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Ageing and temperature effect on the fatigue performance of bituminous mixtures

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ABSTRACT: The ageing of asphalt mixes, together with their exposure to low temperatures, causes a progressive increase of cracking. In this paper, the effect of ageing and temperature on the fatigue of asphalt concretes made with two types of binders, conventional (50/70) and polymer modified bitumen (PMB), is studied. For this purpose, specimens previously subjected to an accelerated laboratory ageing process were tested by a strain sweep test at different temperatures (-5ºC, 5ºC and 20°C). Results were compared with the obtained from the unaged specimens showing the relative importance of ageing, temperature and type of bitumen on the parameters that determine the fatigue life of the mixture. The mixtures behaviour becomes more brittle with ageing and the decrease of temperature. However, ageing hardly has an effect on fatigue at lower temperatures. In general, mixtures made with polymer modified bitumen have a better fatigue performance to ageing and temperature.

KEYWORDS: Ageing; Temperature; Fatigue; Bitumen; Asphalt concrete

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RESUMEN: *Efecto del envejecimiento y de la temperatura en el comportamiento a fatiga de las mezclas bituminosas*. el envejecimiento de las mezclas, unido a su exposición a bajas temperaturas, provoca un progresivo aumento de su fisuración. En este trabajo, se estudia el efecto del envejecimiento y la temperatura en la fatiga de una mezcla semidensa fabricada con dos tipos de ligantes, 50/70 y PMB 45/80-65. Para ello, probetas previamente sometidas a envejecimiento acelerado en laboratorio fueron ensayadas mediante un ensayo de barrido de deformaciones, a diferentes temperaturas (-5, 5 y 20ºC). Los resultados fueron comparados con los obtenidos en mezclas no envejecidas mostrando la importancia del envejecimiento, temperatura y ligante sobre los parámetros que condicionan la vida a fatiga de la mezcla. El comportamiento de las mezclas es más frágil debido al envejecimiento y la disminución de la temperatura. Sin embargo, el envejecimiento apenas influye en la fatiga a temperaturas bajas. En general, las mezclas con betún modificado muestran mejor respuesta a fatiga frente a envejecimiento y temperatura.

PALABRAS CLAVE: Envejecimiento; Temperatura; Fatiga; Betún; Mezclas asfálticas

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1. INTRODUCTION

Asphalt layers suffer a progressive deterioration when they are exposed to repeated loads caused by traffic and environmental conditions such as heat, wind, rain or ultraviolet radiation. All of these factors lead to an increase of cracking of the asphalt layers in the pavement structure, which leads to them breaking up (1).

An important factor in cracking resistance of mixtures due to fatigue is ageing (2). This phenomenon causes, firstly, bitumen hardening which affects the rheological and mechanical properties of the mixture (3). It causes a change in their behaviour which goes from ductile to brittle. Bitumen hardening due to ageing is a convergence of several processes (4). It can be attributed to a chemical ageing and physical ageing or steric hardening (5, 6). Chemical mechanisms, volatilization and oxidation are irreversible whereas steric hardening is reversible and is due to a structural rearrangement.

Ageing occurs in two stages (7, 8): short-term ageing and long-term ageing. Short-term ageing takes place at the time of manufacture and laying of the hot mix. This stage is characterized by the mixture undergoing volatilization and oxidation very quickly (the process is carried out within hours). Long-term ageing is associated exclusively to the degradation due to the environment and it occurs during the service life of the mixtures. In this case, pavement surface molecules react with ambient conditions and, in consequence, oxidation occurs. In contrast to the first stage, this process is slow and its effects are detected over the years.

There are a number of methods for artificially ageing bituminous mixtures in the laboratory. The basic procedure involves exposing the mixture to high temperatures for a specified period of time. Much of the research on ageing in asphalt mixtures follows the ageing procedure established by the SHRP (9). This procedure is divided into the STOA (Short Term Oven Ageing) and the LTOA (Long Term Oven Ageing). STOA consists of ageing the loose mixture in an oven for 4 hours at 135ºC. To age the mixture over the long term, LTOA, mixtures previously subjected to a short-term ageing are compacted and maintained in the oven for 5 days at 85ºC. A new ageing procedure has been established within the framework of the RILEM technical committee. This procedure involves ageing the loose mixture for 4 hours at 135°C in the case of short-term ageing. For long-term ageing, the loose mixture is aged at 85°C for 9 days (10). Piérard and Vanelstraete (11) developed a new test called BRRC ageing. It consists of placing the loose mixture in the oven at 135°C for 1.5 hours for short-term ageing. For long-term ageing, the procedure involves ageing the loose mixture for 14 days at 60°C.

A bituminous mixture should be designed and manufactured not only to withstand the traffic loads imposed, but also the action of the environment (12). It is necessary to carefully investigate all the variables that influence ageing. In fact, the ageing of asphalt mixtures depends on multiple factors, such as temperature, air and water, which therefore can have a great effect on the durability of asphalt mixtures (13). In the case of temperature, bituminous mixes show significant changes in their mechanical properties due to differences in the thermal susceptibility and the viscoelastic behaviour of the bitumen (14). Studying the behaviour of the mechanical properties of bituminous mixtures at low and intermediate temperatures is vitally important (15). In that temperature range, cracking due to mechanisms associated with fatigue failure by application of repeated loads, thermal stress cracking or a combination of both occurs.

The fatigue behaviour of bituminous mixtures has been studied extensively in the last four decades. Because of the fact that it is a complex phenomenon and is influenced by many factors, there is not now a universal testing procedure to characterize it completely. The classical fatigue tests, described in the current standards (EN and ASTM), are time sweep tests. They are usually based on the application of a cyclic load under controlled conditions of strain or stress until failure of the mixture occurs.

In order to estimate the fatigue law, several samples are tested under different amplitudes of stress/strain (16). To reduce the time needed to determine the fatigue law of a mixture, cyclic load tests in a strain sweep mode can be used. In these tests, the cyclic load is applied with an increase of strain amplitude until failure (17).

The paper presented here studies the effect of ageing on the fatigue behaviour of an asphalt mixture. This mixture, a bituminous concrete type, is made with two types of bitumen, a penetration bitumen and a polymer modified bitumen. The fatigue behaviour will be analyzed at different temperatures by applying a strain sweep test, called EBADE (the initials of the strain sweep test in Spanish, Ensayo de Barrido de Deformaciones) (18).

2. EXPERIMENTAL STUDY

A semi-dense bituminous mixture was selected to study the effect of ageing on the fatigue behaviour of bituminous mixtures. This type of mixture was an asphalt concrete (AC16S, according to the Spanish Specifications) and the particle size was centred on the envelope (Figure 1). The mixture was manufactured with two types of bitumen, a conventional 50/70 penetration bitumen and a polymer modified bitumen, PMB 45/80-65. The bitumen characteristics are shown in Table 1. The binder content for the manufacture of the mixture was 4.5% by weight of the mixture. At least three replicates were tested for each condition studied. The experimental study carried out is shown in Table 2.

Long-term ageing of the mixture was simulated in the laboratory by maintaining the loose mixture at 85ºC for 7 days. During the ageing, the mixture was stirred three times, on days 2, 4 and 5, with a time interval between agitations greater than 24 hours. Although the RILEM recommendations establish 9 days, De La Roche, *et al*. (10) concluded that the results of 7 days of ageing were good enough (19).

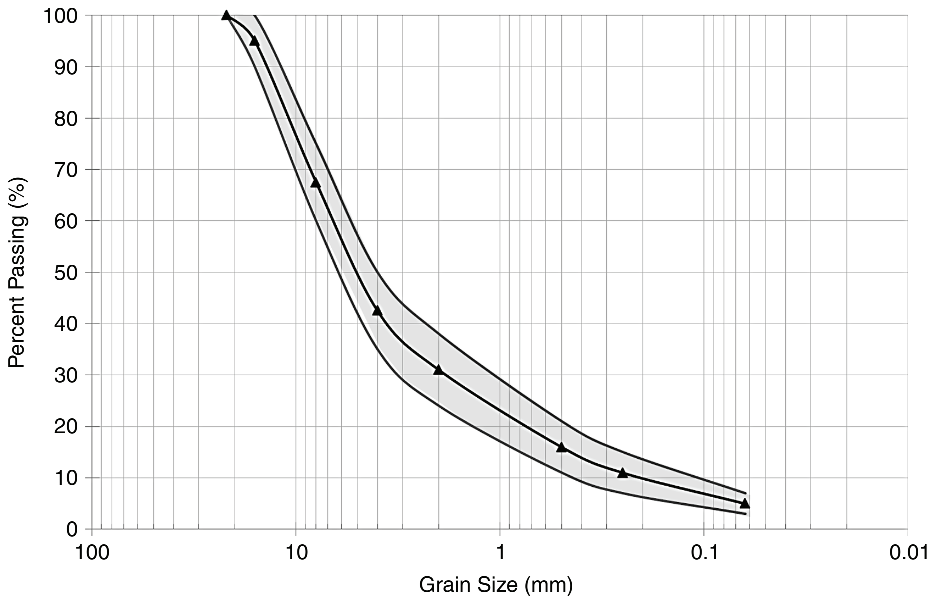

FIGURE 1. Grain size distribution for the mixture AC16S.

TABLE 1. Bitumen characteristics

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

TABLE 2. Summary of the experimental study carried out

Mixture	Bitumen	Conditioning	Test temperature (ºC)
AC16S	50/70	Unconditioned	−5
			5
			20
		Aged	−5
			5
			20
	PMB 45/80-65	Unconditioned	−5
			5
			20
		Aged	−5
			5
			20

Furthermore, it seemed that the ageing procedure established by the RILEM committee led to a greater ageing of bitumen compared with classical bitumen ageing tests.

Unaged and aged specimens were tested by EBADE test to evaluate the fatigue behaviour of the mixture and analyze the effect of ageing. This test consists of performing a sweep strain in a cyclic tension-compression test. The test is performed by applying a number of cycles at a constant level of strain, which increases gradually in magnitude until the material failure occurs. The EBADE test can be performed at different temperatures. In this case, the test was performed at -5ºC, 5ºC and 20ºC. These temperatures allowed the effect of medium and low temperatures to be evaluated where the fatigue response of the mixture could be more critical.

In the execution of the test, a prismatic specimen was used. Two slots were made in the central area of the specimen to reduce the area in its middle section and induce its failure. Although dimensions of the specimens are not fixed, they are usually 5-6 cm wide and long, and 6-9 cm high (Figure 2).

During the test, cyclical series of 5,000 repetitions were applied at different strain amplitudes in ascending order at a frequency of 10 Hz. 5,000 cycles were chosen because they are enough to observe the tendency of the dissipated energy density and also allowed the test to be carried out more quickly than the time sweep tests (20). The frequency of 10 Hz is common in fatigue tests and is related to the vehicle speed and the application of loads on the asphalt pavement. Each stage of 5,000 cycles at the same strain amplitude is called a step. The strain amplitude in the first step was 25 μm/m, and every 5,000 cycles the strain was increased by 25 μm/m until the material failure occurred. In this way, the number of cycles and strain amplitude will be directly related. The failure of the mixture was established as the cycle in which the maximum dissipated energy density obtained during the test was reduced by 50%, and the failure strain was obtained for this cycle.

The modulus and dissipated energy density during each cycle of the test were calculated as shown in equations [1] and [2].

$$\left|E^*\right| = \frac{\sigma_{max}}{\varepsilon_{max}} \qquad [1]$$

$$DED = \frac{1}{2}\Big|\left(\sigma_1\varepsilon_2 + \sigma_2\varepsilon_3 + \ldots + \sigma_{n-1}\varepsilon_n + \sigma_n\varepsilon_1\right) - \left(\sigma_2\varepsilon_1 + \sigma_3\varepsilon_2 + \ldots + \sigma_n\varepsilon_{n-1} + \sigma_1\varepsilon_n\right)\Big| \qquad [2]$$

where $\sigma_i\varepsilon_i$ are the n values of stress and strain obtained during each cycle in a clockwise or anticlockwise direction.

The cumulative dissipated energy density was obtained as the sum of all dissipated energy densities, as shown in equation [3].

$$DED_c = \sum_{i=1}^{n} DED_i \qquad [3]$$

3. RESULTS AND DISCUSSION

3.1. Complex modulus and energy evolution with the number of cycles

Figures 3 and 4 show the evolution of the complex modulus during the test for both types of bitumen respectively. Tests on unaged and aged mixtures were performed under three test temperatures (-5ºC, 5ºC and 20ºC). These figures allow the progressive deterioration of the mixture to be observed during fatigue under different study conditions.

On analyzing the effect of the temperature, firstly, an increase of the initial modulus of the mixture was observed with the decrease of temperature, as was expected. Secondly, on analyzing the evolution of the modulus with the number of

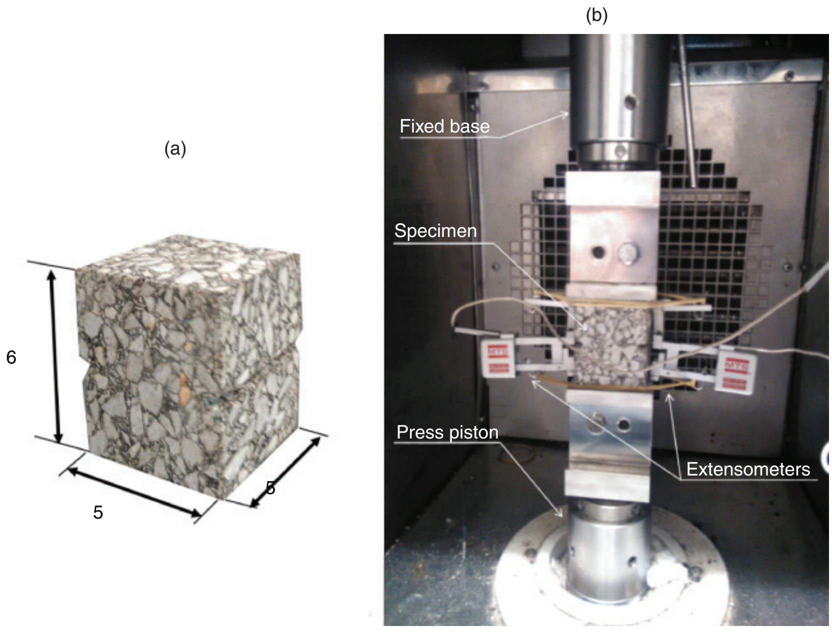

FIGURE 2. (a) Specimen dimensions (cm) and (b) specimen during the EBADE test.

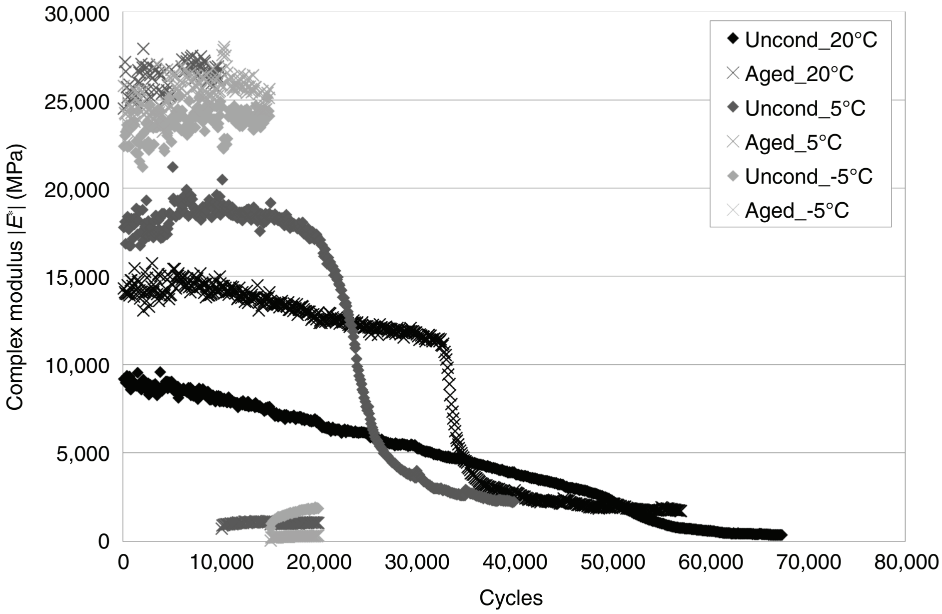

FIGURE 3. Complex modulus, |E*|, versus cycles for the unconditioned (Uncond) and aged mixtures. Bitumen 50/70.

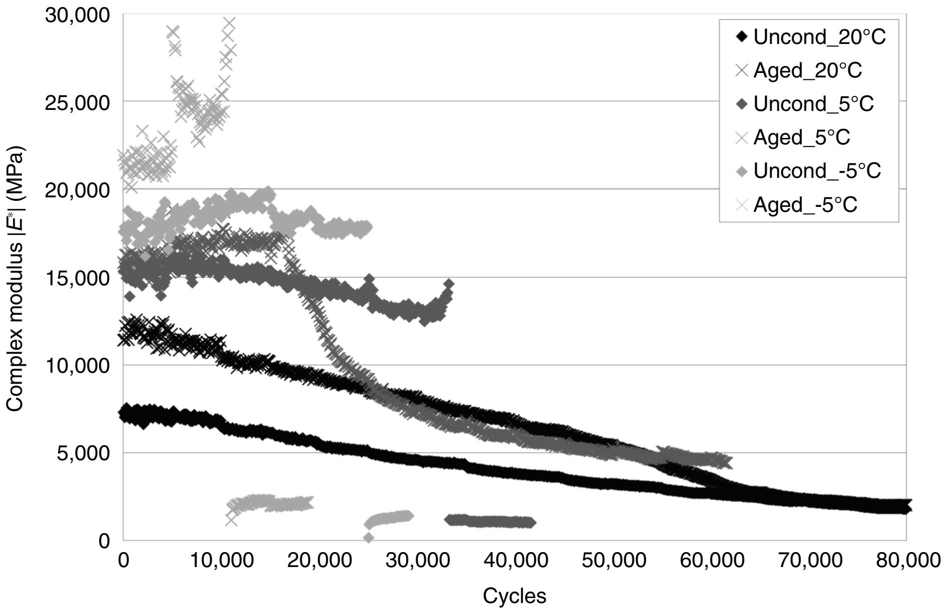

FIGURE 4. Complex modulus, |E*|, versus cycles for the unconditioned (Uncond) and aged mixtures. Bitumen PMB 45/80-65.

cycles, the behaviour observed was clearly different for the different test temperatures considered in this study. At a temperature of 20°C, the modulus tended to decrease progressively as the number of cycles in the test increased. However, the modulus fell more quickly from a certain number of cycles for a temperature of 5ºC. Until then, the value of the modulus tended to remain constant, being quite close to the initial modulus, and the drastic drop of the modulus showed the brittle behaviour of the mixture at low temperatures. At a temperature of -5ºC, the behaviour was even more brittle. In this case, the modulus remained constant until the specimen broke, going from the initial value to a residual value close to zero in the same step.

If the behaviour of each bitumen is compared, the modified bitumen presented initial modulus values lower than those achieved with conventional bitumen for each temperature studied. In addition, the modified bitumen for each temperature was able to withstand a higher number of cycles to reduce the value of the modulus and, therefore, before breaking.

Finally, the ageing effect was analyzed. It was observed that the initial modulus of the aged mixture increased substantially with regard to the modulus of the unaged mixture, both for the mixture manufactured with conventional bitumen (50/70) and for the mixture made with modified bitumen (PMB 45/80-65). However, for the degree of ageing considered in this work, the increase of the initial modulus due to the ageing of the mixture was less than that produced due to the test temperature decrease. At low temperatures (-5°C), ageing hardly affected the complex modulus especially in the case of the mixture made with conventional bitumen. At that temperature, the mixture had such a rigid behaviour that the modulus could no longer increase.

In any case, the mixture increased its modulus as it was stiffened either by ageing or by decreasing the temperature. This produced a decrease in the number of cycles that the mixture could withstand before the modulus decreases.

Figures 5 and 6 show the variation in dissipated energy density with the number of cycles for the mixture manufactured with conventional bitumen 50/70, and the polymer-modified bitumen, PMB 45/80-65, respectively, for the different study conditions (unconditioned or aged and for the test temperatures of -5ºC, 5ºC and 20°C). The fatigue failure criterion of the mixture was established from the curve of dissipated energy density as the level of strain in which the maximum dissipated density was reduced to half. It is noted that the trends for each of bitumen were similar, the mixture manufactured with modified bitumen showing higher values of the dissipated energy density.

The greater the maximum dissipated energy density, the higher the temperature, the curves in the figures tended to move to the right, which means a greater number of cycles to halve the peak of the dissipated energy density. The mixture was capable of withstanding fewer strain steps before the mixture failed when the temperature decreased. This showed a sudden change in the dissipated energy density, this was more pronounced at lower temperatures, similar to the trends observed for the modulus of the mixture.

These figures also show how unaged mixtures, made from either of the bitumens, could accumulate a larger amount of dissipated energy during the fatigue process than the aged mixtures (as was the case with the mixture tested at the highest temperature).

In the case of unaged mixtures, several strain steps were necessary for the mixture failure to occur, once the energy in each cycle started to decrease. Whereas mixtures broke faster (for a lower number

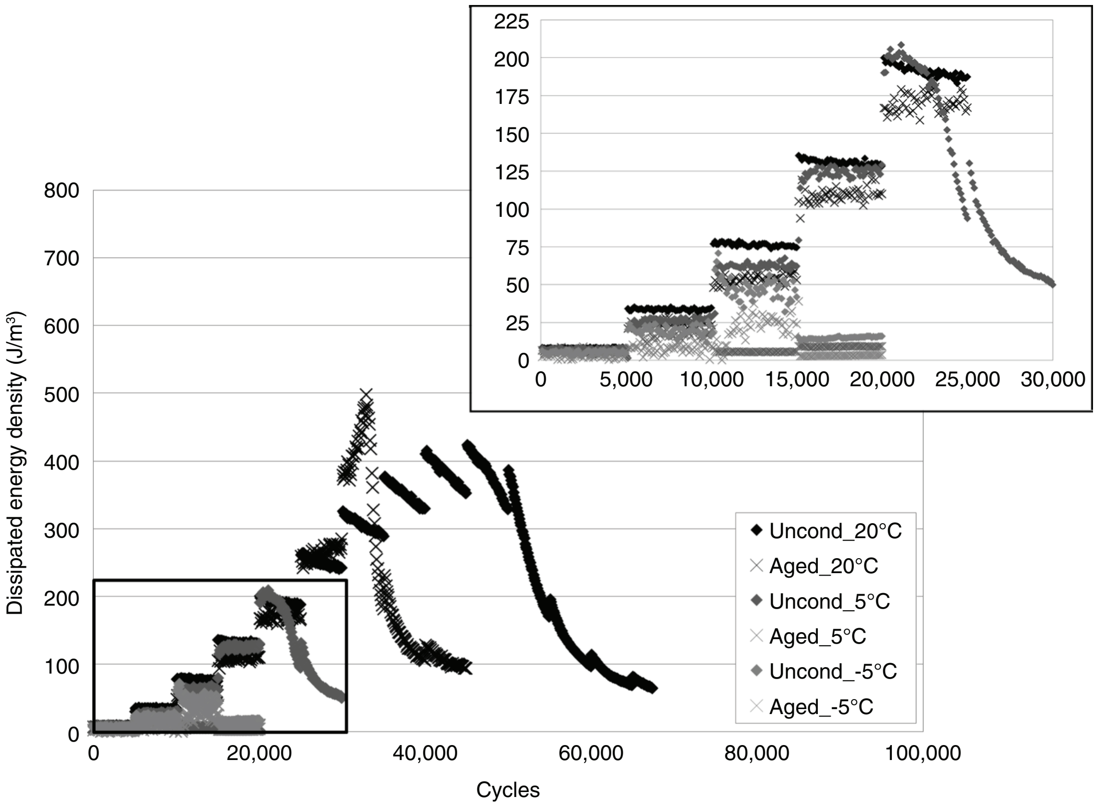

FIGURE 5. Dissipated Energy Density versus cycles for the Unconditioned (Uncond) and aged mixtures. Bitumen 50/70.

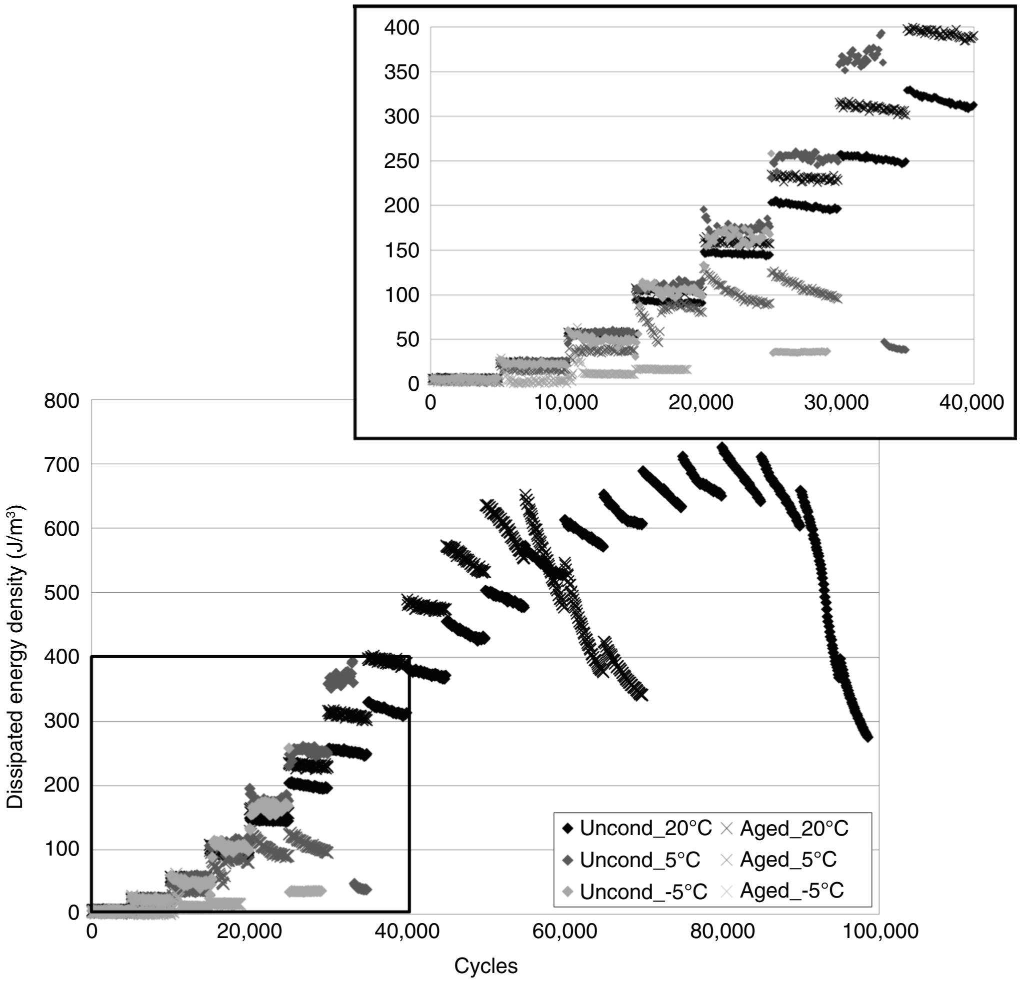

FIGURE 6. Dissipated Energy Density versus cycles for the unconditioned (Uncond) and aged mixtures. Bitumen PMB 45/80-65.

of cycles) and more abruptly (less steps) when they were aged, showing a more brittle behaviour (21).

The response of both bitumens is compared. The mixture made with the modified bitumen (PMB 45/80-65) showed how it not only dissipated more energy than the mixture made with conventional bitumen (50/70), but also several strain steps were necessary for breaking after ageing. However, the mixture made with conventional bitumen broke in a single strain step. This fact was also observed when the temperature decreased, indicating that the modified bitumen has a better performance against ageing and temperature variation. Nevertheless, for a very low temperature test, the behaviour of both bitumens was similar, showing that the type of bitumen has less effect on the behaviour of the mixture.

3.2. Studied parameters: initial modulus, failure strain and cumulated energy from the EBADE test

Figure 7 presents the initial modulus values for all conditions of the study. These values were calculated as the complex modulus average in the first 5,000 cycles of the test, i.e. the average in the first strain step. In general, the initial modulus increased with the decrease of temperature and ageing of the mixture. Although in the case of the mixture manufactured with modified bitumen, the differences between the initial modulus at 5ºC and -5ºC were minimal. On the other hand, the effect of test temperature on the initial modulus was greater than the effect of ageing, for the degree of ageing the specimens were subjected to. These results coincide with the obtained by Moreno-Navarro, *et al*. (22). If the temperature is too low, the initial modulus tends to be quite similar whether or not the mixture is aged, especially in the case of the mixture made with conventional bitumen.

According to the failure criterion specified in the EBADE test, the failure strain was defined as the value equivalent to the strain step in which the maximum dissipated energy density was reduced to half. The failure strain values for all the conditions of the study are shown in Figure 8. It is noted that the failure strain significantly decreased as the

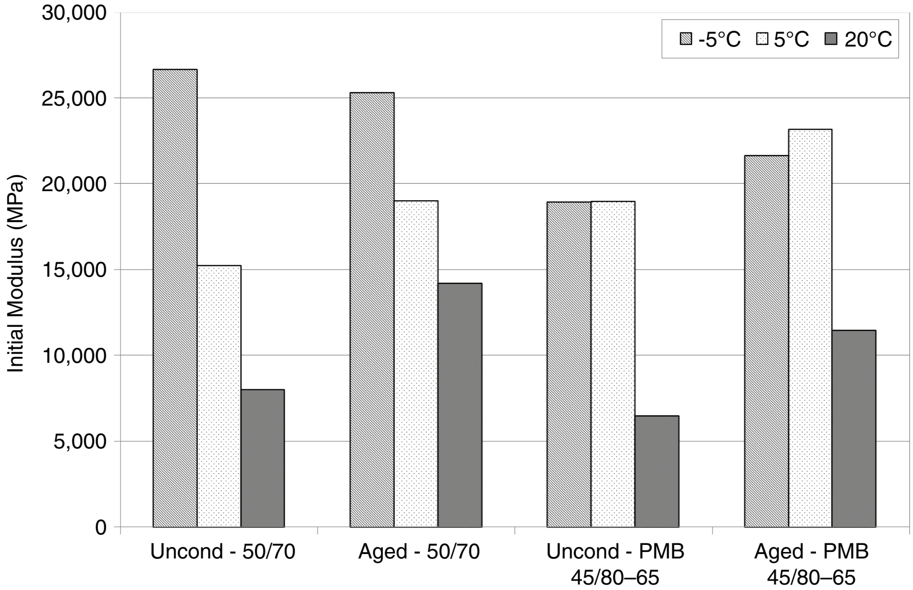

FIGURE 7. Initial modulus for the unconditioned (Uncond) and aged mixtures.

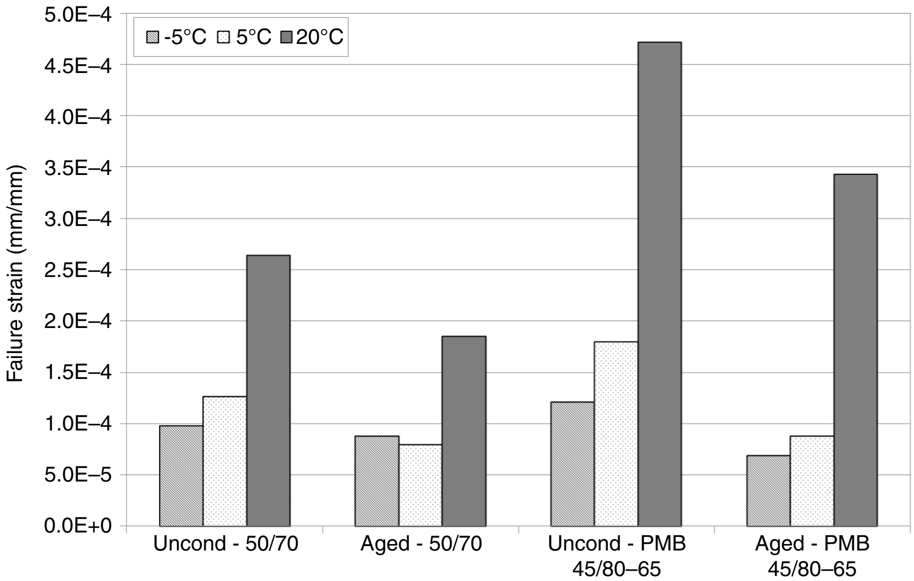

FIGURE 8. Failure strain for the unconditioned (Uncond) and aged mixtures.

temperature decreased from 20ºC to 5°C. When the temperature fell from 5ºC to -5ºC, it decreased much more slowly, regardless of the type of bitumen and ageing condition. This is probably because the effect of a low temperature was so severe that, even modifying other properties of the mixture, the variations between both of them were minimal. Moreover, it was observed how the failure strain decreased with ageing. But, as stated before, test temperature had a greater effect than ageing, causing the mixture to break due to the low temperatures rather than as a result of ageing.

Finally, by comparing the response of both bitumens it was shown that the modified bitumen resisted higher strain before breaking, for all the conditions studied. Nevertheless, it was also observed that the modified bitumen mixture was more susceptible to the effects of ageing and temperature than the conventional bitumen one. Similar conclusions were obtained by Miró, *et al*. [23].

Comparing the values of the initial modulus with the failure strain values, failure strain increased as the initial modulus values decreased. This indicates that the increase in the stiffness of the mixture increases its brittleness, and it can withstand lower strain values.

Figure 9 shows the values of cumulative dissipated energy density for the different conditions of the study. It is noted that the accumulated dissipated energy density for the mixture decreased when the test temperature was low. Again, it was found that the variation between 5ºC and -5°C was relatively small, especially for the mixture made with conventional bitumen. At low temperatures, the stiffness of this mixture was so high that its behaviour tended to be similar regardless of the current state (unaged or aged) or composition (made with conventional or modified bitumen).

On the other hand, cumulative dissipated energy density for the mixture made with conventional bitumen was noticeably lower than the one made with modified bitumen for medium test temperatures. In either case, it decreased as the mixture aged.

Figure 10 shows the variation of the failure strain against the initial modulus for the conditions of the study. It was observed that the increase of the initial

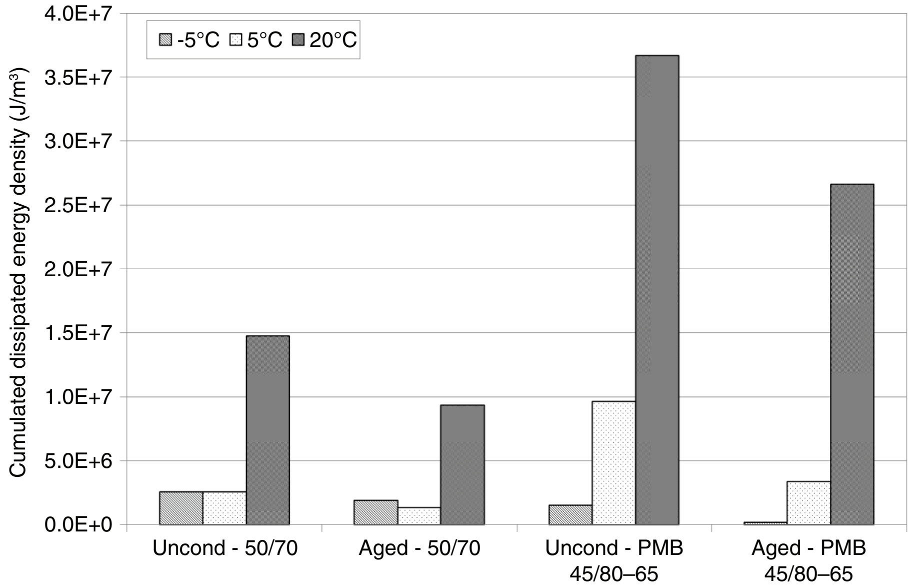

FIGURE 9. Cumulated dissipated energy density for the unconditioned (Uncond) and aged mixtures.

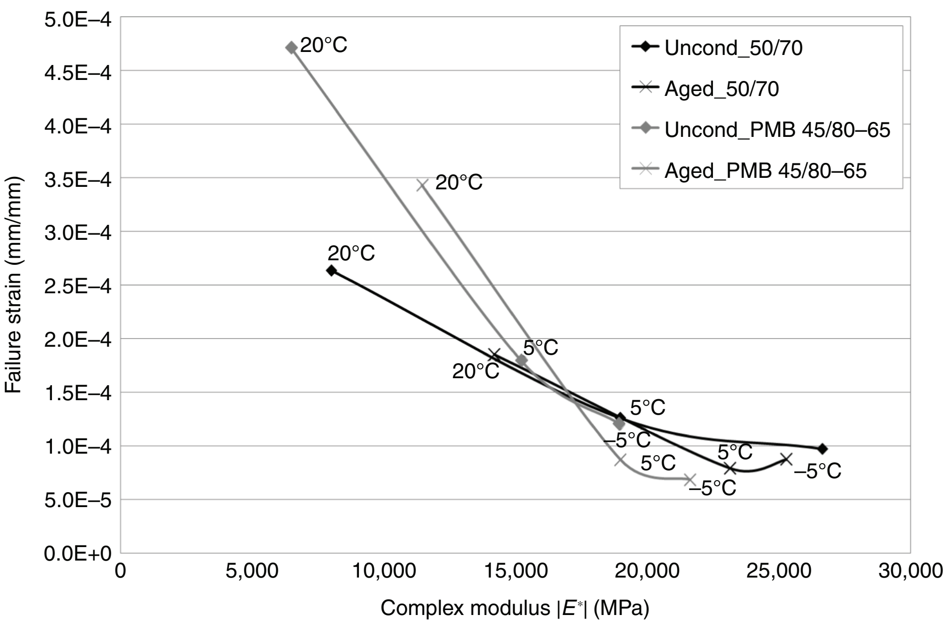

FIGURE 10. Failure strain versus complex modulus, |E*|, for the unconditioned (Uncond) and aged mixtures.

modulus resulted in a decrease in the strain. This fact occurred both with the decrease of the test temperature and the ageing of the mixture. Both factors stiffened the mixture, which increased the initial modulus, and at the same time, weakened it. This was reflected by a decrease in the failure strain.

The curves obtained when the temperature of the unaged and aged mixtures decreased for each of the bitumen almost overlapped and tended to converge in one area, regardless of the type of bitumen used. Although the range of values through which they move and how quickly was different for each bitumen. So, the mixture made with modified bitumen started from lower modulus values and higher strain values (at 20°C without ageing) than the mixture made with conventional bitumen. Furthermore, the slope of the modulus-strain curve was greater for the mixture manufactured with modified bitumen than for the one made with conventional bitumen.

The convergence of the curves suggests that, regardless of the type of bitumen used and the conditions to which the mixture was subjected (more or less aged), critical values of modulus and failure strain is reached by lowering the temperature. These values are characteristics of each type of mixture.

4. CONCLUSIONS

In this paper the effect of ageing, test temperature and type of bitumen in the fatigue behaviour of a semi-dense bituminous mixture, a bituminous concrete type, have been studied. A tension-compression strain sweep test, EBADE test, was applied. For this, the mixture was manufactured from two different bitumens (a conventional bitumen, 50/70, and a polymer modified bitumen, PMB 45/80-65). This mixture was aged rapidly in the laboratory by keeping the loose mixture in an oven at 85°C for 7 days. Specimens were tested at different temperatures (-5ºC, 5ºC and 20°C), and their response compared with the same mixture unaged.

The EBADE test allows the progressive deterioration of the mixture to be shown with the number of cycles both from the change in the modulus and from the dissipated energy density during the fatigue process. However, this variation is highly dependent on the three variables analyzed in this study: the test temperature, the degree of ageing and the type of bitumen.

For medium temperatures (20°C), the modulus decreases progressively with the number of cycles. But on lowering the temperature, the modulus values suffer a sharp drop from a certain number of cycles. The more brittle behaviour of the mixture is pointed out. As the temperature decreases, the mixture is able to withstand fewer strain steps (fewer number of cycles) before the mixture fails. A more sudden change in the dissipated energy density is shown, the lower the temperature, the sharper the change.

The ageing of the mixture causes the initial modulus to increase substantially compared to the unaged mixture. However, the effect of ageing (for the degree of ageing considered in this work) is smaller than the temperature effect, since the increase of the initial modulus due to the ageing of the mixture is lower than the effect of the test temperature.

As the mixture ages, failure occurs at a lower number of cycles and more steeply (for fewer load steps) than when the mixture is unaged, due to its high degree of brittleness. But at lower temperatures (-5°C), ageing hardly affects the modulus of the mixture. At these temperatures, the mixture displays such stiffness behaviour that the modulus can no longer increase. So its condition (aged or unaged) hardly influences its fatigue life.

The use of different types of bitumen has a significant effect on the fatigue behaviour of the mixture at medium temperatures. In general, although the mixture made with polymer modified bitumen is more susceptible to the effects of ageing and temperature than the one made of conventional bitumen, it has a better response to ageing and temperature. It was shown to be less brittle with a higher failure strain than the mixture made with conventional bitumen. However, the stiffness of the mixture at low temperatures is so high that its behaviour tends to be similar regardless of the type of bitumen used.

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