SELF-HEATING AND OTHER REVERSIBLE PHENOMENA IN CYCLIC TESTING OF BITUMINOUS MATERIALS

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ABSTRACT

This paper's objective is to evaluate the reversible phenomena that take place when asphalt materials are subjected to cyclic loads, i.e., self-heating and thixotropy. A strain sweep test was adapted to capture the stiffness variation of binders with the change in strain amplitude. The evolution of the internal temperature of the binder during the test was measured. Results show that the temperature can increase very significantly during cyclic testing and can account for a great part of all stiffness reduction captured during the test at different strain amplitudes. These results led to the conclusion that internal heating should be very important in asphalt mixtures as well. For that reason two types of time sweep tests were performed on the same mixture, with the introduction of rest periods in one of them long enough to let the inside temperature of the material lower after cycling. The results showed that the specimen that was allowed to cool down did not experience any loss of stiffness, while the specimen submitted to the conventional time sweep test failed in a few cycles. These results show the importance of the sequencing of loading and discourage the application of the Miner's law to estimate pavement life.

Keywords: self-heating, thixotropy, asphalt, fatigue, strain sweep test.

INTRODUCTION

Fatigue behavior of asphalt mixtures is a matter of great importance to pavement engineers all around the world. It depends on several properties of the mixture, one of the most important being the properties of the asphalt binder that is used in its manufacture [1-6]. For that reason, several researchers have developed different methods to characterize the fatigue behavior of asphalt binders [7-12], the majority of them based on cyclic testing. However, bituminous materials exhibit a complex behavior when exposed to cyclic loading, which leads to different interpretations of the results of these kinds of tests.

It is well known that asphalt materials exhibit a non-linear behavior during the initial stage of any kind of cyclic test. For that reason, several authors divide the stiffness evolution of bituminous materials during cyclic tests into three phases. Phase I corresponds to that initial stage in which a fast and non-linear loss of stiffness is observed. The explanation for this phenomenon is normally attributed to non-linear viscoelastic effects, thixotropy and/or self-heating [13-19]. Phase II corresponds to a change in the stiffness reduction pattern. After the initial non-linear phase, phase I, the material exhibits a linear loss of stiffness with the number of cycles. Typically this loss is associated with irreversible damage produced by the repetition of loads. The higher the strain/stress applied the steeper is the slope of this linear phase, leading to failure in fewer cycles. Finally phase III is associated with a final deviation from the linear behavior observed during phase II, resulting in a rapid loss of stiffness. This stage is considered the failure stage of the specimen, and the cause of this behavior is normally attributed to the coalescence of the micro-cracks formed during phase II to form macro-cracks that cause the complete failure of the material.

These kinds of cyclic tests are very time consuming, and normally several of them are required in order to portray the fatigue behavior of the mixture, i.e., obtain the fatigue law of the material. For that reason, recently, different alternatives have been developed to accelerate this process. Such is the case of the procedures in which a variable strain/stress amplitude is applied, i.e., strain/stress sweep tests [9-20]. Combining this method with the viscoelastic continuum damage theory, a fatigue law can be estimated. This procedure is much faster than the classical approach based on computing the fatigue law of the material from several time sweep tests.

The EBADE test [20, 21] is based on this strain sweep test concept. Its name stands for the Spanish words for strain sweep test. This procedure provides information on the variation of the dissipated energy density, DED, the complex modulus, $|E^*|$, and the phase angle, δ, of the material at different strain amplitudes. It provides the maximum strain amplitude the material can sustain without permanent change to its properties, and the maximum strain amplitude it can endure under cyclic conditions before failing completely. These two strain values may be used to sketch an approximation of the fatigue law of the material [22]. The fatigue laws obtained through this procedure were compared with those obtained by applying the classical method based on time sweep tests, showing a good agreement between them [23, 24]. These time sweep test results were also used to found a linear correlation between the complex modulus and the dissipated energy density that propagated through phases I and II. It was also found that the slope of these linear correlations depended on the strain amplitude applied, leading to the same slopes for the same strain amplitudes in time and strain sweep tests [25]. In addition, the superposition of results from the time and strain sweep test showed that the complex modulus and dissipated energy density values were the same after 5,000 cycles at the same strain amplitude in time and strain sweep tests, regardless of the previous loading history. This result led to the hypothesis that the complex modulus loss was related only to the strain amplitude, independently of the previous loading history, and that it could be recovered if the strain amplitude was decreased or the test stopped. A strain sweep test performed with increasing and decreasing strain amplitudes alternatively proved this hypothesis [17]. This kind of reversible behavior could be explained by the thixotropic nature of the material or its capacity to convert the dissipated energy into a temperature increase, or both.

Benedetto et al. [16] measured the increase of the inner temperature of asphalt mixtures during cyclic testing and determined the amount of complex modulus they can recover. Afterwards they separated this recovery into three phenomena: self-heating, thixotropy and non-linear effects, assigning different quantities of complex modulus to each one. In addition, they proposed that the thixotropy effect could be modeled as an increase in the inner temperature of the material.

Thixotropy is a very complex phenomenon, so much so that there is not full agreement in the scientific community as to what its exact definition should be [26, 27]. The most general definition that it is accepted nowadays is as follows: “the continuous decrease of viscosity with time when flow is applied to a sample that has been previously at rest and the subsequent recovery of viscosity in time when the flow is discontinued” [27]. Viscoelasticity is not referenced in the definition, but it is not excluded either. The implications of this can lead to some ambiguous interpretation of the results, because self-heating, if it happens, has to be related to the energy the material dissipates during cyclic testing, which is a consequence of the viscoelastic response of the material (a pure elastic material would not dissipate energy and therefore it could not increase its temperature by itself). Benedetto et al. [16] showed that the increase in temperature at the beginning of the test was proportional to the dissipated energy. However, a definition of thixotropy from Bauer and Collins [28] clearly states that this phenomenon should take place under isothermal conditions. Therefore, depending on the definition that is adopted, thixotropy and self-heating could be independent phenomena or the second could be the cause of the first.

Measuring thixotropy during cyclic testing presents several technical complications. To fulfill the definition, it is necessary to change bi-directionally the flow applied to the material, i.e., increase and decrease the strain/stress amplitude several times keeping constant flow after each change for enough time to reach stabilization. However, when testing materials whose stiffness is highly dependent on temperature, heating and cooling down may give the same response as that expected from a thixotropic fluid. In that case, the only way to tell one from the other is to measure the temperature inside the material continuously during the test.

Recent research suggests that the increase of internal temperature is fully explained by viscous dissipation [29]. By considering the viscoelastic dissipated energy, obtained in a finite element simulation of a cyclic mechanical loading, as an internal heating source, a temperature increase was obtained close to experimental values from literature.

This paper presents the results obtained in a cyclic test designed specifically to analyze the effect of thixotropy and self-heating in asphalt binders. The procedure is based on the EBADE test, but adapted to capture the stiffness variation of binders with the change in strain amplitude. By embedding a thermocouple probe inside the specimen during its manufacture, it was possible to measure the evolution of the internal temperature of the asphalt binder during the test. Results show that the increase in temperature during cyclic testing can account for an average of 88% of all stiffness reduction captured during the test at different strain amplitudes, before failing. This result was consistent with the work carried out by Mangiafico et al. [18] that found that 90% of the stiffness variation during cyclic testing of asphalt mixtures was completely reversible. For that reason two time sweep tests were performed on the same mixture, introducing rest periods in one of them long enough to let the inside temperature of the material lower after cycling. The results showed that the specimen that was allowed to cool down did not experience any loss of stiffness in more than 180,000 cycles, while the specimen submitted to the conventional time sweep test failed completely after fewer than 100,000 cycles. These results show the importance of the sequencing of loading and discourage the application of the Miner's law to estimate pavement life.

METHODS AND TEST PLAN

EBADE test

The EBADE test takes its name from the Spanish words for the strain sweep test. It consists of a cyclic uniaxial tension-compression test in which the strain amplitude increases at a constant value every certain number of cycles. In its common configuration, each strain amplitude is applied for 5,000 cycles at a frequency of 10 Hz. This test can be performed on asphalt binders, asphalt mastics and asphalt mixtures, Figure 1.

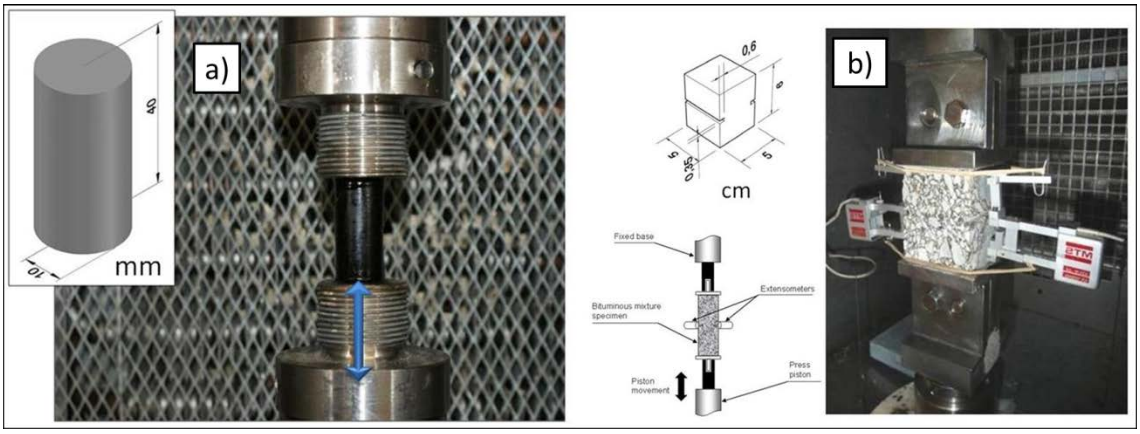

Figure 1. EBADE test set up for a) binders, mastics, and b) mixtures [20, 21].

The strain amplitudes are different for the binder and mixture modalities of the test, since it has been documented that the strain level in the binder phase is around ten times higher than the average strain level in the mixture [30]. The test on asphalt binder starts at 650 µm/m and increases by the same amount every 5,000 cycles, while the initial and the increment in mixture modality is 25 µm/m.

During the test the norm of the complex modulus, |E*|, is calculated by dividing the stress amplitude by the strain amplitude. Since the complex modulus is defined in the linear domain at high strains the norm of the complex modulus should be called the norm of the apparent or effective complex modulus. For simplicity reasons, from now on it will be referred to as the "complex modulus" or |E*|. The dissipated energy density, DED, is obtained by calculating the area inside the stress-strain hysteresis loop using the Gauss determinant formula. These measures are taken every 100 cycles, typically [20].

Test plan

Using the EBADE test set up, different strain amplitudes and frequency combinations were applied.

First, to obtain the master curve of the binder, a frequency sweep test was designed consisting of applying 50 cycles at 0.1 Hz, 500 cycles at 1 Hz, and 1,000 cycles at 5, 10, 15, 20, 25 and 30 Hz. This test was conducted at three different temperatures, 1.8, 10.5 and 19.7ºC. The strain amplitude was adjusted for each temperature and frequency to be as small as possible and not cause any irreversible effect on the binder.

Second, a test was designed to evaluate the effect of self-heating and thixotropy on the stiffness of the binder. The whole test was performed at 10 Hz and 10.5ºC and it consisted of applying an initial strain amplitude of 650 microstrains for 5,000 cycles to obtain an initial and reference value for the complex modulus. After that the strain amplitude was doubled (1300 µm/m), for 15,000 cycles, and returned to 650 microstrains afterwards for another 15,000 cycles. In the next step the strain amplitude was tripled (1950 µm/m) for the same amount of cycles, to return afterwards to the initial strain amplitude. This process was repeated until the strain amplitude applied was high enough to break the specimen. The duration of the steps, 15,000 cycles, was chosen taking into account the prediction made by the thermoviscoelastic model developed by Riahi et al. [29] which uses the 2S2P1D rheological model developed by Olard et al. [31]. These simulation results showed that less than 1,500 seconds were needed to reach thermal stabilization for each strain step. To measure temperature during the test, four thermocouples were employed, one embedded in the geometrical center of the specimen during its fabrication, and three on the surface of the binder, one in the middle, one at the top and one at the bottom of the specimen's surface. This test was repeated at 1.5ºC.

Finally, the same strain sweep test structure was applied to two asphalt mixtures using the EBADE configuration developed for this material. In this case, the duration of each strain level was reduced to 5,000 cycles, the test temperature was set at 20ºC and the frequency was 10 Hz. The two mixtures tested were composed of a gap-graded gradation (BBTM[1]) and a conventional (50/70) and a Styrene-Butadiene-Styrene Polymer Modified Binder (PMB 45/80-65).

MATERIALS

[1] BBTM is the denomination of one kind of gap graded mixture in the European Standards. It stands for the French words for very thin bituminous mixture (*Béton Bitumineux Très Mince*).

The asphalt binder employed for the master curve calculation and self-heating and thixotropy evaluation was a conventional binder of a penetration grading at 25ºC of 35 to 50 0.1mm (35/50).

The mixtures employed were manufactured with a conventional binder of a penetration grading at 25ºC of 50 to 70 0.1mm (50/70) and a SBS polymer modified binder with a penetration grading at 25ºC of 45 to 80 0.1mm and a softening point higher than 65ºC (PMB 45/80-65). The gradation employed was gap-graded with a maximum aggregate size of 8 mm. The binder content was 5% by mixture weight and the air void content was on average 3.6% for the 50/70 mixture and 3.3% for the PMB mixture.

RESULTS

Master curve

In order to obtain the temperature-frequency dependence of the asphalt binder studied, the master curve of the material was calculated using the Williams-Landel-Ferry model [32], Equation 1. For that purpose, short cyclic tests at small strain amplitudes were performed on a binder sample at different frequencies, i.e., frequency sweeps. This test was performed at three different temperatures: 1.8, 10.5 and 19.7ºC. Figure 2 and Equation 1 show the master curve and the coefficients for the shift factor obtained, respectively.

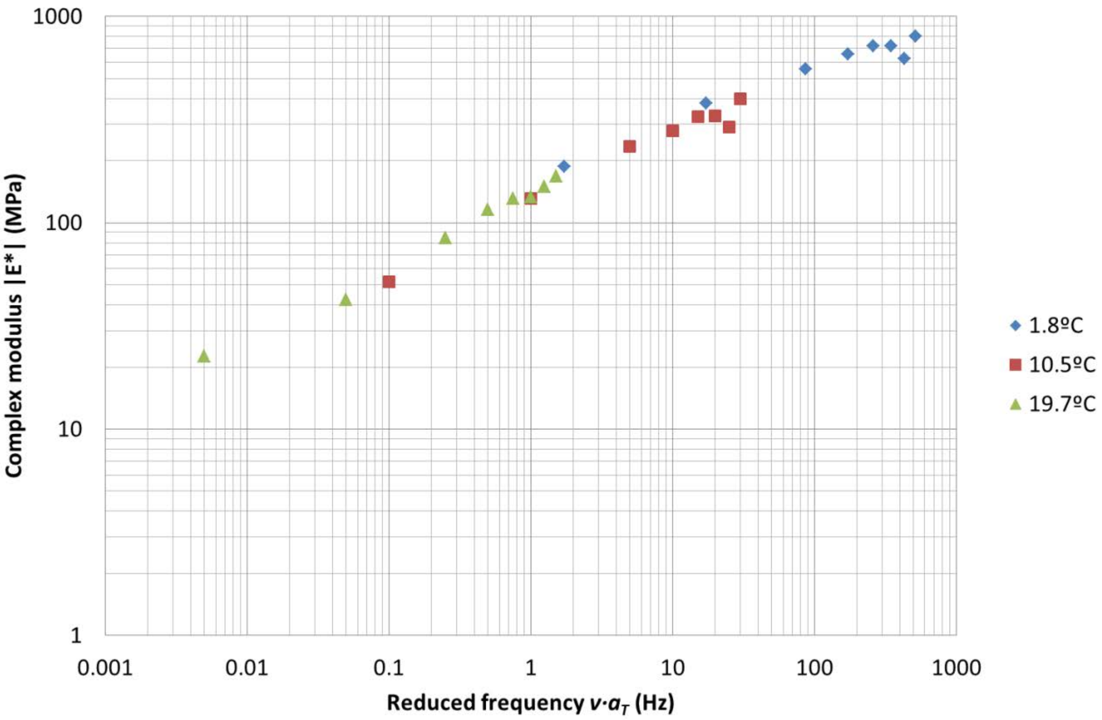

Figure 2. |E*| values at different temperatures and frequencies.

$$\log a_T = \frac{-26 \cdot (T - 10.5\ ºC)}{190 + T - 10.5\ ºC} \quad (1)$$

The complex modulus values follow the expected behavior with frequency and temperature, however, some unexpected results were obtained at frequencies higher than 20 Hz. This was caused by the inability of the test equipment to produce a smooth strain input signal at those frequencies. A linear regression was fitted to the double-logarithmic master curve (Log|E*| vs. Log $v \cdot a_T$) to later interpolate values of |E*| at intermediate temperatures, Figure 3.

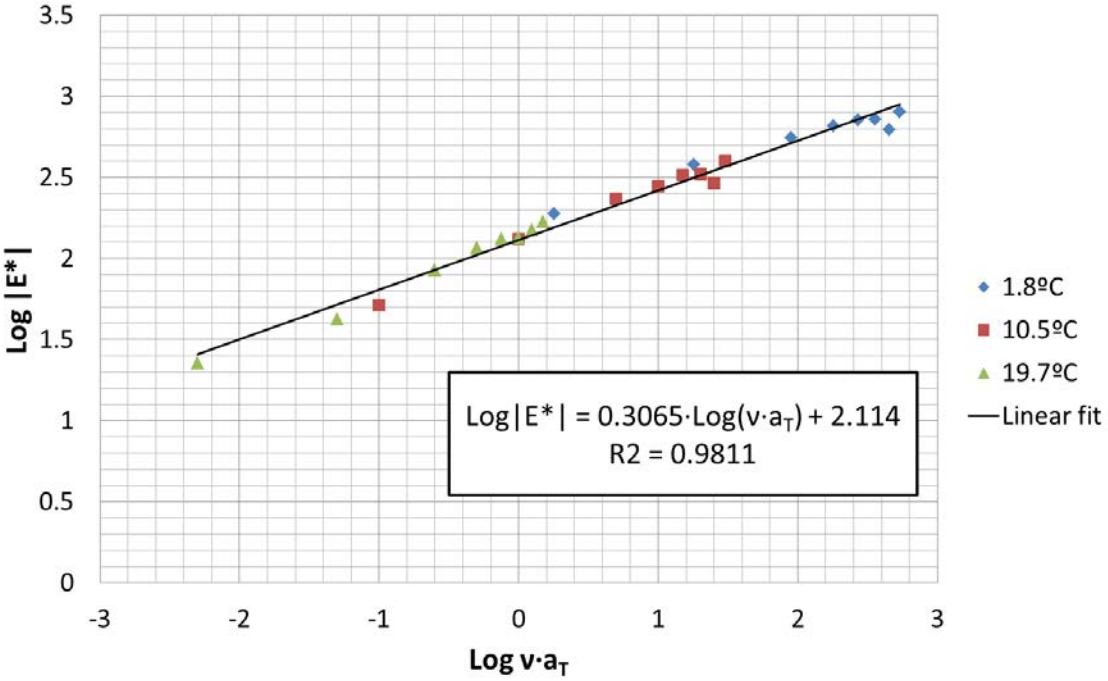

Figure 3. Linear regression of the double-logarithmic representation of the complex modulus versus the reduced frequency.

This interpolation was employed later as will be explained in the next section.

Self-heating evaluation

The evolution of the complex modulus during the test designed to evaluate the self-heating and thixotropy effect on the binder is shown in Figure 4.

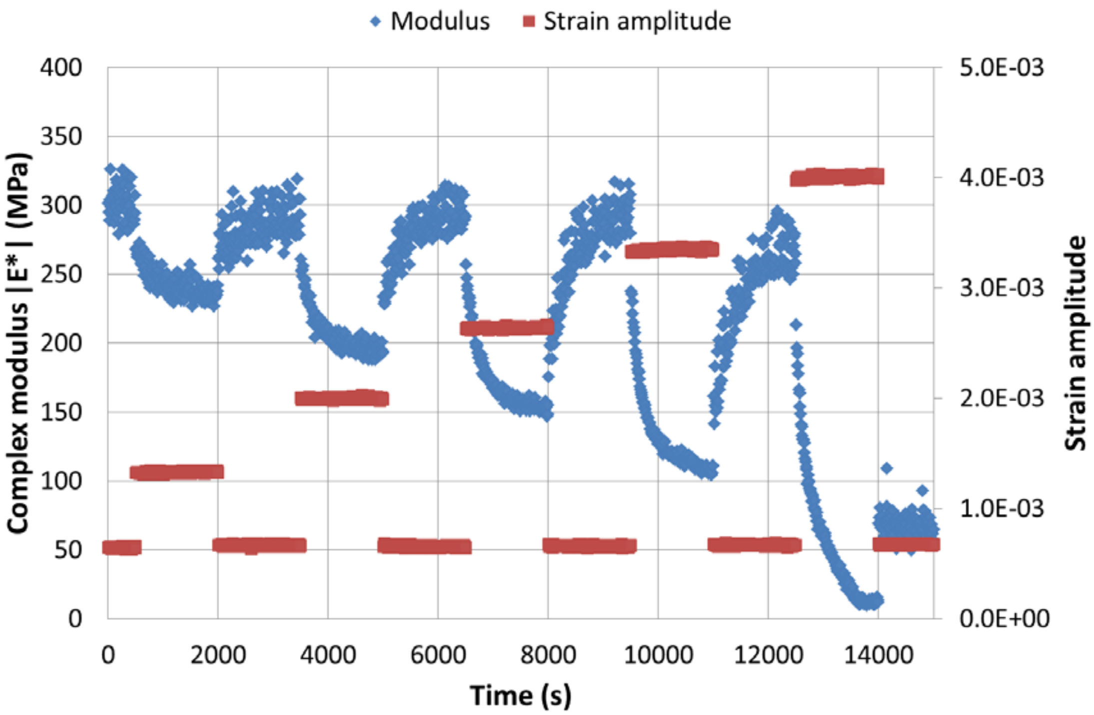

Figure 4. |E*| evolution for the 35/50 binder at 10 Hz and 10ºC.

It is clear that the |E*| exhibited a gradual loss when the strain amplitude increased and a gradual increase when the strain amplitude decreased. Furthermore, after enough time at the initial strain amplitude, the |E*| returned to the same values it showed before undergoing higher strain amplitudes. This behavior repeated up to 3250 μm/m. After this strain level the binder was unable to recover the |E*| values it showed previously, although it came very close. It is also interesting to observe the behavior of the DED during the test, Figure 5.

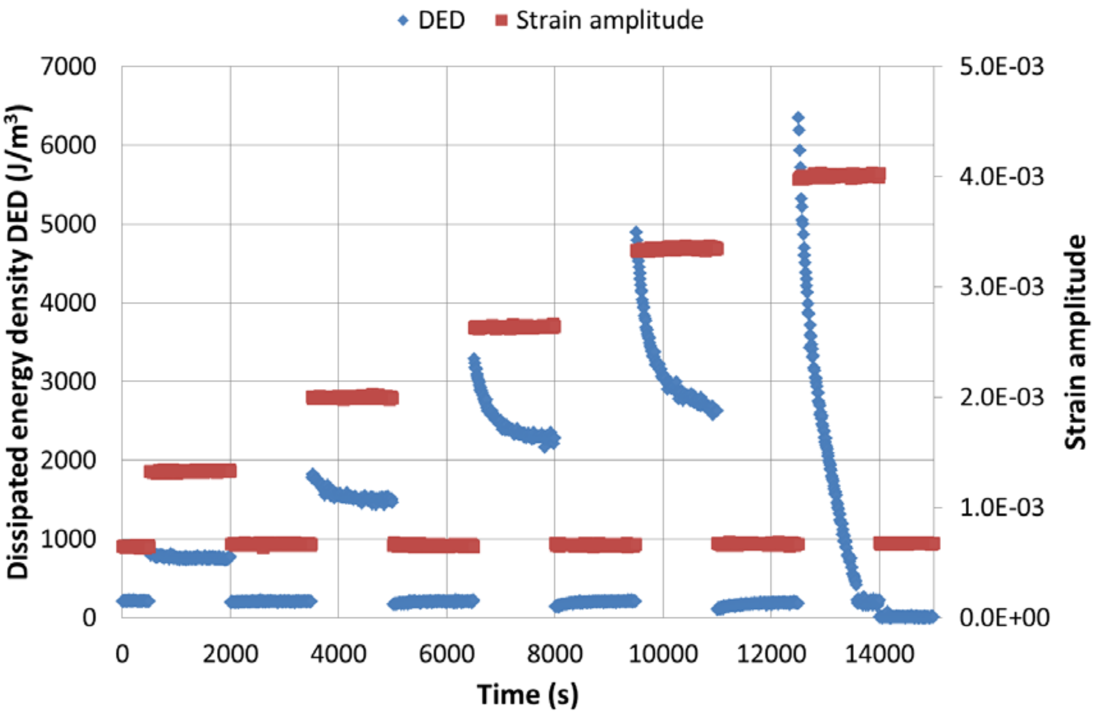

Figure 5. DED evolution for the 35/50 binder at 10 Hz and 10ºC.

At the lowest strain level, the DED remained almost constant, showing a small increase at the beginning of each section when the previous strain applied was higher. This increase was bigger the higher the previous strain amplitude was. It can also be observed how, at 3250 µm/m, some kind of irreversible process took place, since there was no stabilization in the DED values as happened at previous strain amplitudes.

The explanation for this behavior was clear when the temperature evolution during the test in the specimen was analyzed, Figure 6.

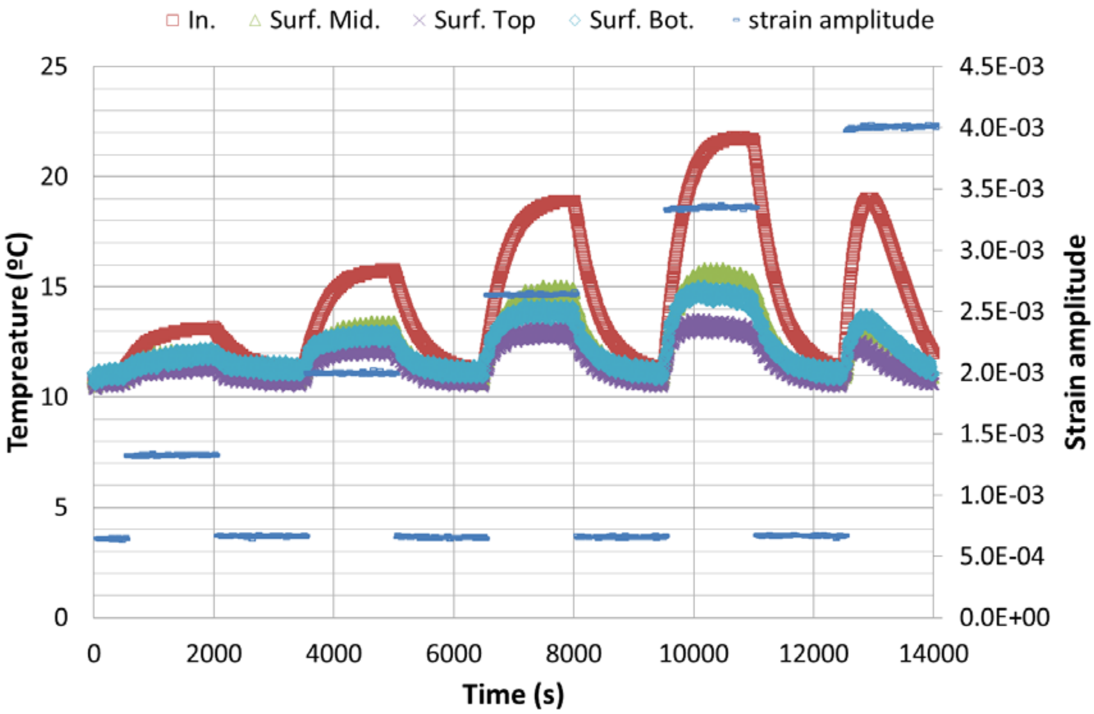

Figure 6. Specimen temperature evolution during the test performed at 10ºC and 10 Hz. In.: geometrical center, Surf. Mid.: surface middle, Surf. Top.: surface top, Surf. Bot.: surface bottom.

As can be seen in Figure 6, the increase in temperature in the geometrical center of the specimen experienced a significant increase and it was higher the higher the strain amplitude. It is important to notice that at 2600 µm/m the temperature stabilized close to 19ºC, almost twice the temperature set for the test, and it reached 21.8ºC at 3250 µm/m. Clearly, that had an important effect on the |E*| recorded during the test. Although there was also a temperature increase detected on the specimen's surface, the temperatures recorded in the center of the specimen were much higher. The only source of energy available to produce such an increase in temperature was the viscous dissipation characteristic of asphalt materials. That dissipation per unit volume is the physical meaning of the DED. For that reason, the increase in temperature for a given period of time should be proportional to the cumulated dissipated energy density during the same period of time, Figure 7.

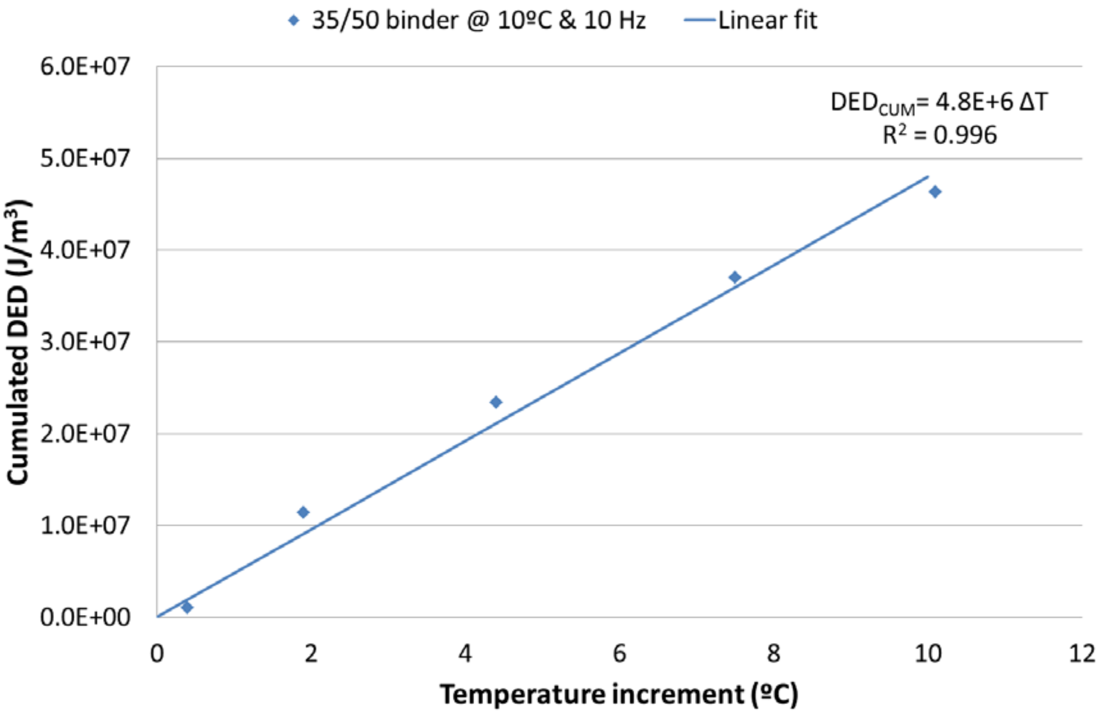

Figure 7. Correlation between the inside temperature increment at stabilization and the cumulated DED for each strain amplitude applied.

As expected, a very good correlation exists between the increase in the inside temperature measured with the embedded thermocouple and the cumulated DED measured by adding all the areas of all hysteresis stress-strain loops measured during the test (since the data is acquired every 100 cycles, the sum of the DEDs has to be multiplied by 100 to account for the loops not measured). The linear regression was forced to go through the origin since an increment of temperature with zero dissipated energy cannot exist. If it is assumed that all the DED was invested in raising the temperature of the area where the thermocouple was placed, the relationship between the DED and ΔT should be the volumetric heat capacity, *s*, equation 2:

$$s = \frac{\Delta Q}{\Delta T} \qquad (2)$$

The volumetric heat capacity obtained from the experimental measurements conducted on the 35/50 binder was 1.83 MJ/m^3K, which is within the same order of magnitude as the slope obtained for the linear regression in Figure 7. The discrepancy is due to the fact that equation 2 is valid only for adiabatic processes. In this case, the specimen is interchanging heat with the environmental chamber air. A part of the DED is lost by heat transfer at the surface of the specimen, causing the temperature to be lower at the surface than in the geometrical center, therefore the real temperature of the material is lower than that predicted by equation 2. For that reason the volumetric heat capacity, calculated through equation 2 is higher than the value obtained experimentally.

It is known that the |E*| of asphalt binders is highly dependent on temperature [3, 33], and its dependency can be modeled using the master curve [34-36]. Therefore, the next step was to calculate the |E*| that would correspond to each temperature measurement that was taken during the test and compare this result with the experimental |E*| measured directly in the test. For that purpose, the linear interpolation shown in Figure 3 was used in combination with the temperature data from the test, equation 3.

$$|E^*| = 10^{(0.3065 \cdot \log(\nu \cdot a_T) + 2.14)} \quad (3)$$

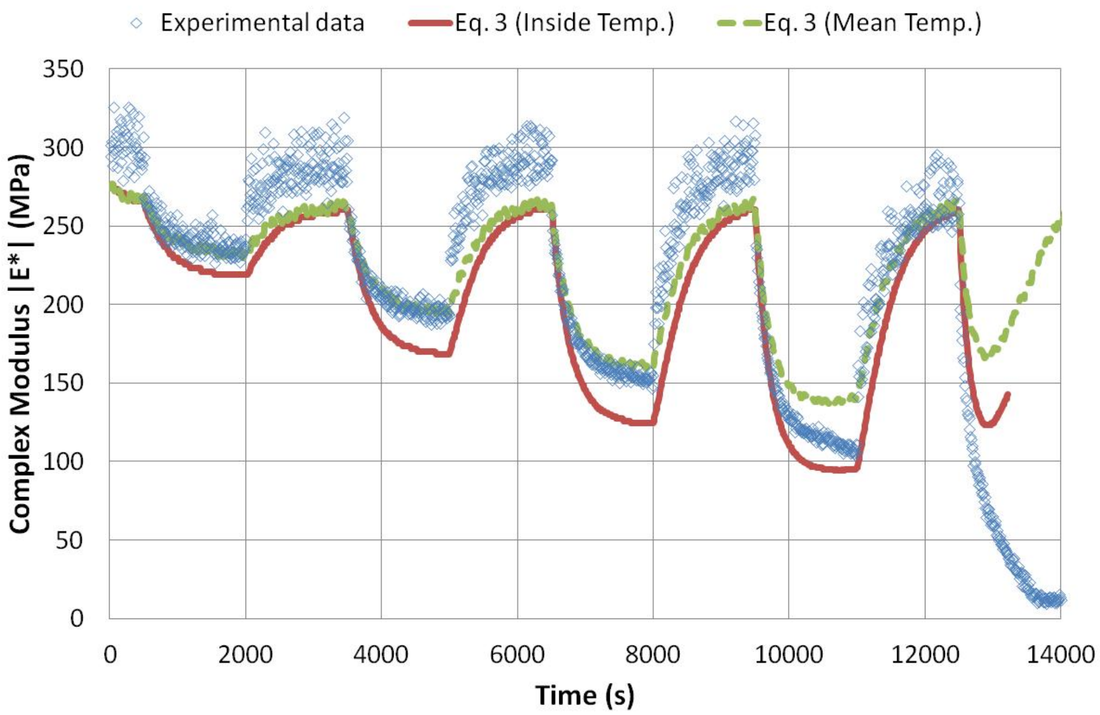

Figure 8. Comparison between the experimental |E*| values and those obtained using equation 1.

Figure 8 compares the experimental data with the |E*| obtained using equation 3 with the inside temperature (red continuous line) and an average between the average surface temperature and the inside temperature (green dashed line). It is interesting to see that just by accounting for the temperature effect on |E*| the whole test could be modeled very closely. The discrepancy between the experimental data and the red continuous line was expected since the average temperature of the bulk of the material that contributed to the overall DED computation was lower than that measured in the geometrical center of the specimen. Considering the specimen homogeneous and isotropic, the geometrical center should be the area with the highest temperature increase. The data generated using equation 3 and the approximation to the average temperature better fits the experimental results. Figure 8 shows that temperature can explain the reversible phenomenon that takes place during cyclic testing of asphalt binders.

Also worth noticing is how the modulus computed using the temperature interpolation, equation 3, and the experimental data take different paths just before the test finishes. This means that at some point there is a reduction of |E*| without an increase in temperature, meaning that this reduction is related to a reduction of contact surface (crack initiation). When this happens, the dissipated energy is invested in creating a crack instead of heating the binder. Therefore, the comparison shown in Figure 8 can also be used to detect crack initiation in the binder.

Given the temperature reached inside the binder specimen, one may expect a ductile failure. However, the specimen broke in half, a little above the plane at which the thermocouple was embedded, leaving two clean surfaces, Figure 9. It is important to mention that, in contrast to what was expected, the thermocouple tip did not cause the failure, since the failure plane was above it, and it was necessary to scratch some material to unbury the thermocouple, Figure 11a.

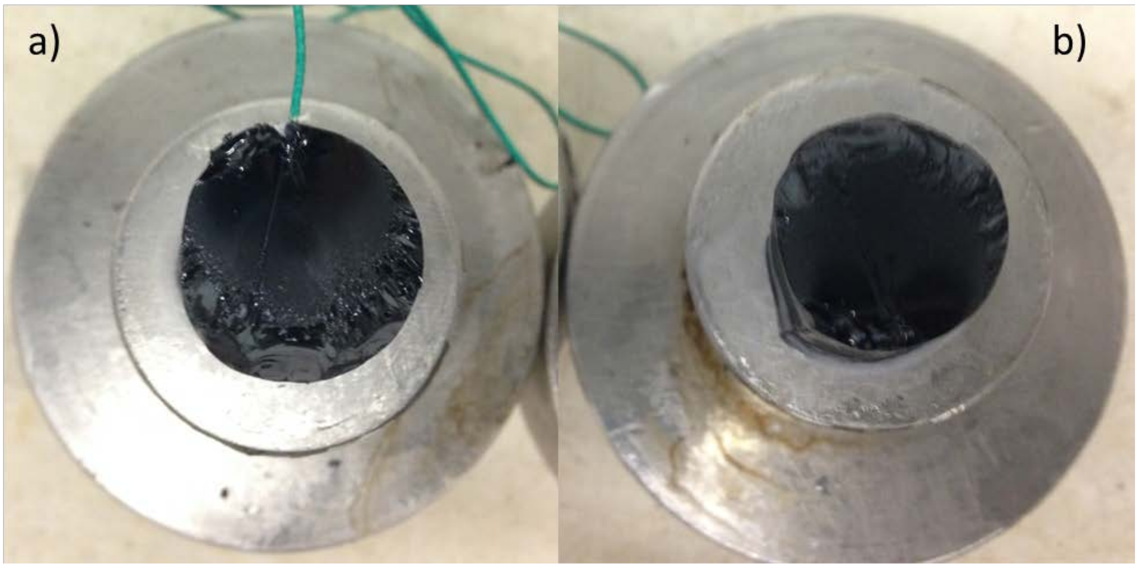

Figure 9. Pictures of the failure surfaces taken after testing. a) Bottom section with the thermocouple, b) Top section.

A possible explanation for this type of failure may be related to the temperature gradient in the bulk of the asphalt binder. While locally the inside temperature can increase to almost 22ºC, other parts of the asphalt specimen may be at lower temperatures, as was confirmed by the surface temperature measurements. Those small areas inside the specimen at high temperature may act as a defect due to their locally low stiffness causing a concentration of stresses around them, the same way an air bubble or a crack tip would do. Since outside of this heated area the temperature is lower, and therefore, the material is stiffer, the crack can propagate critically leaving the clean surfaces observed in Figure 9.

The same test was performed at 0ºC and 10 Hz. The |E*| and the inside temperature evolution are plotted in Figure 10.

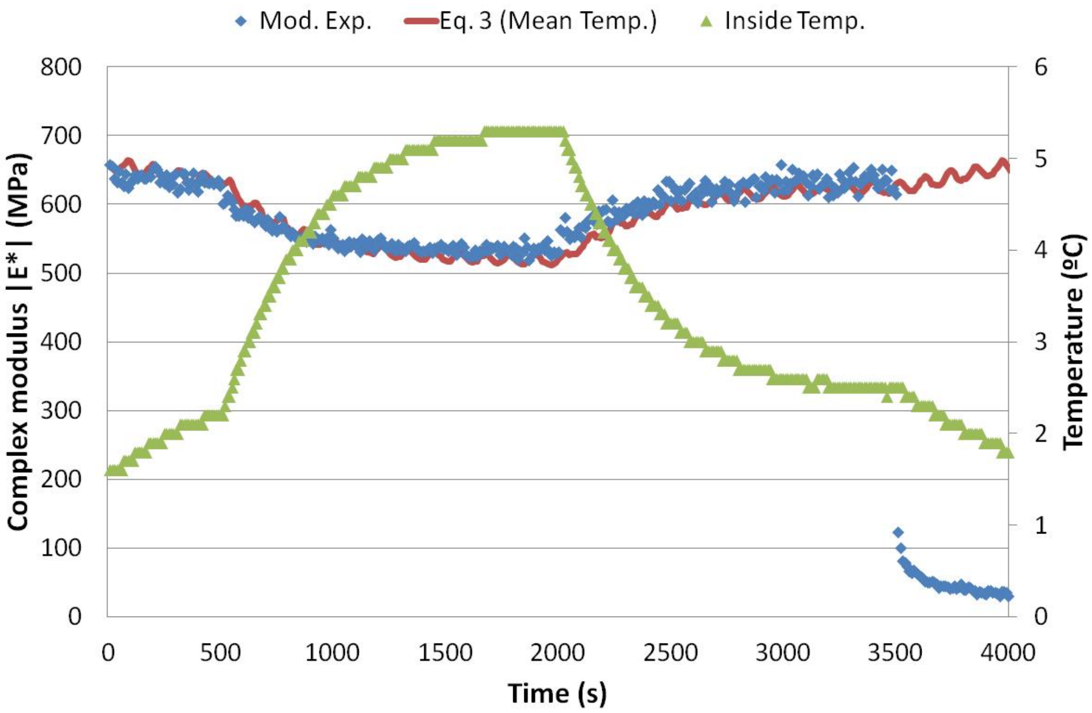

Figure 10. |E*| and inside temperature evolution during the test at 0ºC and 10 Hz. The |E*| predicted by equation 3 as a function of inside temperature is also presented.

At 0ºC there is an increase in temperature even at the lowest strain amplitude, i.e., 650 µm/m. The second strain section started before having reached the stabilization temperature for the previous strain level, which is around 2.5ºC as can be derived from the section between 3,000 and 3,500 seconds. The stabilization temperature at 1300 µm/m was 5.3ºC. In this case the |E*| values calculated using equation 3 and the approximation to the mean temperature of the specimen fit perfectly the experimental |E*| values obtained. Therefore, at 0ºC, all stiffness reduction can be explained by the specimen's temperature change.

Self-heating in Asphalt Mixtures

Although the component that gives the mixture most of its properties is the asphalt binder, the behavior of the final mixture is quite different from that of the binder. The mineral skeleton and the aggregate composition affect strongly the mechanical behavior of the mixture. However, having observed the importance of self-heating in cyclic testing of asphalt binders, an obvious question arises: Does self-heating takes place in asphalt mixtures?

To answer that question, a similar strain sweep test was designed to be performed on two asphalt mixtures using the EBADE configuration for these materials. In this case the time of application for each strain amplitude was limited to 500 seconds (or 5,000 cycles) to keep the test duration within practical limits. The lowest strain amplitude was 25 µm/m and the increase was of the same value. The tests were conducted at 20ºC and 10 Hz. Figure 11 shows the results obtained for gap-graded mixtures (BBTM) manufactured with a conventional binder (50/70) and an SBS polymer modified binder (PMB).

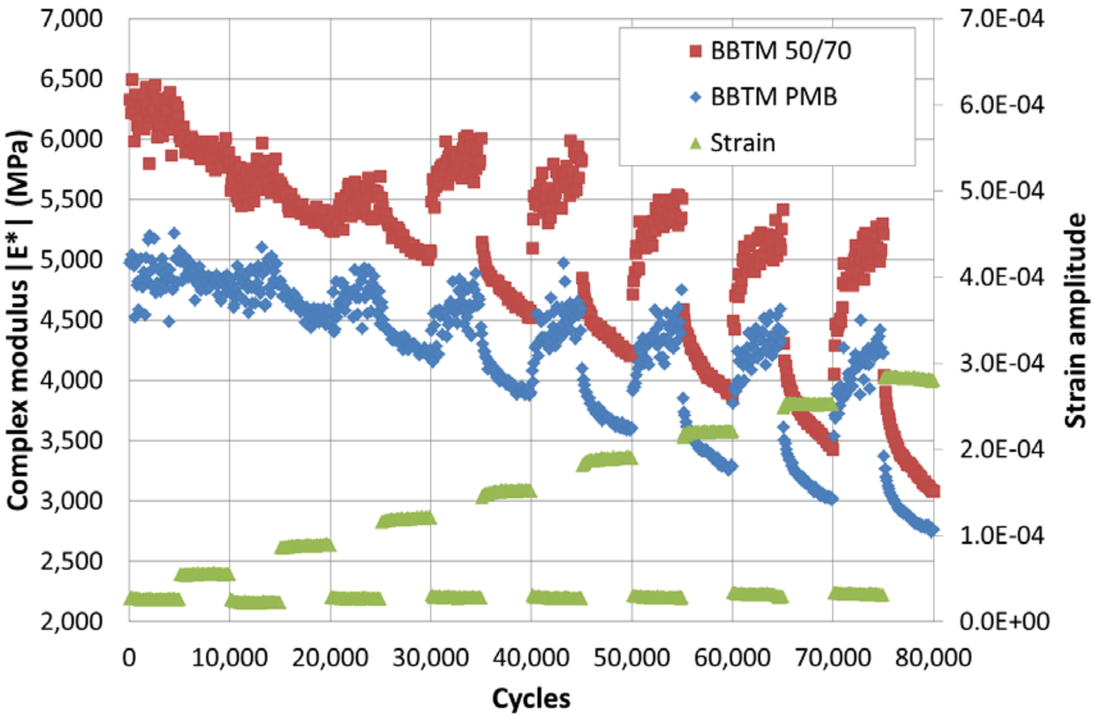

Figure 11. |E*| evolution in a strain sweep test at 20ºC and 10 Hz during the first 80,000 cycles.

The behavior observed in Figure 11 differs from that of the binder, Figure 4. In this case the |E*| values do not recover to their initial value at any of the intermediate low strain levels. This may be caused by the short duration of the strain sections (5,000 cycles) that did not allow the material to cool down after having been heated at a higher strain, or because some irreversible changes took place during those higher strain sections. However, the trend observed in the |E*|, especially from 30,000 cycles upwards, is quite similar to that exhibited by the binder, i.e., a nearly exponentially shaped drop when the strain amplitude increases, followed by a nearly logarithmically shaped increase when the strain amplitude is decreased. As expected, in this case there was no stabilization observed, since the time devoted to each strain level was three times shorter than in the binder test.

It is known that asphalt mixtures are also very susceptible to temperature changes, although not as much as the asphalt binder. Having proved that self-heating is the main mechanism that causes asphalt binder stiffness to reduce during the beginning of cyclic testing, it is very likely that this mechanism is also responsible for the modulus loss observed in the initial phase of cyclic testing of asphalt mixtures.

Embedding a thermocouple probe inside an asphalt mixture specimen represents a technical problem. If it is done during its manufacture, the probe can be crushed during compaction. If it is placed once the specimen has hardened, drilling is required, which would cause a defect in the bulk of the material, even if it is filled afterwards with asphalt binder. In any case, the integrity of the thermocouple probe may be compromised.

However, there is a kind of test that can indicate very clearly if the modulus loss is caused by self-heating or by any other irreversible phenomena, i.e., damage. Binder tests showed that the temperature increased during the first phase of cyclic testing until a stationary regime was reached. If the strain amplitude was high enough, the stabilization temperature at a certain point in the specimen increased over a limit at which this area became a defect in the bulk of the material causing failure. What would happen if the same strain amplitude is applied, but before the stabilization temperature is reached the test stops and the specimen is allowed to cool down before starting again? If it is just the temperature increase that is causing failure, then the test could go on indefinitely, as long as this temperature threshold is never reached.

Extrapolating this reasoning to asphalt mixtures, an experiment was designed. Using the mixture manufactured with the conventional binder, two tests were performed at the same constant strain amplitude (20ºC and 10 Hz). In the first one, a 10 minute rest period was applied every 200 cycles. The second one was a classical fatigue test, i.e., the strain amplitude was applied continuously. Figure 12 shows the results.

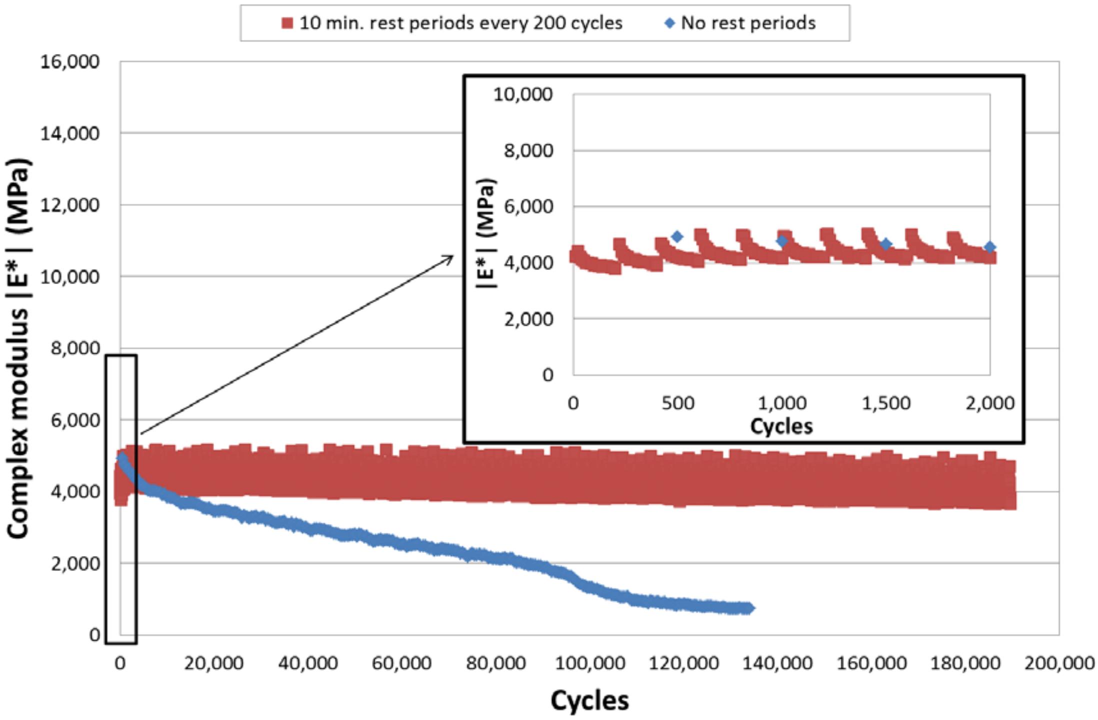

Figure 12. Comparison between the |E*| with and without rest periods. BBTM mixture with 50/70 binder at 20ºC and 10 Hz. Strain amplitude of 200 μm/m.

Without rest periods, the specimen exhibited a continuous loss of |E*| until it failed, at around 100,000 cycles, where a small deviation from the previous trend was observed in the |E*|-cycles curve. However, if the test was stopped every 200 cycles, avoiding an excessive temperature increase in the mixture, and allowing the temperature to lower for 10 minutes, the |E*| remained at the same values for almost double the number of cycles. Within each 200 cycles block, the |E*| loss was practically constant (around 800 MPa), and the maximum and minimum values remained between 5,200 and 3,800 MPa throughout the entire test for at least 180,000 cycles. Mangiafico et al. [18] were able to measure the temperature change inside an asphalt mixture specimen and found similar results in a similar test, i.e. increase in temperature during cycling and decrease to the original temperature during resting.

The results shown in Figure 12 not only indicate there is a high probability that self-heating causes the majority of the modulus loss observed during cyclic testing in asphalt mixtures, but also questions the validity of Miner's rule for these kinds of materials, hence the validity of the fatigue law concept. The Miner's rule states that the fatigue life consumption can be assessed as a linear combination of the different stresses applied during different durations, i.e., the material has a maximum number of cycles to failure at each stress amplitude and by accumulating cycles at different stresses the fatigue life of the material is shortened in proportion, regardless of the sequence in which these stresses are applied. However, if damage is assessed using any modulus related parameter and self-heating is acknowledged, rest periods can affect strongly the so-called fatigue life of the material.

CONCLUSIONS

This paper's objective was to evaluate the reversible phenomena that take place when asphalt materials are submitted to cyclic loads. Literature states that these phenomena are mostly self-heating and thixotropy. As explained in the introduction section of this paper, these two phenomena may or may not be related, depending on which definition of thixotropy is adopted.

The tests performed on asphalt binders in which the temperature at the geometrical center of the specimen was measured throughout the test showed that there is a significant increase in the inside temperature of the material. At 10.5ºC the inside temperature can double that value, while at 1.8ºC it can triple. Given the strong dependency of the mechanical properties of these materials on temperature, this phenomenon severely affected the test results. Furthermore, it was proven that, as expected, this phenomenon was reversible, i.e., the material heated when the loading amplitude was increased and cooled down when the loading amplitude decreased. The increase in temperature measured at constant loading amplitude fitted a linear correlation with the total amount of energy dissipated by the material. The data obtained from the master curve of the binder together with the temperature measurements help reproduce very closely the evolution of the norm of the apparent or effective complex modulus during the test. Therefore, indicating that most of the modulus variation during cyclic testing was caused by a change in the inner temperature of the material.

The type of failure observed in the binder specimen indicated that the inside temperature of the materials is highly inhomogeneous. Having recorded temperatures over 21ºC in the geometrical center of the specimen, the breakage left two smooth and flat surfaces, typical of fracture of binders at temperatures around 10ºC. This may be explained by a temperature gradient inside the specimen that caused a local area to soften in excess and act as a defect or a crack tip, which later propagated critically through areas of the binder at lower temperatures.

Given the results obtained in an asphalt binder, it was important to analyze to what extent this behavior replicates in asphalt mixtures. Due to several technical complications it was not possible to embed a thermocouple probe inside the asphalt mixture specimen. The same loading and unloading test configuration was applied to mixtures, obtaining very similar results in the evolution of both complex modulus and dissipated energy density, which indicated that there was also self-heating in mixtures. Finally, to further corroborate this point without measuring inside temperature, two cyclic tests were conducted. This comparison showed that if the loading amplitude was applied by blocks with long rest periods in between, the complex modulus did not vary outside of a constant range and the material may not fail at all. If the loading amplitude was kept constant without rest periods, the complex modulus suffered a continuous loss until failure took place, which is what normally happens in most cyclic tests. A temperature change in the bulk of the material would perfectly explain that difference in behavior: When constant loading amplitude is applied, the temperature of the material increases, reducing its stiffness. If the temperature increases too much, the stiffness of the material becomes too low and the specimen starts to become irreversibly damaged and the test ends in a finite number of cycles. However, if the loading amplitude is applied discontinuously, the temperature increase during loading lowers during rest periods, and the temperature can never build up in the material to the critical value that leads to failure.

This last result represents an important finding. In pavement engineering very often the fatigue law of asphalt mixtures is used to predict the pavement life. However, traffic loads are far from constant, and several rest times take place between loading cycles in the field. In addition, two vehicles do not necessarily pass over the same exact section. Therefore, a temperature buildup such as the one observed in laboratory continuous cyclic tests is highly improbable in the field. In addition, the reversibility of the self-heating phenomenon totally invalidates Miner's rule, which is the basis of most calculus models that predict pavement life.

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