

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.

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52 **1. Introduction**

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

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

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

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

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

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

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

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

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

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

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

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

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134 **2. Methodology**

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

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

145 First, standard tests (penetration, softening point, brittle point, elastic recovery, force-
146 ductility and dynamic viscosity) were conducted in order to establish the physical
147 characteristics of the bitumen. After that, the visco-elastic characteristics of the unaged
148 and aged binders were then established using the Dynamic Shear Rheometer (DSR) in
149 order to define the reference temperatures to conduct the fatigue tests. Finally, the

150 fatigue behaviour of the bitumens both before and after ageing was evaluated by using a
151 new cyclic tension-compression test at controlled strain (strain sweep test) and at the
152 temperatures defined in the previous step.

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154 2.1. DSR Test

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156 The rheological response of the various binders was analysed using the frequency sweep
157 test at various temperatures (10, 20, 30, 40, 45, 52, 58, 64, 70, and 80°C). This test was
158 carried out using the Dynamic Shear Rheometer (DSR) and oscillatory shear loading
159 was applied at constant amplitude (0.1% strain) over a range of loading frequencies
160 (from 0.1 Hz to 20 Hz). During the tests, complex shear modulus (G^*) and phase angle
161 (δ) were recorded at each frequency (EN 14770). The results are shown using the Black
162 diagrams, which display the values of complex shear modulus and phase angle at
163 different temperatures for each binder. Further, in order to analyse the influence of this
164 parameter on the viscoelastic response of the mixture, the results for a fixed frequency
165 (5 Hz) at different temperatures are displayed. Based on the results, the reference
166 temperatures to conduct the fatigue tests were selected to assess the influence of this
167 parameter on the effect of ageing in bituminous binders and the impact of biased visco-
168 elastic phenomena.

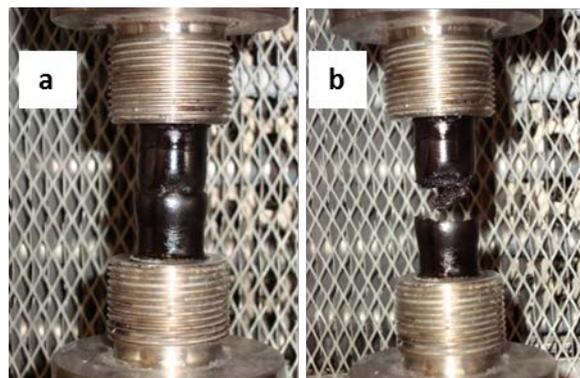
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170 2.2. EBADE Test

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172 The resistance of these binders to repeated loads was assessed using a new cyclic
173 tension-compression test at controlled strain - the EBADE test - see Figure 1 [25]. This
174 test has been developed at the Road Research Laboratory of the Technical University of
175 Catalonia and is described below. EBADE is the Spanish acronym for strain sweep test.
176 All the specimens were fabricated with the aforementioned bitumen. The specimens
177 were cylinders of 20 mm of diameter and around 40 mm in height (see Figure 1a). The
178 asphalt binder was heated to 165°C in the oven. Specimens were left to cool at room
179 temperature, after which they were removed from the mould and glued to a servo-
180 hydraulic press in order to conduct the tests (see Figure 1b).

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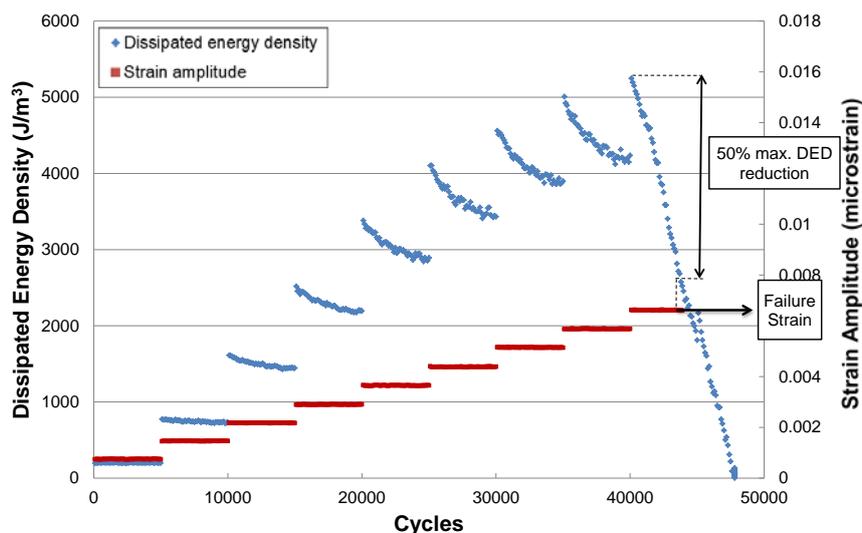
184 Figure 1. EBADE test in bitumens: (a) initial strain, and (b) specimen failure.

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

190 The strain amplitude applied in the first step was $7.6E-4$, and every 5,000 cycles the
 191 strain was increased by $7.6E-4$. Thus, the number of cycles and the strain amplitude
 192 were directly correlated. The test finished upon total failure of the specimen.
 193 Several parameters were computed during the test, being the most important maximum
 194 stress, complex modulus, and density of dissipated energy.
 195 The initial modulus generated by the test was obtained by calculating the average of the
 196 moduli registered in all cycles corresponding to the first strain step (amplitude of $7.6E-$
 197 4). At these low strain levels the behaviour of the material was linear viscoelastic.
 198 Due to the delay between stress and strain, an ellipse is formed in the stress vs. strain
 199 plot. The density of dissipated energy is proportional to the area of the ellipse in the
 200 tension–compression graph.
 201 Given the characteristics of the test, it is possible to obtain the strain at which the
 202 material is completely broken: the failure strain. In particular, the typical shape of the
 203 curves of dissipated energy density versus number of cycles allows to easily determine
 204 the value of the failure strain. The reason for this is that DED increases throughout the
 205 test with the number of cycles (up to a maximum), after which it begins to decrease
 206 rather rapidly as a result of specimen failure.
 207 Consequently, the failure strain is defined as the strain at which the density of dissipated
 208 energy is reduced by 50% of the maximum value reached during the test (see Figure 2).
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 212 Figure 2. Failure criterion. Obtainment of failure strain.
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215 In order to evaluate the behaviour of the aged and unaged bitumens under a range of
 216 conditions, the test was conducted at three different temperatures: a considerably low
 217 temperature where biased visco-elastic phenomena would not interfere in the evaluation
 218 of fatigue behaviour of bituminous binders (-5°C); a higher temperature where biased
 219 visco-elastic phenomena are plausible to co-exist with fatigue damage (10°C); and an
 220 intermediate temperature which could help to extract conclusions from the study (3°C).
 221 These temperatures were selected based on the results obtained in the DSR tests
 222 conducted in the previous step.
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224 **3. Analysis of results**
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226 3.1. Conventional tests

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

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231 Table 1. Properties of the binders studied.

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

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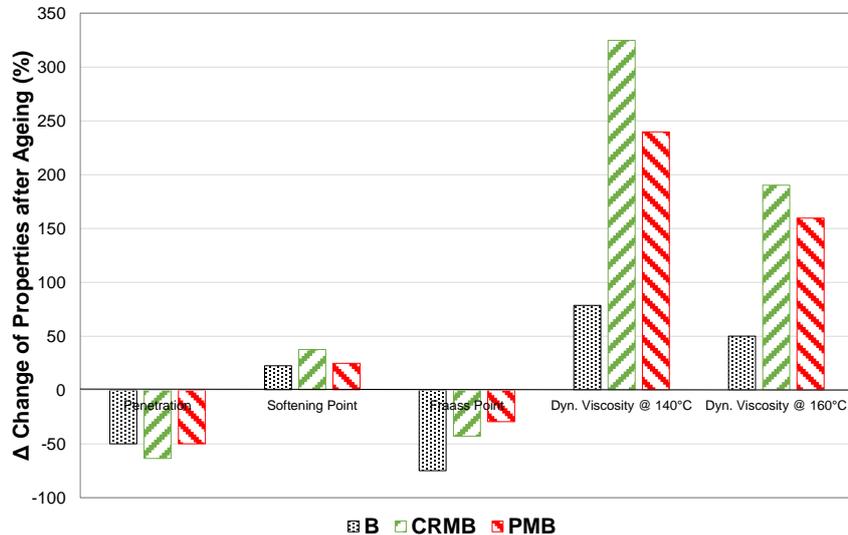
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235 The polymer and crumb rubber modified bitumens had higher penetration values than
 236 the conventional bitumen. The polymer-modified bitumen had the highest softening
 237 point R&B and the lowest Fraass brittle point, while the crumb rubber bitumen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

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

247 Figure 3 shows the changes produced in the main properties of the binders after the
 248 ageing process (in terms of percentage of the rate of variation - positive when the value
 249 of the property measured increases after ageing, and negative when it decreases). It is
 250 clear that in terms of most of the properties measured, the ageing effect had a bigger
 251 impact on the modified binders than on the neat binder. This is the result of stiffening in

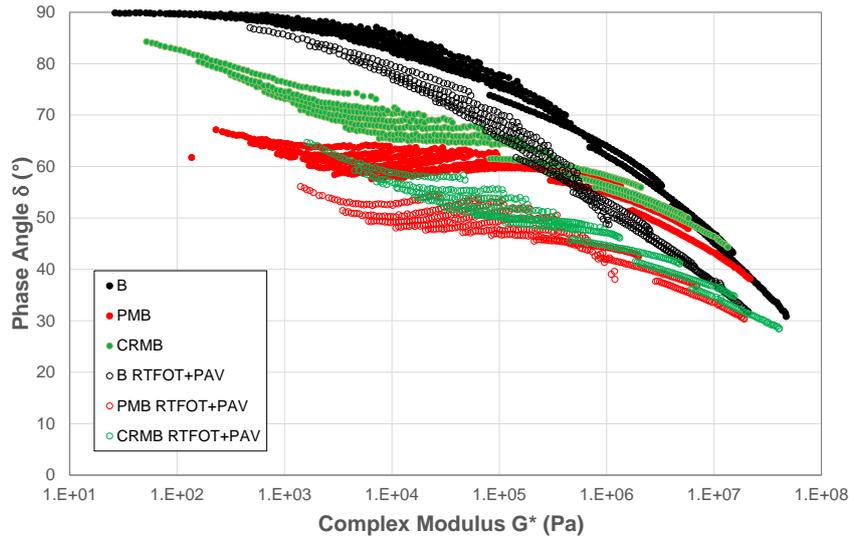
252 the base bitumen (through an increase in the content of the asphaltenes) and to some
 253 extent, degradation of the polymer due to a decrease in its molecular size [26, 27]. Thus,
 254 as previous research has demonstrated, more homogenous binders (such as the neat
 255 binder) change to a lower extent due to ageing than the modified ones [19].
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 259 Figure 3. Variations in the properties of the binders following the ageing process.
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262 3.2. DSR Frequency sweep tests

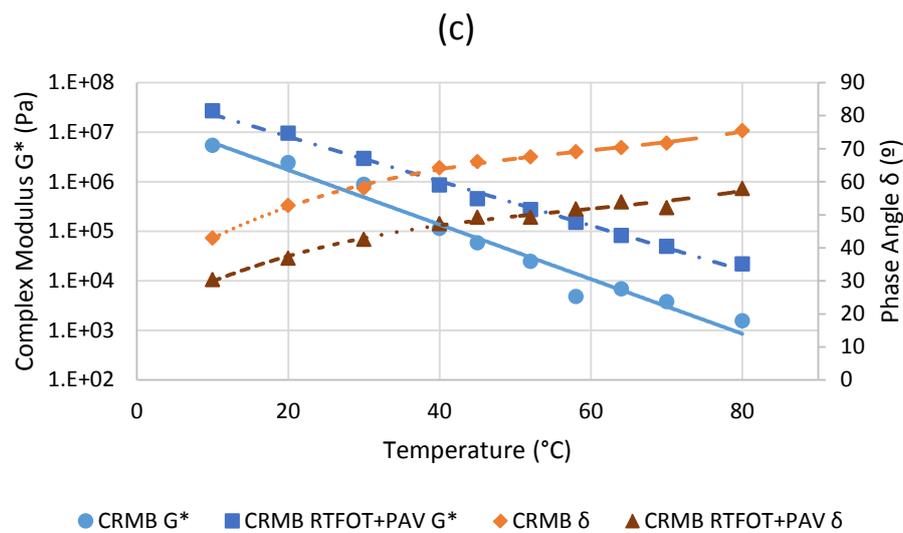
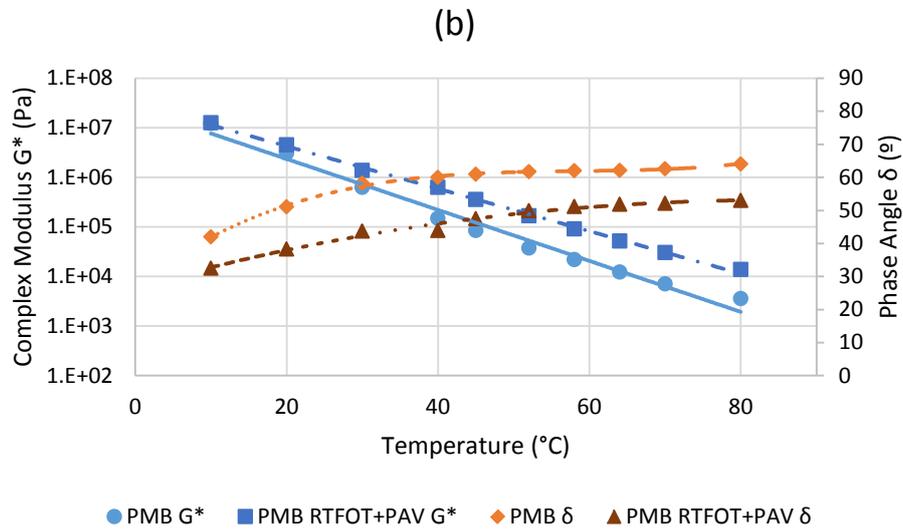
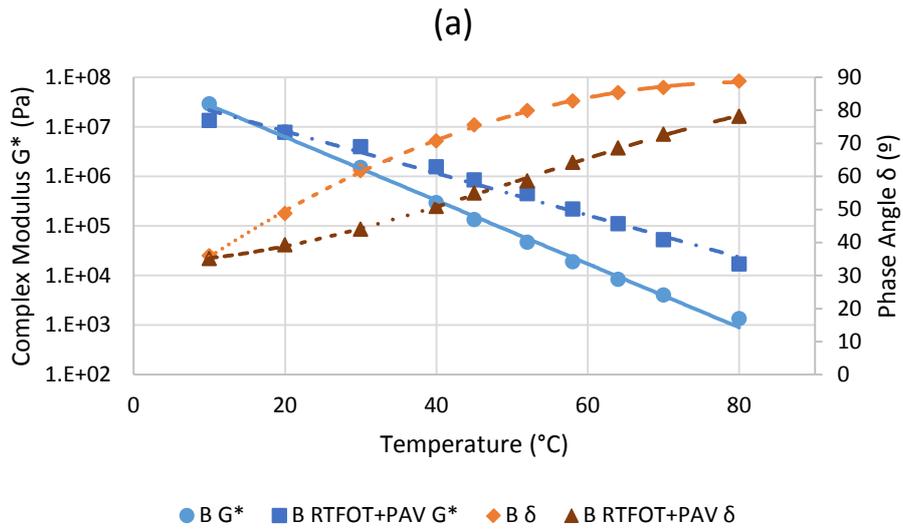
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 264 Figure 4 shows the results (Black diagrams) of the frequency sweeps conducted on the
 265 bitumens, both with and without ageing. Without ageing, at low temperatures, the Black
 266 curves of the modified bitumens overlap each other, showing a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



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

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

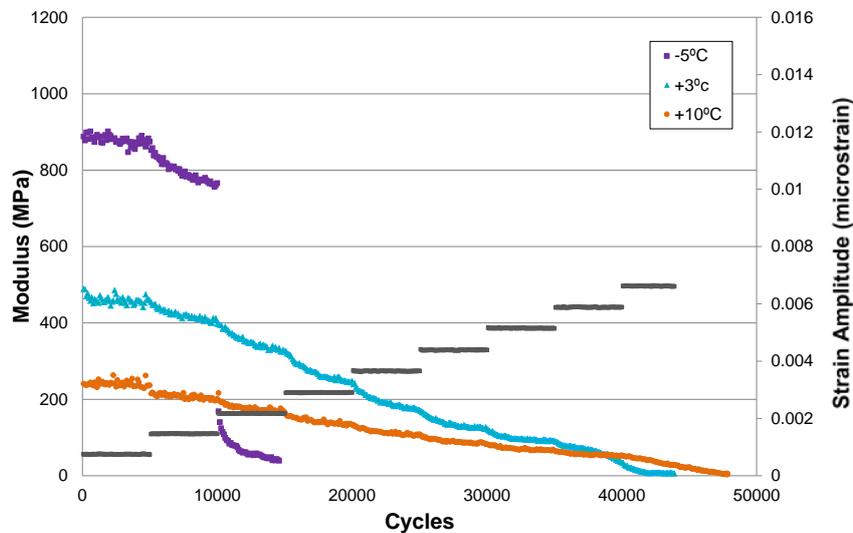
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318 3.3. EBADE tests

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

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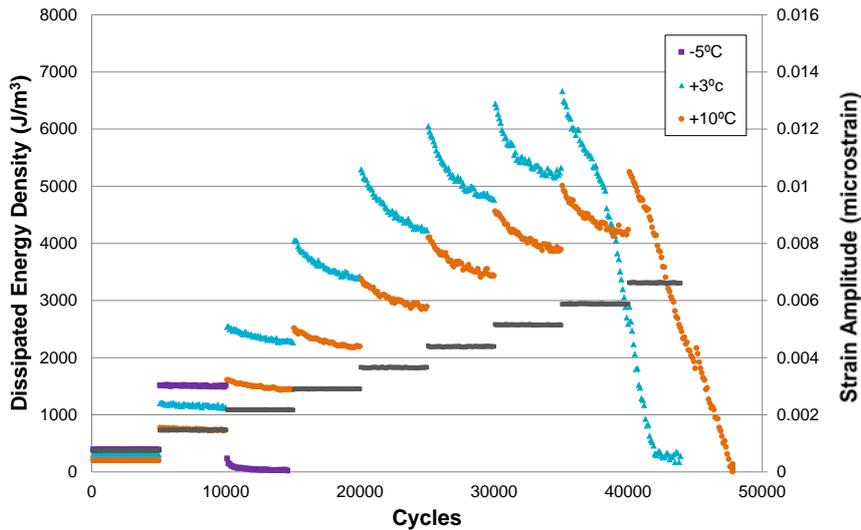


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329 Figure 6. Apparent modulus versus number of cycles for the conventional binder (B) at
330 -5, 3 and 10°C.

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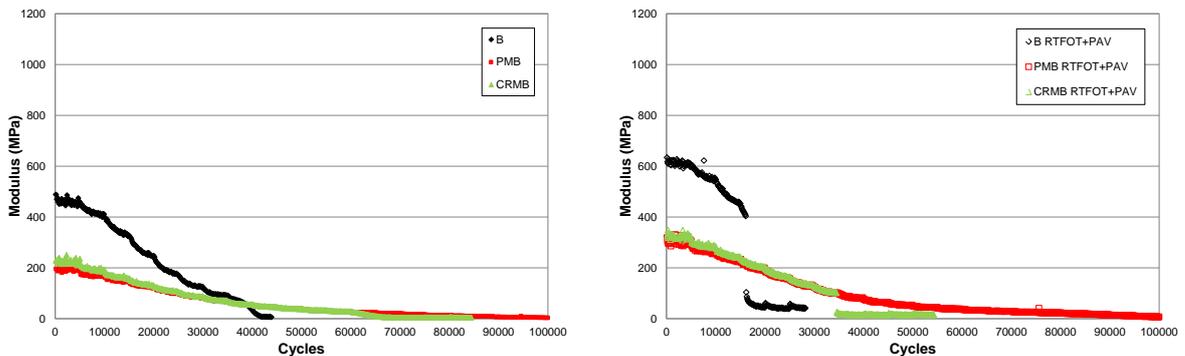
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Figure 7. Dissipated energy density versus number of cycles for the conventional binder (B) at -5, 3 and 10°C.

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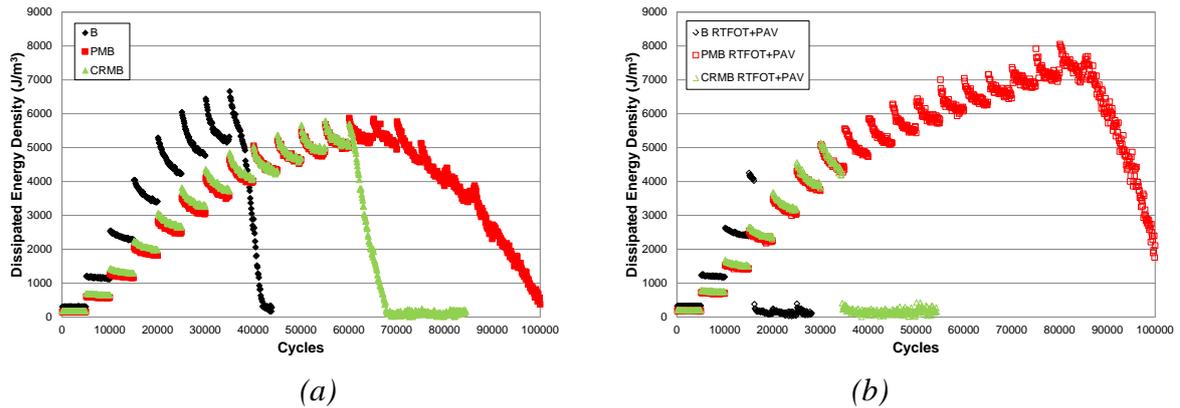
It is clear that initial modulus increased with a decline in temperature, whereas both failure strain and failure cycle gradually decreased.

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.



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



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 352 Figure 9. Dissipated energy density versus number of cycles at 3°C for the tested binders:
 353 (a) without ageing and (b) after ageing (RTFOT+PAV).
 354

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

360 Two parameters that allow for the characterization of the fatigue behaviour of the binder
 361 were obtained from this average result, these being initial modulus and failure strain.
 362 Table 2 summarizes the mean values of three replicates for these parameters at the three
 363 test temperatures for each of the bitumens, and for each ageing condition analysed, as
 364 well as the standard error. In the case of the modulus, this standard error is between
 365 0.2% and 3.6% of the mean value, while in the case of the failure strain, it can
 366 occasionally reach up to 17%.
 367

368 Table 2. Average values of initial modulus and failure strain for the tested binders.
 369

Binder	Temperature (°C)	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

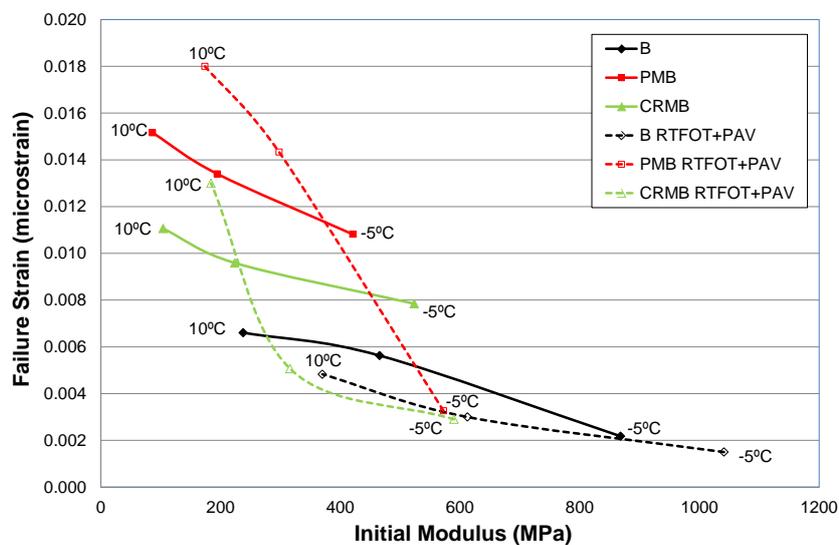
371 Failure strain versus initial modulus (for all binders and at all temperatures) is plotted in
 372 Figure 10. The behaviour of the binders without ageing is shown in solid lines, and that
 373 of aged binders in dashed lines. In this type of graph, a comparison of the fatigue
 374 behaviour of the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

376 A comparison of the results of the binders without ageing revealed that the polymer-
 377 modified binder, PMB, had the lowest initial modulus and the highest failure strain,
 378 whilst the crumb rubber modified binder, CRMB, exhibited similar behaviour, with a
 379 lower failure strain and a slightly higher modulus (which agrees with previous research
 380 [28]). Finally, the conventional binder, B, had a much higher initial modulus than those
 381 of the two modified binders at all temperatures (approximately 100% higher) with a
 382 much lower failure strain compared with the modified binders.

383 After ageing, it is clear that in all cases there was an increase in initial modulus, which
 384 was anticipated on the basis of the findings obtained from both conventional
 385 (penetration, softening point, etc.) and DSR tests. However, as observed in the DSR
 386 tests, the temperature of testing also played a significant role in the influence of ageing
 387 on the mechanical response of the binders to fatigue. In this respect, it is observed that
 388 the mechanical response of modified binders (PBM and CRMB) at high temperatures
 389 (10°C in both binders, and also 3°C in PMB binder), seems to be not consistent, as an
 390 increase in the failure strain is obtained after ageing (which means that aged binders
 391 would resist better fatigue than unaged binders). This results could be due to the
 392 presence of biased visco-elastic phenomena during the fatigue damage evaluation of the
 393 binders at these temperatures, that could induce the variation of apparent modulus and
 394 dissipated energy. As can be observed in Figure 9, the failure criterion observed in the
 395 curves described by the PMB binder is less clear due to the presence of such
 396 phenomena.

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

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

407
408

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

428

429 **4. Conclusions**

430

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

440

441 The following conclusions that can be drawn from the results:

442

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

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

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

478

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480

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484

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