addition, by looking at the highest strain levels applied in the EBADE test, this relation can be obtained, and then back-calculate the complex modulus/cycles slope during phase II in a time sweep test at lower strain amplitudes.

5. Self-healing of asphalt mixtures

One aspect which is often mentioned when analysing the response to fatigue of bituminous mixtures is that of its self-healing capability. When a controlled strain fatigue test is stopped at a number of cycles at which an appreciable loss of the modulus has been observed, and then starts again after a rest period the modulus shows an important recovery. It is as if, during this period of time, a self-repair of the mixture has taken place, a phenomenon known as healing. What it is also important to note is that, when the test is restarted, the modulus rapidly descends again to the level it was at before, and the fatigue process continues at a similar rate of deterioration as at first, Fig. 11.

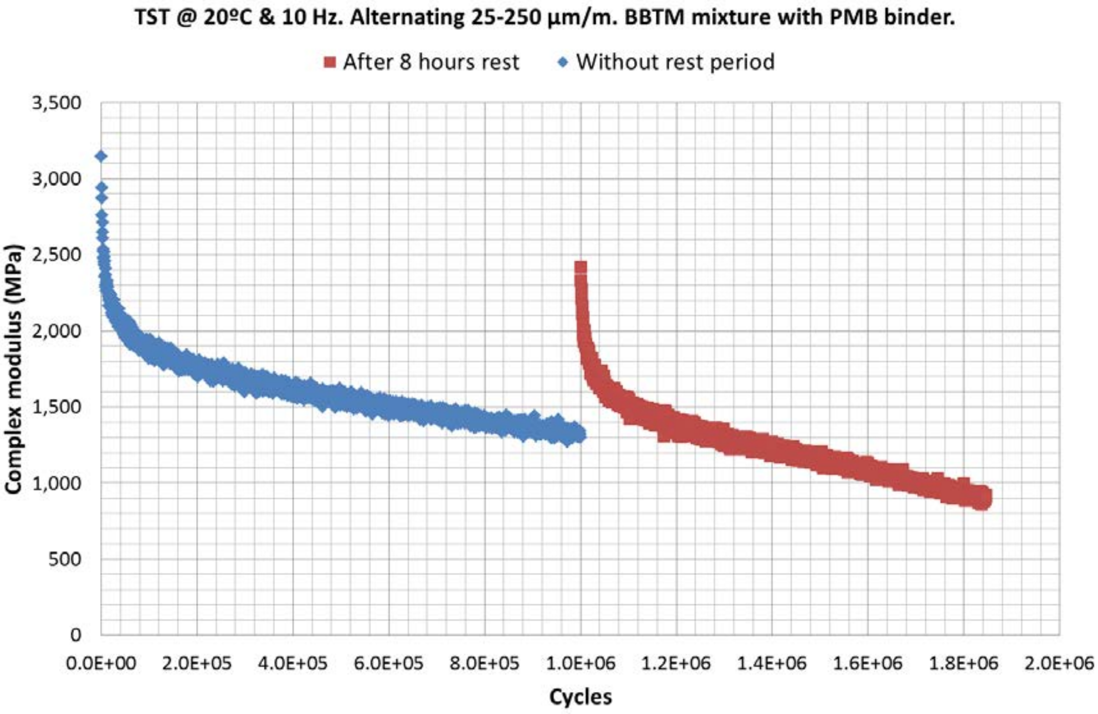


Fig. 11. Effect of the rest period on the fatigue tests. Momentary self-healing and continuity of deterioration.

The recovery of the modulus can also be observed if we carry out a stepped test in which we raise and lower the amplitude of the imposed strain, as shown above in Fig. 11. At the beginning, the modulus decreases as the strain amplitude increases. At each load step, a balance situation is reached with a semi-stable modulus value. As the amplitude of the strain is reduced, the same effect occurs in reverse, and the modulus is recovered until the initial values are reached. That is, a large part of the loss and recovery of the modulus, especially at the start of the fatigue process, is associated with the thixotropic response of the mixture.

This thixotropic behaviour can also be observed of the bituminous mixtures if, in the fatigue test, we apply, instead of a constant strain, time sweep test, a series of repetitions of load blocks. For instance, in the data shown in Fig. 12, these load blocks are made up of 5000 cycles at a low strain (25 µm/m) and 5000 cycles at a strain amplitude ten times higher. It is observed how a significant loss of the modulus occurs as a consequence of the applied high strain, but it is recovered partially again when the lower strain is applied.

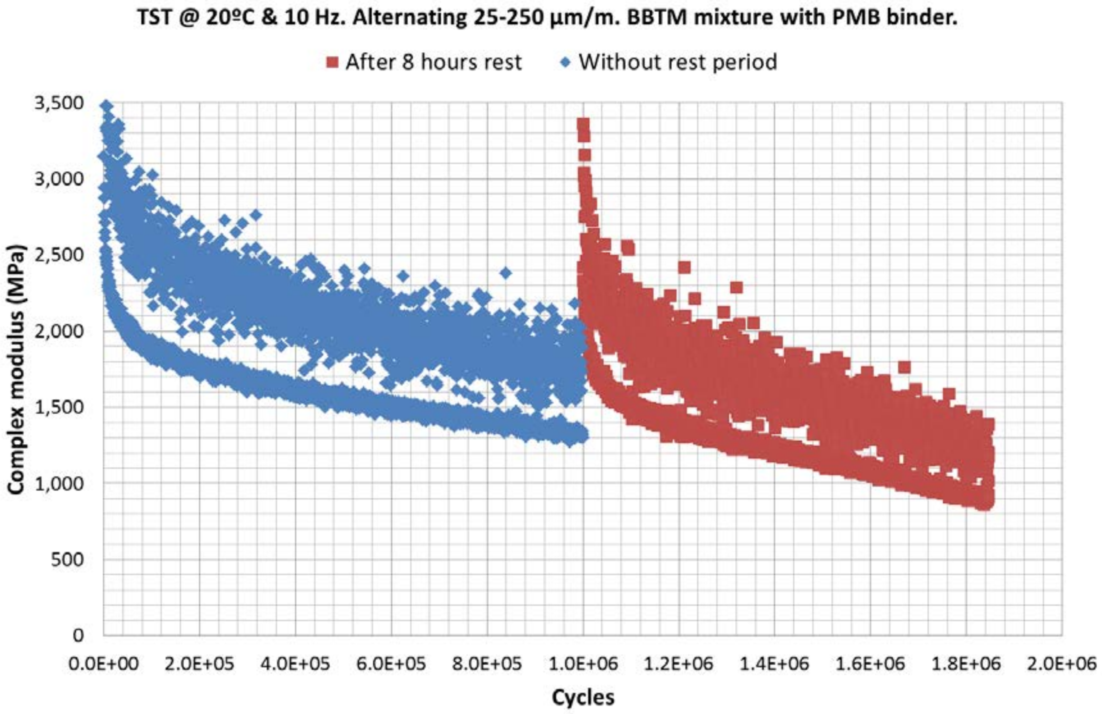


Fig. 12. Variation of the modulus of the mixture due to the effect of the rest period and the strain amplitude change.

6. Application of EBADE Test

The EBADE test offers clear advantages of efficiency and improvements in the assessment of the fatigue resistance of the bituminous mixtures compared to conventional tests.

Firstly, it is a quick test to carry out. The strain sweep test takes barely three hours to complete, while the time sweep test can take more than 24 hours per test and to obtain the fatigue law of a mixture (6 to 8 specimens must be tested as a minimum) can take 1 to 2 weeks.

From the EBADE test, the following parameters that help evaluating the resistance to fatigue of the mixture can be obtained:

6.1. Variation of the complex modulus of the mixture with the applied strain level

As mentioned above, the modulus of the mixture varies with the applied strain amplitude. This value can be obtained for the entire range of strain amplitudes. While in the conventional tests, the complex modulus value comes from the average of the values obtained at cycle 100 in tests performed at different strain amplitudes, and therefore at different loading rates. Those values corresponds to phase I of the time sweep test, during which the mixture is adapting itself to the loading rate and therefore not reliable. In opposition to that, in the EBADE test the complex modulus at very low strain amplitude, 25 µm/m in mixtures and 760 µm/m in binders, is calculated as the average of the first 5,000 cycles, providing a more reliable measure.

6.2. Strain at which rapid failure of the mixture occurs

In the EBADE test, the level of strain is increased until a step is reached in which the failure of the mixtures occurs. The step before to that of failure coincides with the strain amplitude at which a conventional time sweep test would cause failure in short number of cycles, between 5,000 and 20,000 cycles.

6.3. Strain limit for fatigue failure

It is usually considered that there is a strain level under which fatigue failure does not occur. This level of strain, according to various authors, is around 70 µm/m. In the EBADE test, the relationship between the dissipated energy and modulus can be represented for the different load steps. This study shows that in those cases, in which the slope of the straight line that relates both variables is close to 0, the fatigue failure does not occur or the specimens can withstand a very high number of load applications.

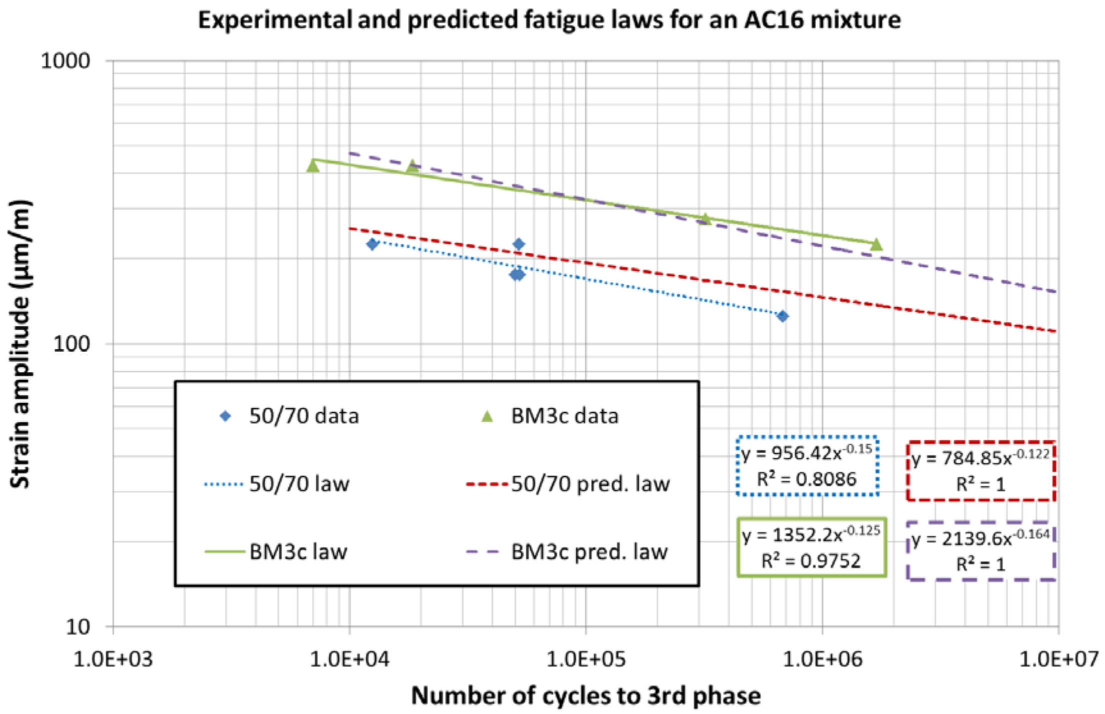


Fig. 13. Fatigue laws obtained by means of a time sweep and EBADE test.

6.4. Fatigue law

Classically the fatigue law in asphalt materials is obtained by performing several time sweep test at different strain or stress levels and registering the number of cycles to failure for each one of them. That leads to a very time consuming procedure. Those data points are then fitted to a power law that relates the strains or stress level with the number of cycles to failure. The approach proposed consist on obtaining a first approximation to that fatigue law using two extreme data points, very high and very low strain levels, and arbitrarily assigning to them a high and low number of cycles. The two extreme strain values are that of the step before the failure strain, associated with 10^4 load applications, and the maximum strain amplitude in which no deterioration is observed, associated with 10^7 load applications. Fig. 13 shows the good agreement that exists between the fatigue law obtained with this method and that obtained by applying the conventional method using time sweep test and using as failure criterion the beginning of phase III.

7. Conclusions

This paper has presented several results on bituminous binders and mixtures that indicate that the dependence of these materials in the strain rate is too important to be neglected in the fatigue characterization of these materials.

The comparison between time and strain sweep tests in bituminous binders has shown that after an initial loss of modulus, this property stabilize at a value that depends on the strain amplitude applied but is independent of the previous loading history. That indicates that the damage caused by previous strain steps is non-existent, and therefore, if the loading is decreased the complex modulus could be recovered. That is proven in Fig. 7. The modulus decrease when the loading rate is increased, and its subsequent recovery when the loading rate is decreased can be mistaken by self-healing, while the results of this paper indicate that this phenomenon it is mostly due to the thixotropic behaviour of the asphalt binder.

Continuing on the comparison between time and strain sweep tests, it has been confirmed the relation between the dissipated energy density and complex modulus described by equation 2. In addition, it has been seen that this relation remains constant during phase I and phase II of the time sweep tests, and it depends on the strain amplitude applied. Furthermore, the variation of this relation with the type of binder is very small, or in some cases, non-existent. This relation has been proven to be linearly related to the slope of the complex modulus vs. cycles curve during phase II in time sweep tests. As a consequence, by performing one EBADE test, the rate of damage accumulation during phase II in a time sweep test at any given strain amplitude can be estimated. Following this concept, a methodology to estimate the fatigue law of the material using the data from the EBADE test has been proposed. This methodology consist of relating the failure strain and the maximum strain amplitude at which the material does not suffer a change in the dissipated energy density with a high (10^7) and a low (10^4) number of cycles, respectively. This estimation has shown a reasonably good adjustment to the experimental data from time sweep test.

Finally, the tests performed in mixtures changing the strain amplitude alternatively and adding a long rest period have shown that the dependency of the mixture behaviour on the strain rate is very high, showing different complex modulus at different strain rates. This change in modulus is more important than that related with the self-healing of the mixture. Therefore, is concluded that the distribution of resting periods in a cyclic testing can have a very strong effect on the final number of cycles the material can sustain. This phenomenon is more affected by the strong rate dependency of the mixture, caused by the thixotropic nature of the asphalt binder, than by its self-healing.

These results indicate that the characterization of the fatigue behaviour of bituminous materials based on defining a number of cycles to failure at a given strain amplitude is not representative of the real behaviour the mixture will exhibit in the pavement. Instead, these analyses should be based on the comparison of the initial complex modulus obtained at low strain amplitudes, its variation with the strain rate applied and the maximum strain the material can sustain before failing in cyclic testing.

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