Effect of ageing and temperature on the fatigue behaviour of bitumens

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Abstract

Bitumen ageing plays a significant role in determining the resistance of asphalt mixes to fatigue cracking. Regardless of the type of ageing (oxidation during manufacture or during the service life), hardening effects increase the risk of cracking. The objective of this work is to examine the combined effect of the loss of volatiles and oxidation produced during ageing on the fatigue behaviour of the bitumen. To this end, different types of bitumen were subjected to accelerated ageing in the laboratory, simulating long-term ageing (RTFOT+PAV). They were then subjected to traditional tests (penetration, softening point, Fraass fragility point, dynamic viscosity, etc.), Dynamic Shear Rheometer tests (frequency and temperature sweep), and the EBADE test (a fatigue strain sweep test at different temperatures). Different temperatures have been used to evaluate the effect of visco-elastic phenomena on aged binder fatigue. The results showed that, in terms of their response to ageing, modified binders show a higher rate of variation in their general properties than conventional binders. In addition, it was shown that temperature plays an important role in the impact of ageing on the fatigue response of bituminous binders, and in the same way, in the mechanical response of these materials.

Keywords: bitumen; fatigue; ageing; temperature; DSR; strain sweep test.

1. Introduction

The ageing of bitumen plays a critical role in determining how asphalt mixtures are able to resist fatigue cracking [1]. Bitumen hardening due to ageing is primarily linked to two factors; one is the loss of volatile components and bitumen oxidation that occurs during the manufacture of asphalt mixtures and the other is the progressive oxidation of the material during the service life of the mixture. Both factors cause an increase in bitumen viscosity and a consequent stiffness of the mixture.

From a mechanical viewpoint, it is universally accepted that ageing takes place in two stages [2]. The first stage, known as short-term ageing (STA), occurs during asphalt mixing and laying. The second stage, referred to as long-term ageing (LTA), results from the environmental conditions that prevail during the service life of the mixture, although its effect is greater at the pavement surface, and decreases with depth.

Hardening due to ageing is the result of several processes that occur during the life of asphalt mixtures [3] and can be attributed to chemical ageing and physical ageing or steric hardening [4, 5].

Physical ageing is a reversible process that consists of a re-orientation of the molecules in the bitumen structure, combined with the slow crystallization of waxes at room temperature [6]. This process results in increased viscosity (without chemical modification) of the bitumen components. This phenomenon can be reversed through heat or mechanical work [7].

Chemical ageing is the most important and complex process, and includes loss of volatiles, exudative hardening, and oxidation process. Together, these three chemical processes lead to a hardening of the mixture [8] caused by the ageing of the bitumen, which becomes hard and brittle [9]. The oxidation and volatilization processes, slow at room temperature, are accelerated when the bitumen is exposed to high temperatures, such as during the manufacturing, transportation, and laying of the mixture. Unlike physical hardening, this process is irreversible.

Volatilization only plays an important role during the manufacturing of asphalt concrete (at high temperatures), i.e., this process is linked to short-term ageing of the bituminous mixture. Temperatures reach and exceed 150°C, causing lighter fractions of the bitumen to evaporate. An additional temperature of 10-12°C could double the emissions of volatiles [8].

With respect to the oxidation process, it is known that oxygen diffuses rapidly through interconnected air voids following compaction of the mixture. Gradual chemical reactions between oxygen and the aggregate-binder interface then appear. This phenomenon, known as "oxidative ageing" [10, 11, 12], is one of the most important factors that substantially contributes to the hardening and embrittlement of the mixtures. This process leads to an increase in stiffness and a decrease in ductility that most probably affects the resistance of the mixture to cracking [13], thereby reducing the fatigue life of the pavement [14]. In addition, recent studies have demonstrated that UV photo-radiation could considerably increase the rate of oxidation of bituminous binders, and compared with thermal ageing, it could be dominant in the increase of binder’s hardening [15].

Regardless of the type of ageing, hardening effects increase the risk of cracking. Bitumen loses its ability to relax the stresses suffered under repeated traffic loads and during the cooling process [16]. This is the reason why durability problems are closely linked to the ability of the bitumen to resist oxidation and/or physical hardening.

Among the most influential variables involved in ageing is the composition of the bitumen. Bitumens derived from various crude oils have differing compositions and therefore do not have the same sensitivity to ageing. This is particularly important in the case of polymer-modified bitumens, where polymer degradation must also be considered [17], since it could reduce the effectiveness of the modification [18]. In this sense, it must be remarked that the oxidation produced after ageing may lead to more or less important modification of the mechanical response of bituminous binders according to their original composition [19].

Temperature appears to be the extrinsic variable which plays the most important role in bitumen ageing, since during the manufacturing of the asphalt mixture the bitumen is heated to high temperatures, promoting the volatilization of some bitumen components and polymerization of some molecules. Depending on the temperature, there are considerable variations in the degree of ageing [20].

Based on all these considerations, it can be said that one of the main aspects affected by ageing would be the long term mechanical behaviour of bituminous materials, and therefore their resistance to fatigue (as the effect of oxidation is produced progressively and affects the visco-elastic response of the bitumen). Nonetheless, the evaluation of this phenomenon on asphalt binders through the variation of stiffness modulus is not an easy task due to the co-existence of fatigue damage with other visco-elastic phenomena (plastic flow, thixotropy, heating, etc.) that also produce changes on this property, but they are not related to fatigue damage [21]. In this respect, several authors have shown that to evaluate “true” fatigue in asphalt binders it is necessary to conduct the tests under certain temperature conditions [22, 23], to ensure that the stiffness provided by the material is enough to avoid the appearance of such visco-elastic phenomena that could hide real damage. Thus, temperature conditions would also play an interesting role in the effect caused by ageing on the fatigue resistance of bituminous binders.

The objective of this work is to analyse precisely the combined effect of both the loss of volatiles, and oxidation produced during ageing, on the fatigue behaviour of bitumen. In addition, the influence of temperature conditions and the presence of biased visco-elastic phenomena have been also assessed. In order to achieve this, different types of bitumen were subjected to accelerated ageing in the laboratory by RTFOT and PAV, simulating LTA and then tested with Dynamic Shear Rheometer (DSR) and a specific fatigue strain sweep test (EBADE).

2. Methodology

In order to analyse the effect of ageing on the fatigue behaviour of asphalt bitumens, three different types of bitumen were considered: a conventional bitumen (B), a crumb rubber modified bitumen (CRMB), and an SBS polymer modified bitumen (PMB).

These bitumens were aged in the laboratory by means of the standardized combined procedures of the RTFOT (Rolling Thin Film Oven Test) and PAV (Pressure Ageing Vessel) to simulate long-term ageing. Although some researchers suggest that these procedures could underestimate the real evolution of ageing in bituminous binders (as they do not apply UV radiation [15]), this type of thermal ageing was selected as it is the reference in the Spanish Specifications [24].

First, standard tests (penetration, softening point, brittle point, elastic recovery, force-ductility and dynamic viscosity) were conducted in order to establish the physical characteristics of the bitumen. After that, the visco-elastic characteristics of the unaged and aged binders were then established using the Dynamic Shear Rheometer (DSR) in order to define the reference temperatures to conduct the fatigue tests. Finally, the fatigue behaviour of the bitumens both before and after ageing was evaluated by using a new cyclic tension-compression test at controlled strain (strain sweep test) and at the temperatures defined in the previous step.

2.1. DSR Test

The rheological response of the various binders was analysed using the frequency sweep test at various temperatures (10, 20, 30, 40, 45, 52, 58, 64, 70, and 80°C). This test was carried out using the Dynamic Shear Rheometer (DSR) and oscillatory shear loading was applied at constant amplitude (0.1% strain) over a range of loading frequencies (from 0.1 Hz to 20 Hz). During the tests, complex shear modulus (G*) and phase angle (δ) were recorded at each frequency (EN 14770). The results are shown using the Black diagrams, which display the values of complex shear modulus and phase angle at different temperatures for each binder. Further, in order to analyse the influence of this parameter on the viscoelastic response of the mixture, the results for a fixed frequency (5 Hz) at different temperatures are displayed. Based on the results, the reference temperatures to conduct the fatigue tests were selected to assess the influence of this parameter on the effect of ageing in bituminous binders and the impact of biased visco-elastic phenomena.

2.2. EBADE Test

The resistance of these binders to repeated loads was assessed using a new cyclic tension-compression test at controlled strain - the EBADE test - see Figure 1 [25]. This test has been developed at the Road Research Laboratory of the Technical University of Catalonia and is described below. EBADE is the Spanish acronym for strain sweep test.

All the specimens were fabricated with the aforementioned bitumen. The specimens were cylinders of 20 mm of diameter and around 40 mm in height (see Figure 1a). The asphalt binder was heated to 165ºC in the oven. Specimens were left to cool at room temperature, after which they were removed from the mould and glued to a servo-hydraulic press in order to conduct the tests (see Figure 1b).

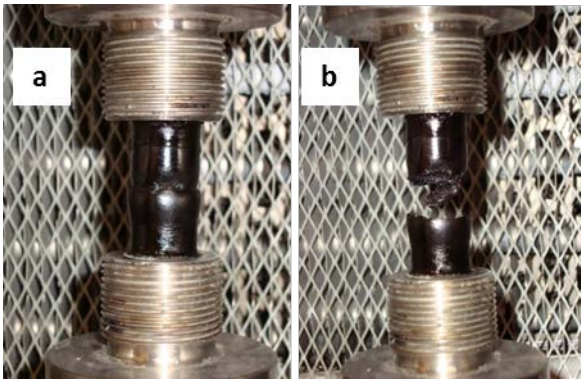


Figure 1. EBADE test in bitumens: (a) initial strain, and (b) specimen failure.

The EBADE test is a cyclic tension-compression test at controlled strain. Several strain amplitudes were applied, in ascending order, in stages of 5,000 loading cycles at a frequency of 10 Hz.

The strain amplitude applied in the first step was 7.6E-4, and every 5,000 cycles the strain was increased by 7.6E-4. Thus, the number of cycles and the strain amplitude were directly correlated. The test finished upon total failure of the specimen.

Several parameters were computed during the test, being the most important maximum stress, complex modulus, and density of dissipated energy.

The initial modulus generated by the test was obtained by calculating the average of the moduli registered in all cycles corresponding to the first strain step (amplitude of 7.6 E-4). At these low strain levels the behaviour of the material was linear viscoelastic.

Due to the delay between stress and strain, an ellipse is formed in the stress vs. strain plot. The density of dissipated energy is proportional to the area of the ellipse in the tension–compression graph.

Given the characteristics of the test, it is possible to obtain the strain at which the material is completely broken: the failure strain. In particular, the typical shape of the curves of dissipated energy density versus number of cycles allows to easily determine the value of the failure strain. The reason for this is that DED increases throughout the test with the number of cycles (up to a maximum), after which it begins to decrease rather rapidly as a result of specimen failure.

Consequently, the failure strain is defined as the strain at which the density of dissipated energy is reduced by 50% of the maximum value reached during the test (see Figure 2).

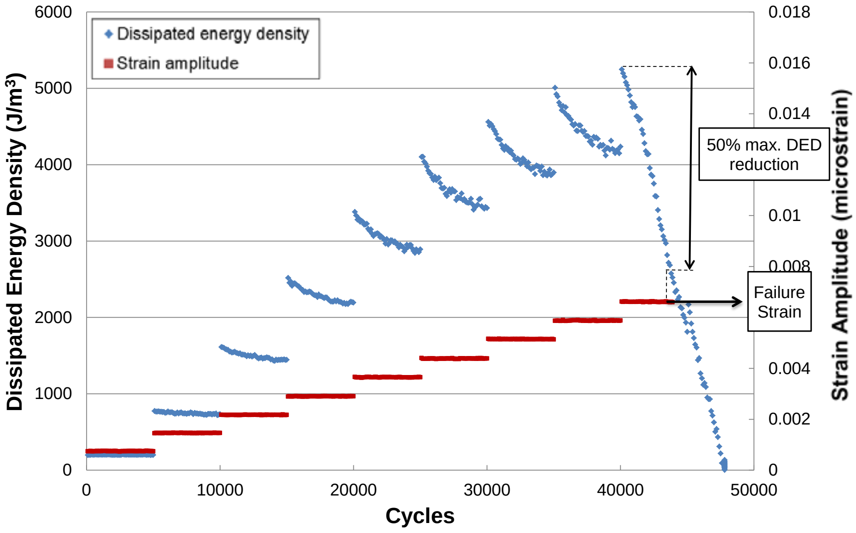


Figure 2. Failure criterion. Obtainment of failure strain.

In order to evaluate the behaviour of the aged and unaged bitumens under a range of conditions, the test was conducted at three different temperatures: a considerably low temperature where biased visco-elastic phenomena would not interfere in the evaluation of fatigue behaviour of bituminous binders (-5°C); a higher temperature where biased visco-elastic phenomena are plausible to co-exist with fatigue damage (10°C); and an intermediate temperature which could help to extract conclusions from the study (3°C). These temperatures were selected based on the results obtained in the DSR tests conducted in the previous step.

3. Analysis of results

3.1. *Conventional tests*

Table 1 summarizes the main characteristics of the binders, both before and after ageing.

Table 1. Properties of the binders studied.

Binder Characteristics		**Unit**	**Standard**	**B (35/50)**	**CRMB (50/70)**	**PMB (45/80-65)**
Penetration at 25ºC		(0.1 mm)	EN 1426	44	66	62
Softening Point R&B		(ºC)	EN 1427	53.4	55.8	68.4
Fraass Brittle Point		(ºC)	EN 12593	-8	-14	-17
Elastic Recovery at 25ºC		(%)	EN 13398	-	61	91
Force-ductility at 25 ºC		(J/cm^2)	EN 13585	-	0.20	0.13
Dynamic Viscosity at 140ºC		(mPa.s)	EN 13302	700	1083	1717
Dynamic Viscosity at 160ºC		(mPa.s)	EN 13302	300	517	700
Storage Stability	Penetration	(0.1 mm)	EN 13399		0	0
	R&B	(ºC)	EN 13399		1.4	0.2
After RTFOT						
Penetration at 25ºC		(0.1 mm)	EN 1426	32	44	44
Softening Point R&B		(ºC)	EN 1427	57.2	64.0	72.0
Fraass Brittle Point		(ºC)	EN 12593	-6	-13	-15
Elastic Recovery at 25ºC		(%)	EN 13398	-	62	85
Force-ductility at 25 ºC		(J/cm^2)	EN 13585	-	0.47	0.33
Dynamic Viscosity at 140ºC		(mPa.s)	EN 13302	967	2167	2717
Dynamic Viscosity at 160ºC		(mPa.s)	EN 13302	350	867	967
After RTFOT+PAV						
Penetration at 25ºC		(0.1 mm)	EN 1426	22	24	31
Softening Point R&B		(ºC)	EN 1427	65.4	76.8	85.4
Fraass Brittle Point		(ºC)	EN 12593	-2	-8	-12
Elastic Recovery at 25ºC		(%)	EN 13398	-	62	74
Force-ductility at 25 ºC		(J/cm^2)	EN 13585	-	1.69	1.36
Dynamic Viscosity at 140ºC		(mPa.s)	EN 13302	1250	4600	5833
Dynamic Viscosity at 160ºC		(mPa.s)	EN 13302	450	1500	1817

The polymer and crumb rubber modified bitumens had higher penetration values than the conventional bitumen. The polymer-modified bitumen had the highest softening point R&B and the lowest Fraass brittle point, while the crumb rubber bitumen had similar values to those of the conventional bitumen. Moreover, the elastic recovery of the polymer-modified bitumen was higher than that of the crumb rubber bitumen.

Following the ageing process, all the bitumens showed a decrease in penetration and an increase in softening point R&B and Fraass brittle point, the crumb rubber modified bitumen being the one that displayed the greatest reduction of penetration and the greatest increase in softening point R&B. However, the elastic recovery was not affected in the crumb rubber bitumen, while a significant decrease was observed in the recovery of the polymer-modified bitumen. Dynamic viscosity increased after the ageing process in all of the bitumens, particularly in the case of the modified binders.

Figure 3 shows the changes produced in the main properties of the binders after the ageing process (in terms of percentage of the rate of variation - positive when the value of the property measured increases after ageing, and negative when it decreases). It is clear that in terms of most of the properties measured, the ageing effect had a bigger impact on the modified binders than on the neat binder. This is the result of stiffening in the base bitumen (through an increase in the content of the asphaltenes) and to some extent, degradation of the polymer due to a decrease in its molecular size [26, 27]. Thus, as previous research has demonstrated, more homogenous binders (such as the neat binder) change to a lower extent due to ageing than the modified ones [19].

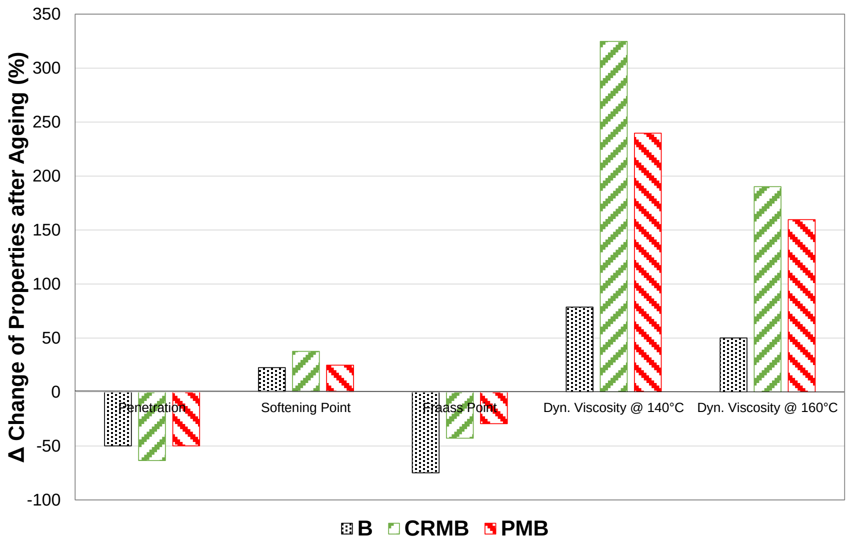


Figure 3. Variations in the properties of the binders following the ageing process.

3.2. *DSR Frequency sweep tests*

Figure 4 shows the results (Black diagrams) of the frequency sweeps conducted on the bitumens, both with and without ageing. Without ageing, at low temperatures, the Black curves of the modified bitumens overlap each other, showing a simple instance of thermo-rheological behaviour. However, above a certain temperature (≈50°C), the effect of modifiers (polymer and crumb rubber) became more marked, showing a local minimum in the phase angle (typical for such modifiers). The less overlap on the corners, and the greater the degree of parallelism between the curves, the greater the structural complexity of the binder. At low values of complex modulus (higher test temperatures), the modified binders presented lower values of phase angle, which translates to a more elastic response and thus more resistance to plastic deformations. However, at high values of complex modulus (lower test temperatures), the values of phase angle presented by the three binders were similar. This aspect of the results denotes a more stable viscoelastic response of the modified binders, which is due to the fact that they are less susceptible to changes in temperature.

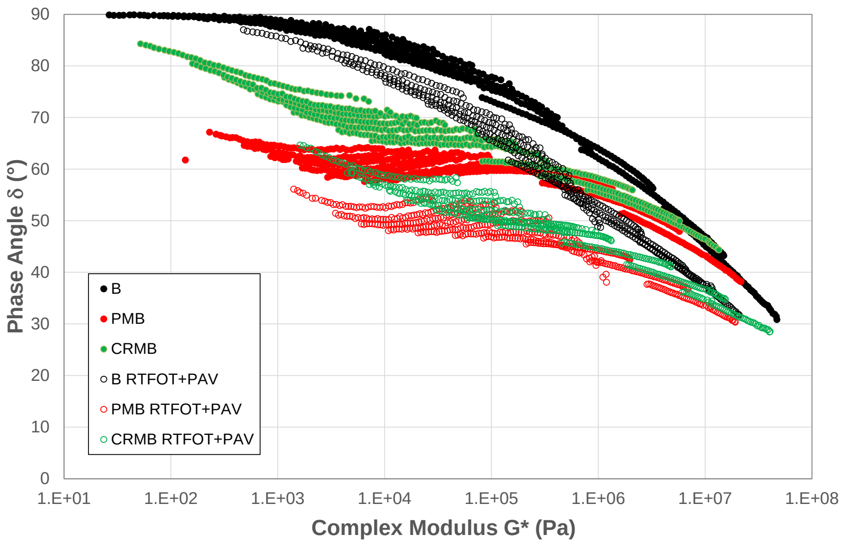


Figure 4. Black Diagram of the binders studied, with and without ageing.

After ageing, all the binders became more elastic and showed a higher degree of stiffness (at a given temperature, the phase angle values decreased and the complex modulus values increased). Thus, it appears that the ageing phenomenon induces a more brittle behaviour in the binders, which could crack at lower strains. This can be clearly observed in Figure 5, which shows, for the three bitumens, the changes of the complex modulus (G*) and phase angle (º) with temperature, at a fixed frequency of 5 Hz. The effect of the ageing phenomenon was observed at any given temperature in the three binders studied. Nonetheless, this effect was more or less marked, depending on the test temperature. In particular, the viscoelastic properties (i.e. complex modulus and phase angle) of the polymer-modified binder (PMB) were less affected by this phenomenon at medium-high temperatures than in the case of either crumb rubber modified bitumens (CRMB) or conventional bitumens (B). At lower temperatures, the effect of ageing in the neat binder (B) became less marked. With respect to the CRMB, higher variations were found at any temperature, which shows that CRMB could be the material that is most susceptible to the effects of ageing.

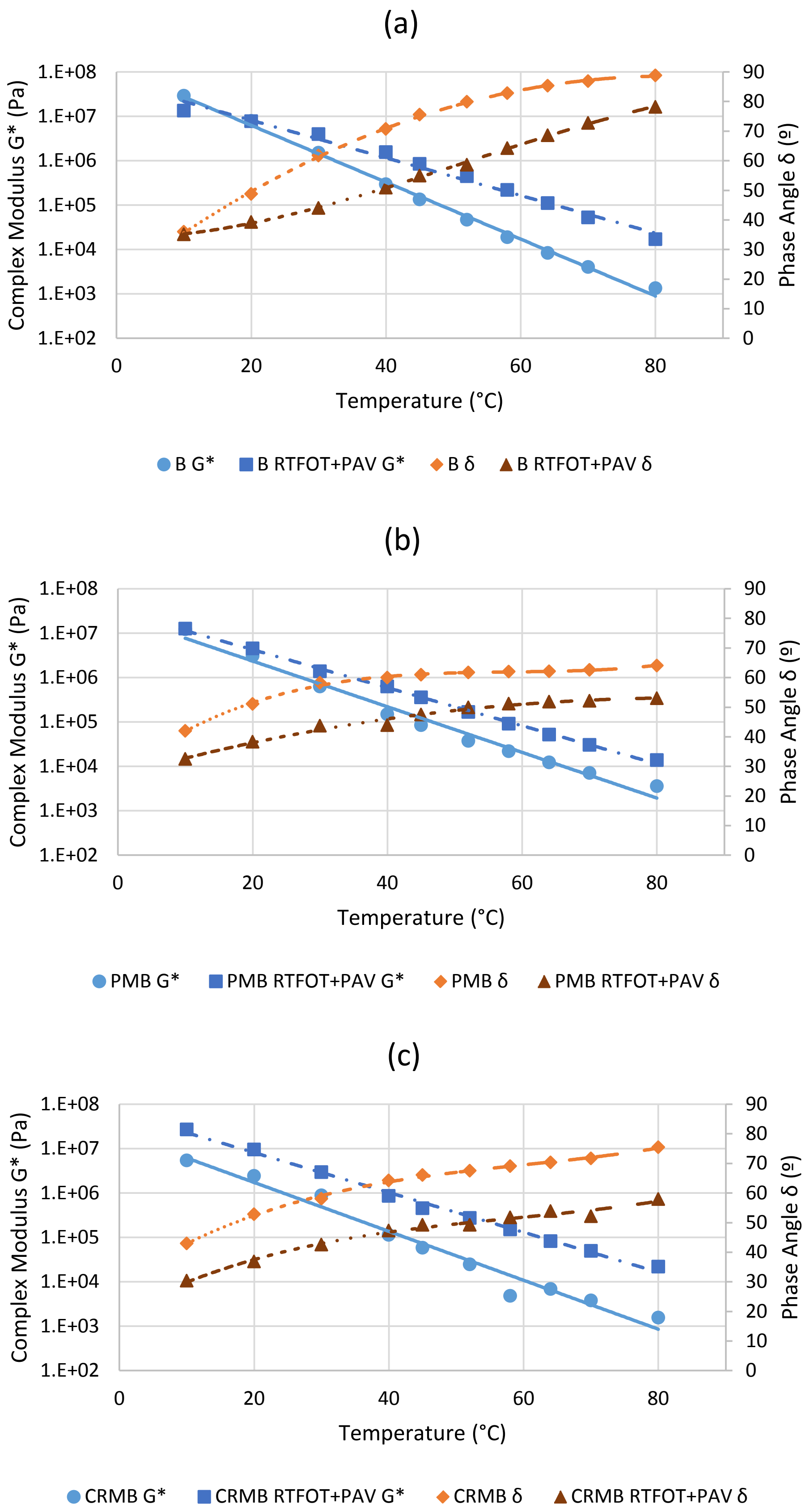


Figure 5. Variation of complex modulus and phase angle with temperature: (a) B; (b) PMB; (c) CRMB.

Based on the results obtained in Figure 5, it can be observed that at 10°C, all the binders (modified and unmodified, aged and unaged) have a complex modulus superior to 1 MPa (which is considered by some authors as the minimum complex modulus value to conduct a fatigue test without the influence of biased visco-elastic phenomena [22]) and a phase angle inferior to 45° (which can be considered the maximum value of the visco-elastic response that can be governed by fatigue phenomena, as over this value the binder will offer a more viscous response that would be governed by plastic flow phenomena). Therefore, this temperature was set as the maximum temperature to conduct the fatigue tests. Based on the same results, and in order to ensure the absence of biased visco-elastic phenomena during fatigue evaluation, a considerably low temperature was also selected (-5°C) to perform EBADE tests. Finally, an intermediate temperature of 3°C was also used to establish a correlation between the results obtained at 10°C and at -5°C.

3.3. *EBADE tests*

The EBADE tests were conducted on 3 specimens for each binder, test temperature, and ageing condition. Using the results yielded from the 3 specimens, the average curves that represent the behaviour of the binder for each test condition were generated. Figures 6 and 7, for example, show these average curves for apparent modulus and density of dissipated energy, together with the imposed strain steps for binder B (without ageing) at the three test temperatures.

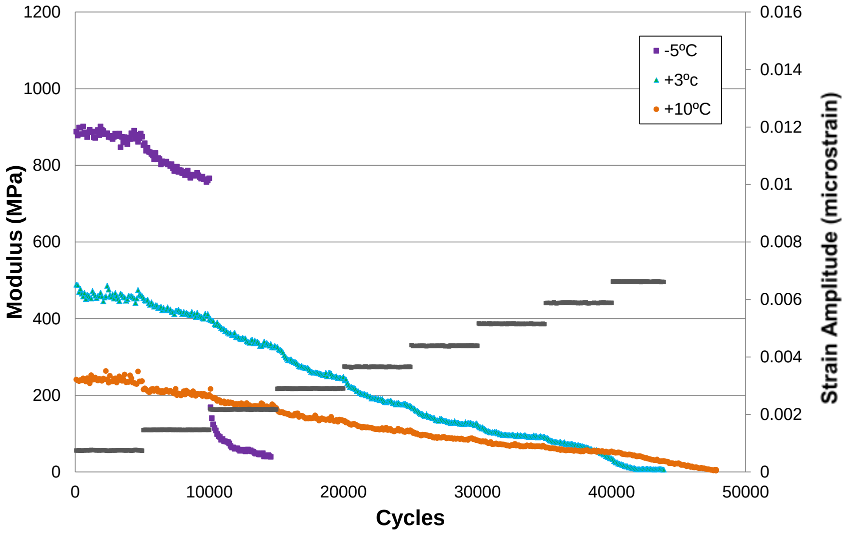


Figure 6. Apparent modulus versus number of cycles for the conventional binder (B) at -5, 3 and 10ºC.

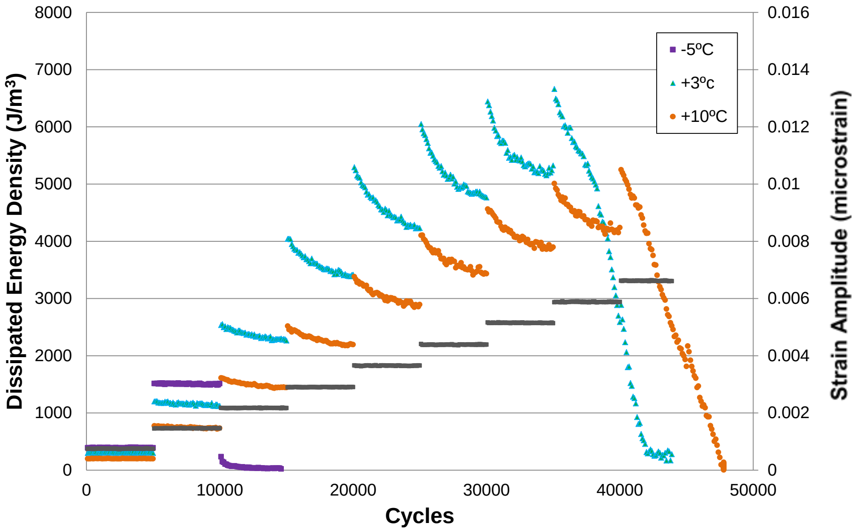
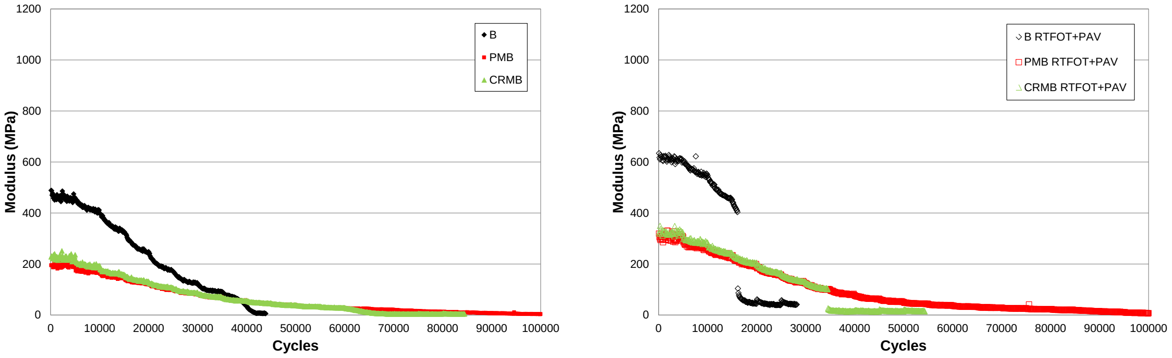


Figure 7. Dissipated energy density versus number of cycles for the conventional binder (B) at -5, 3 and 10ºC.

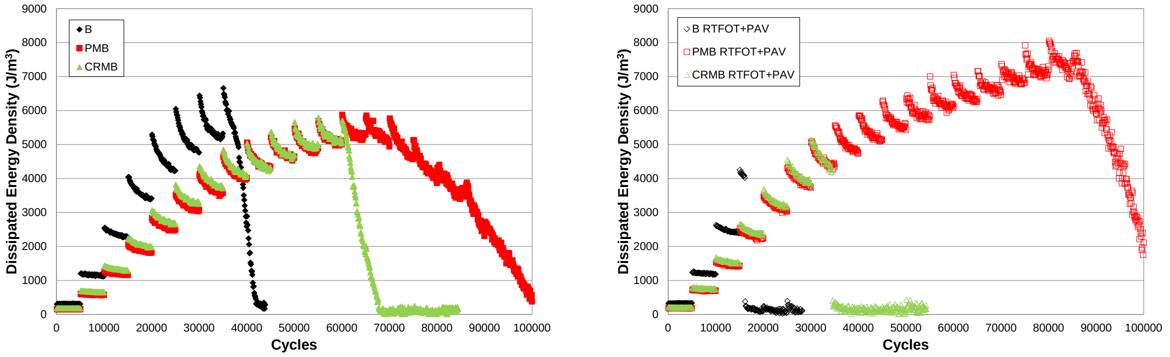
It is clear that initial modulus increased with a decline in temperature, whereas both failure strain and failure cycle gradually decreased.

Figures 8 and 9 show the mean curves for the three bitumens, both before and after ageing, at a test temperature of 3°C. Without ageing, conventional bitumen had a higher initial apparent modulus than that of modified bitumens, but the failure occurred at a much lower strain than the corresponding value of PMB, while CRMB, with a similar modulus to that of PMB, showed an intermediate strain failure.



(a) *(b)*

Figure 8. Apparent modulus versus number of cycles at 3ºC for the tested binders: (a) without ageing and (b) after ageing (RTFOT+PAV).



(a) *(b)*

Figure 9. Dissipated energy density versus number of cycles at 3ºC for the tested binders: (a) without ageing and (b) after ageing (RTFOT+PAV).

After ageing, the initial modulus of all the bitumens increased, showing a more rapid drop in modulus with the number of cycles. In addition, the failure strain decreased, except for the case of PMB, which was able to dissipate more energy during the fatigue process at the given temperature (3ºC), retaining significant ductility, in spite of having undergone the ageing process.

Two parameters that allow for the characterization of the fatigue behaviour of the binder were obtained from this average result, these being initial modulus and failure strain. Table 2 summarizes the mean values of three replicates for these parameters at the three test temperatures for each of the bitumens, and for each ageing condition analysed, as well as the standard error. In the case of the modulus, this standard error is between 0.2% and 3.6% of the mean value, while in the case of the failure strain, it can occasionally reach up to 17%.

Table 2. Average values of initial modulus and failure strain for the tested binders.

Binder	**Temperature (ºC)**	**Initial Modulus (MPa)**	**Standard error (MPa)**	**Failure Strain (µm)**	**Standard error (µm)**
B (35/50)	-5	868	11.00	2.18E-03	2.34E-04
	3	466	3.47	5.63E-03	2.48E-04
	10	238	1.60	6.61E-03	0.05E-04
CRMB (50/70)	-5	524	13.70	7.85E-03	6.46E-04
	3	224	2.40	9.59E-03	0.03E-04
	10	104	0.25	1.11E-02	0.02E-04
PMB (45/80-65)	-5	421	11.30	1.08E-02	2.46E-04
	3	194	1.48	1.34E-02	2.53E-04
	10	86	0.18	1.52E-02	0.09E-04
After ageing (RTFOT+PAV)					
B (35/50)	-5	1041	9.00	1.50E-03	2.67E-04
	3	612	7.80	3.00E-03	0.00E-04
	10	370	2.60	4.83E-03	6.74E-04
CRMB (50/70)	-5	590	10.00	2.90E-03	5.00E-04
	3	316	5.57	5.07E-03	6.74E-04
	10	184	2.65	1.30E-02	1.00E-04
PMB (45/80-65)	-5	572	13.50	3.27E-03	2.67E-04
	3	298	6.33	1.43E-02	3.33E-04
	10	174	6.23	>1.50E-02	0.00E-04

Failure strain versus initial modulus (for all binders and at all temperatures) is plotted in Figure 10. The behaviour of the binders without ageing is shown in solid lines, and that of aged binders in dashed lines. In this type of graph, a comparison of the fatigue behaviour of the different materials can be achieved by simply observing the relative positions of their curves.

A comparison of the results of the binders without ageing revealed that the polymer-modified binder, PMB, had the lowest initial modulus and the highest failure strain, whilst the crumb rubber modified binder, CRMB, exhibited similar behaviour, with a lower failure strain and a slightly higher modulus (which agrees with previous research [28]). Finally, the conventional binder, B, had a much higher initial modulus than those of the two modified binders at all temperatures (approximately 100% higher) with a much lower failure strain compared with the modified binders.

After ageing, it is clear that in all cases there was an increase in initial modulus, which was anticipated on the basis of the findings obtained from both conventional (penetration, softening point, etc.) and DSR tests. However, as observed in the DSR tests, the temperature of testing also played a significant role in the influence of ageing on the mechanical response of the binders to fatigue. In this respect, it is observed that the mechanical response of modified binders (PBM and CRMB) at high temperatures (10°C in both binders, and also 3°C in PMB binder), seems to be not consistent, as an increase in the failure strain is obtained after ageing (which means that aged binders would resist better fatigue than unaged binders). This results could be due to the presence of biased visco-elastic phenomena during the fatigue damage evaluation of the binders at these temperatures, that could induce the variation of apparent modulus and dissipated energy. As can be observed in Figure 9, the failure criterion observed in the curves described by the PMB binder is less clear due to the presence of such phenomena.

In contrast, at low temperatures (-5ºC) where there is an absence of biased visco-elastic phenomena, the results obtained are consistent showing a strain failure drop in the binders tested, indicating that the ageing process had affected the fatigue resistance of the modified binders when subjected to these conditions. Therefore, the temperature conditions not only would influence the fatigue resistance of bituminous binders but would also influence their evaluation through laboratory tests.

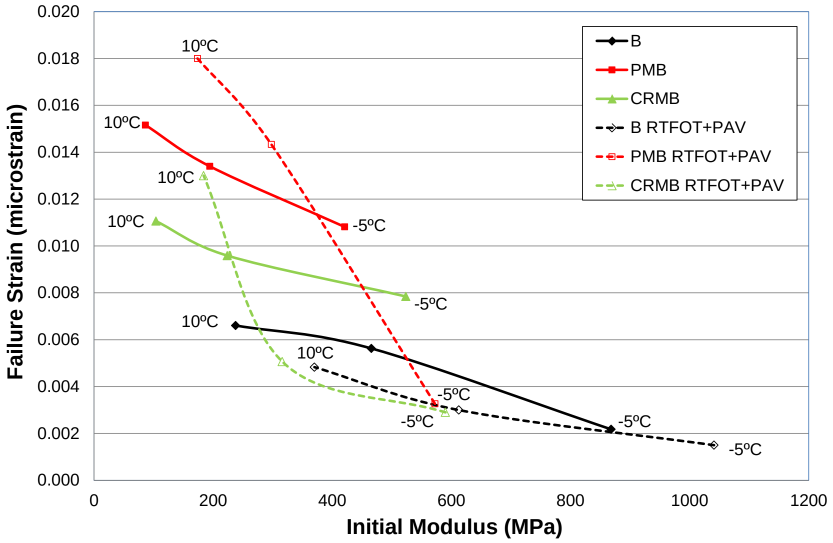


Figure 10. Failure strain versus initial modulus for the tested binders at -5, 3 and 10ºC.

Regardless the effect of visco-elastic phenomena, in general terms it can be said that without ageing, PMB is on one end with the lowest initial modulus and the highest failure strain; conventional bitumen is on the other end with the highest modulus and lowest failure strain, whilst the CRMB curve is in between. It is also clear that as the initial modulus increased (due to a decrease in the test temperature), the differences between the modified binders and the conventional one remained constant (in terms of failure strain), which demonstrates that the comparative fatigue response between the binders is stable with temperature. After ageing, this trend changes. At higher temperatures, aged modified binders displayed a significantly better response against fatigue than the aged neat binder. As the temperature decreased, the differences between the binders were considerably reduced. At low temperatures, the effect of ageing had a lower impact on the conventional binder, B, than on the modified binders (as observed in DSR tests). By analysing the curves, it is clear that the B binder displayed a more stable response against the ageing effect as the temperature decreased, whilst the CRMB began to be susceptible to the ageing effect from 3°C, and the PMB at -5ºC (confirming that the PMB is the most stable under the effect of temperature). It should be noted that at -5ºC, in spite of the fact that the binders show a different modulus, there was little difference between the fatigue behaviours of modified and unmodified binders (in terms of failure strain).

4. Conclusions

Using the EBADE test, this study examined the effect of ageing on the fatigue behaviour of three bitumens: a conventional bitumen (B), a crumb rubber modified bitumen (CRMB), and an SBS polymer modified bitumen (PMB), at various temperatures (10, 3 and -5°C). Long-term ageing was simulated in the laboratory by using a combination of two procedures – the RTFOT (Rolling Thin Film Oven Test) and the PAV (Pressure Ageing Vessel). Previously, the rheological properties of the binders had been established by using both traditional tests (penetration, softening point, Fraass fragility point, dynamic viscosity, etc.) and DRS (frequency and temperature sweep).

The following conclusions that can be drawn from the results:

- Conventional tests allow obtaining an initial approximation of how various bitumens respond to the ageing phenomenon. In comparison with conventional binders, modified binders display a higher rate of variation in their general properties (penetration, softening point, and dynamic viscosity) in response to ageing.
- DSR tests show that temperature could play an important role in the effect of ageing on the mechanical response of bituminous binders. In particular, at medium-high temperatures, modified bitumens offer a more stable response against the effects of ageing, with the PMB being the least affected by this phenomenon. As temperature decreases, the impact of ageing on the neat binder becomes less marked, whilst CRMB seems to be the material most susceptible to the effects of ageing.
- Fatigue tests also show that, when subjected to ageing, the temperature influences the mechanical response of bituminous binders (hence the importance

of determining the behaviour curve at different temperatures). The EBADE test shows that the influence of a decrease in temperature on the mechanical behaviour of aged neat binder is less important, while the fatigue resistance of modified binders is more affected by a temperature variation.

- It must be highlighted that at certain test temperatures, the presence of visco-elastic phenomena that co-exist with fatigue damage (plastic flow, thixotropy, etc.), could lead to a misunderstanding of the effect caused by ageing. Thus, the evaluation of the effect of ageing on fatigue response of asphalt binders should be carried out at temperatures where the effect of these visco-elastic phenomena is avoided (low temperatures). These temperature conditions will vary as a function of the type of binder tested. In the case of the binders tested in this study, it has been demonstrated that the neat binder does not show susceptibility to these visco-elastic phenomena at the temperature used, the CRMB was susceptible at 10°C, and the PMB was susceptible at 10°C and 3°C.
- Irrespective of temperature, modified binders are more susceptible to the effects of ageing (in terms of fatigue resistance) than neat binders. The differences in resistance to fatigue (failure strain) between un-aged and aged conventional binders are lower than those observed between un-aged and aged modified bitumens. This implies that, in spite of the fact that modified binders could offer better fatigue resistance than neat binders, the effect of ageing could cause the mechanical response of modified and unmodified binders to be similar.

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