Research Article

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Effect of temperature on the fatigue behavior of asphalt binder

Abstract: Asphalt pavement is under different climatic conditions throughout its service life, which means that fatigue cracking does not occur at a specific temperature, but at a temperature range. The main objective of this paper is to evaluate the influence of different temperatures in the fatigue life of two asphalt binders: a non-modified binder (penetration grade 30/45) and a highly polymer-modified binder (HPMB). The fatigue resistance characterization was performed by means of a linear amplitude sweep (LAS) test at the temperatures of 10, 15, 20, 25, and 30°C using a dynamic shear rheometer (DSR). From the dynamic shear modulus ($|G^*|$) results, adhesion loss was observed between the binder and the rheometer parallel plate at the lower temperature of 10°C, while at higher temperatures (25 and 30°C) plastic flow was observed rather than fatigue damage. Therefore, considering that the actual test procedure does not specify the testing temperature, the evaluation of failure mechanism is essential to validate test results, because the random selection of test temperature might lead to inconsistent data.

Keywords: Fatigue resistance, asphalt binder, linear amplitude sweep test, temperature

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1 Introduction

Fatigue cracking is one of the most common distresses in asphalt pavements and it is characterized by the accumulation of progressive damage caused by tensile stresses under repeated traffic loading. Cracking usually starts at the bottom of the asphalt layer (for the traditional flexible pavements), propagates to the surface and eventually results in the collapse of the pavement structure. This phenomenon reduces the bearing capacity of the asphalt layer, and impairs its structural and functional performance. Kennedy *et al.* [1] compared the relative effect of asphalt binder in relation to permanent deformation, fatigue cracking and thermal cracking and indicated that the asphalt binder mostly affects fatigue damage.

In many countries, the type of binder for a specific pavement structure is still mainly selected based on empirical tests such as the penetration and softening point tests, which do not provide representative engineering properties of the binders' performance [2]. The selection of a non-suitable binder type may lead to premature fatigue cracking, which requires pavement maintenance at the beginning of its service life. Therefore, different test procedures have been developed in order to better characterize binder performance and diminish the need for maintenance services during the pavement's early-life.

The most recent test procedure developed to evaluate binders fatigue life is the linear amplitude sweep (LAS) test, which has been under several modifications throughout recent years. The LAS test was initially conceived as an accelerated fatigue procedure [3] in comparison with the

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time sweep (TS) test proposed by Bahia *et al.* [4]. Besides the reduced time required for test execution, the data analysis is based on the simplified viscoelastic continuum damage (S-VECD) principle. The major feature of the S-VECD analysis is the damage characteristic curve, which is a fundamental material property that allows the prediction of the binder performance at any testing condition (*e.g.*, temperature, frequency, stress or strain-controlled, among others). The S-VECD analysis has been extensively used to model fatigue damage of asphalt binders and asphalt mixtures [5–13].

In the LAS procedure proposed by Johnson [3], a series of cyclic loads are applied to the binder specimen at linearly increasing strain amplitudes ranging from 0.1 to 20%. Hintz *et al.* [14] proposed to increase the maximum applied strain from 20 to 30%, since 20% strain amplitude was not sufficient to cause fatigue damage in some modified binders. Later, Hintz [15] suggested that the loading amplitude should be increased at a very small amount in each loading cycle, instead of an increasingly stepwise load. This modification would minimize some of the limitations of the Dynamic Shear Rheometers (DSR), which were not designed for significant and steep amplitude changes. In addition, different failure criteria can be used for LAS tests, such as: dissipated energy ratio, loss of 35% of $|G^\star|\times\sin(\delta)$, crack length growth, peak of shear stress, and stored maximum pseudo-energy [9, 16–18].

Thus, considering the several data analysis methods and different test procedures, it is possible to state that asphalt binder fatigue damage is a complex phenomenon that is difficult to be characterized in the laboratory. Therefore, the focus of this study was to evaluate the temperature influence in fatigue resistance of a highly polymer-modified binder (HPMB) in comparison with a neat one (penetration grade 30/45) by means of the LAS tests.

2 Temperature influence in asphalt binders fatigue test

Few studies have focused on the effect of temperature on binder fatigue life by means of the LAS test. In the current LAS testing protocol, the temperature is not specified, despite its major relevance in binder viscoelastic behavior and performance. Since the influence of temperature in asphalt binder fatigue is quite complex, different approaches have been used to select the testing temperature at which cohesive fatigue cracking occurs.

The Superpave specification for asphalt binders limits the $|G^\star| \times \sin(\delta)$ parameter to a maximum value of 5.0 or 6.0 MPa for standard (S) and heavy/very heavy traffics (H/V), respectively, at the testing frequency of 10 rad/s [19]. Notwithstanding, numerous studies suggested that this parameter is not appropriate for characterizing asphalt binders resistance to fatigue damage [3, 4, 20, 21], since the data are collected at the linear viscoelastic (LVE) region; therefore, it is difficult to ensure that cohesive fatigue cracking is occurring when Superpave temperature is used.

Other researchers have used the Cole-Cole diagram to define a fatigue test temperature for asphalt mixtures, based on the concept of energy dissipation. The Cole-Cole diagram is obtained from linear viscoelastic properties results, and is oftentimes used to assess intermediate and low temperature data. The storage modulus E1 (real component) is plotted to the x-axis, and the loss modulus E2 (imaginary component) is plotted to the y-axis [2]. Some authors suggest selecting the temperature that maximizes the loss modulus, since this condition is critical to the fatigue test because of the greatest energy dissipation per loading cycle [22, 23]. Nonetheless, this procedure can be adopted for asphalt mixtures only, since the Cole-Cole diagram resembles a bell-shaped curve, in which loss modulus reaches a peak value. For asphalt binders, the bell shape is not observed; for higher storage modulus values, the loss modulus continuously increases. This phenomenon is related to the absence of mineral aggregates, which restricts the use of the Cole-Cole diagram to determine a critical temperature for LAS fatigue tests.

It is worth noting that the fatigue damage may not occur at a specific temperature. At higher temperatures, plastic flow is observed as the main failure mechanism, but at lower temperatures, the binder's elevated stiffness may contribute to the formation of thermal cracks [24]. Therefore, the cohesive fatigue cracking is observed at a critical and intermediate range, which can vary according to the type of asphalt binder and climatic conditions.

Anderson *et al.* [21] tested different binder types at different temperatures that corresponded to initial stiffness values of 5.0 and 45.0 MPa by means of TS tests. At low temperatures, internal damage (cohesive fatigue) was observed, given that the effect of gap thickness was negligible, and at high temperatures plastic flow was observed at the sample periphery. Similar results were obtained by Hintz and Bahia [25] in TS tests. The edge cracks initiated at the sample periphery and propagated towards the center, reducing the effective sample radius during torsional stresses. In subsequent studies, Safaei and Hintz [24] proposed a $|G^\star|$ interval in which cohesive fatigue cracking would occur. They observed that above this limit (low temperatures), adhesion loss at the sample-plate interface

Table 1: Asphalt binders characteristics

Test	Unit	30/45	HPMB
Performance Grade (PG)	–	64H-XX	82H-XX
		58V-XX	82V-XX
Penetration @ 25°C, 5 s, 100 g	0.1 mm	31	45
Softening point	°C	53.2	84
Elastic recovery @ 25°C, 20 cm	%	–	96
Apparent viscosity @ 135°C, SP21, 20 rpm	cP	468	2,170
Apparent viscosity @ 150°C, SP21, 50 rpm	cP	226	997
Apparent viscosity @ 177°C, SP21, 100 rpm	cP	78	309

became a concern, and below this limit (high temperature) plastic flow was the dominant failure mechanism, instead of cohesive fatigue. More recently, Safaei and Castorena [26] have proposed $|G^\star|$ limits that comprises the cohesive fatigue cracking in LAS tests. These authors suggested that the $|G^\star|$ of binder samples should be within 12 to 60 MPa for cohesive fatigue cracking, but a limited number of binder types were used in the referred study.

Currently, there are several types of asphalt binders and polymer modifications available in the market with specific characteristics in terms of rheological properties and performance. The highly polymer-modified binder (HPMB) has been increasingly used in asphalt mixtures, because of its higher fatigue and permanent deformation resistance if compared to conventional asphalt binders [27–30]. With the continuous growth of traffic load in terms of number of passing loads, HPMB may be an alternative binder to improve the asphalt pavement performance. Since temperature plays an important role, a better understanding of the binder fatigue life is important.

3 Materials and test methods

3.1 Asphalt binder characterization

For the present study, two materials were selected: (i) neat (penetration grade 30/45), and (ii) highly polymer-modified binder, referred to as HPMB. The asphalt binders high-temperature performance grade (PG) values were determined according to AASHTO M 332 [31] for heavy and very heavy traffic levels (10-30 million and >30 million ESALs, respectively), which are commonly observed in Brazilian highways. The asphalt binders' empirical characteristics and the PG grade are presented in Table 1.

The linear viscoelastic (LVE) properties of both binders were obtained before and after the Rolling Thin-Film Oven Test (RTFOT) laboratory aging, which was per-
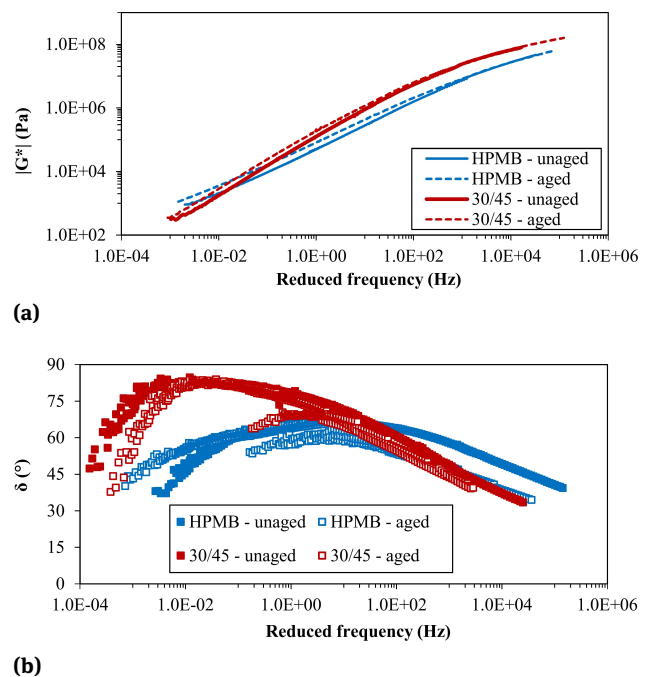

(a)

(b)

Figure 1: Master curves of AC 30/45 and HPMB before and after aging: (a) dynamic shear modulus and (b) phase angle

formed according to the ASTM D 2872 [32] procedure. Figure 1 presents the dynamic shear modulus ($|G^\star|$) and the phase angle (δ) master curves before and after aging at a reference temperature of 40°C. The test was conducted at temperatures between 10 and 70°C. The results show that the HPMB presents greater $|G^\star|$ in comparison with the AC 30/45 at low frequencies (or high temperatures) and lower $|G^\star|$ at high frequencies (or low temperatures). This behavior is due to the presence of polymer in the asphalt binder, which, in general, results in lower thermal susceptibility [33], and improves the binder performance [34–36].

3.2 Linear amplitude sweep (LAS) test

The LAS fatigue tests were conducted according to AASHTO TP 101 [37] after short-term aging in RTFOT. Binder samples (two replicates for each test condition) of 8mm diameter were molded and the DSR plates were heated to 40°C prior to the tests, to ensure proper adhesion between the binder sample and the DSR plates. After that, the test temperature was adjusted. As different temperatures are adopted in binder fatigue tests, a literature review was conducted in order to evaluate the most used temperatures, as summarized in Table 2. The tests were performed at 10, 15, 20, 25 and 30°C, which are the most common temperatures selected for asphalt binder fatigue tests. In addition, recent studies have concluded that, within the aforementioned temperature range, the asphalt binder might experience adhesion loss, plastic flow, or cohesive fatigue cracking. Thus, the selected temperatures can help explain the different failure mechanisms of asphalt binders.

Table 2: Summary of test temperatures in previous studies of fatigue characterization

Country	Source	Test temperature (°C)
USA	Shenoy [38]	15, 20, 25, 30
Brazil	Nuñez *et al.* [39]	25, 35
Brazil	Pamplona [40]	25, 35
Brazil	Martins [9]	19
USA	Safaei and Hintz [24]	5, 10, 15, 20, 25, 35
Spain	Miró *et al.* [41]	−5, 3, 10
Brazil	Quintero *et al.* [22]	0, 10, 20, 30, 40
India	Saboo and Kumar [42]	10, 20, 30
USA	Safaei and Castorena [26]	5, 10, 15, 20, 25, 35
USA	Safaei *et al.* [18]	10, 15, 20, 25

The LAS test consists of two steps: (i) frequency sweep and (ii) amplitude sweep. At the first step, a frequency sweep from 0.2 to 30 Hz is performed using 0.1% applied strain to ensure that the binder strain is within the LVE region. Then, a log-log plot is obtained from the storage modulus (G') and angular frequency (ω) data, and the slope m of the linear regression model is determined; the α value is then calculated as the reciprocal of m. At the second step, a linear amplitude strain sweep is applied (0 to 30%) at 10 Hz and from the damage characteristic curve (C × S), parameters C_1 and C_2 are determined. For the fatigue failure criterion, we considered the maximum shear stress. This corresponds to the stress-strain curve peak. Finally, the A and B coefficients and the fatigue equation are then derived (Equation 1).

$$N_f = A(\gamma)^{-B} \qquad (1)$$

Where

N_f: Number of cycles until failure;

A, B: Fatigue equation coefficients;

γ: Strain amplitude (%).

4 Results and discussions

After the completion of the tests at different temperatures, stress-strain curves were plotted to evaluate the damage evolution and the failure point of each material tested. Figure 2a and Figure 2b show the curves for the AC 30/45 and HPMB binders, respectively. These curves are relevant to observe and to compare the peak shear stress during the test for the different binders and temperature conditions tested.

Figure 2 shows that the peak stress levels for the AC 30/45 are greater than the ones for the HPMB at all tested temperatures. This behavior is related to the 30/45 binder's higher stiffness at intermediate temperatures, as previously depicted by the |G⋆| master curves. However, at 10°C the stress-strain curve of the AC 30/45 showed inconsistent
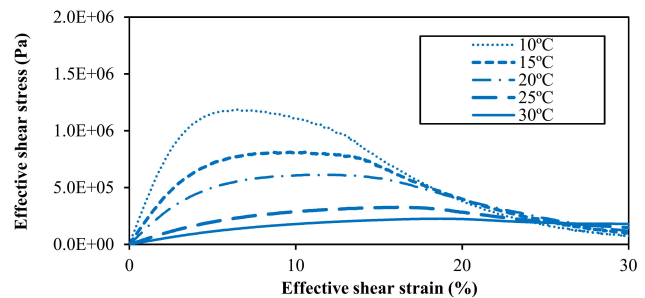
(a)
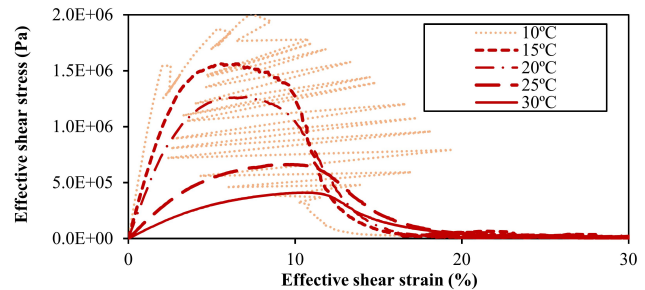
(b)

Figure 2: Stress-strain curves from (a) HPMB and (b) AC 30/45

Table 3: Peak stress and respective strain values for 30/45 and HPMB binders at different temperatures

Temperature (°C)	Asphalt binder			
	30/45		HPMB	
	Peak stress (kPa)	Strain at failure (%)	Peak stress (kPa)	Strain at failure (%)
10	-	-	1,185	6.6
15	1,561	5.6	810	9.7
20	1,262	7.0	612	11.6
25	661	9.9	326	16.4
30	409	10.5	225	18.7

Table 4: Summary of |G*| range recommendation for different failure mechanisms

Source	Binder test	Type of binder	|G*| (MPa)		
			Adhesion loss	Cohesive fatigue	Plastic flow
Anderson *et al.* [21]	TS	Unmodified	-	28-55	5-18
		SB crosslinked	-	15-45	5-10
Planche *et al.* [47]	TS	Not specified	-	> 15	5
Safaei and Hintz [24]	TS	Not specified	> 50	10-50	< 10
Safaei and Castorena [26]	LAS	Not specified	> 60	12-60	< 12

data. This may be attributed to adhesion loss at binder-plate interface, which will be further discussed in the paper. From Figure 2, it is also possible to state that as temperature increases, the peak shear stress value decreases due to binder stiffness reduction at higher temperatures, which requires lower stresses to deform the specimen. Also, as the failure criteria was the peak stress, higher strain levels were necessary to crack the specimen with the increasing temperature. Table 3 presents the peak shear stress values and the respective shear strain for both AC 30/45 and HPMB at the different testing temperatures.

The lower stress levels required to achieve the strain amplitudes during the test in the HPMB specimens might be related to the presence of polymer. In addition, asphalt binders with higher elasticity and lower stiffness normally tend to have better fatigue resistance in strain-controlled tests [43]. These results can also be explained by the type and content of polymer within the HPMB microstructure. When added to the binder, the styrene-butadiene-styrene (SBS) polymer absorbs some saturated branches and rings of bitumen components, swelling 9-10 times from its initial volume. The addition of 7 to 8% of SBS, which is commonly adopted for HPMB formulation [27], causes a phase inversion, and the polymer forms a continuous network. This network imparts greater elasticity to the asphalt binder and, consequently, higher resistance to permanent deformation and to fatigue cracking [27, 28, 44–46]. For this reason, higher strain levels are required before failure occurs in HPMB specimens.

In order to evaluate the influence of temperature, some studies have correlated the |G*| values with the asphalt binder failure mechanisms. Table 4 summarizes the studies which suggest |G*| ranges in which cohesive fatigue would occur, as well as other failure mechanisms, for instance, adhesion loss and plastic flow. From Table 4, it can be seen that according to the binder type or the fatigue test, the same failure mechanism can be related to completely different |G*| values.

Table 5 presents the |G*| values at 10 Hz obtained from the frequency sweep step for each test temperature and color-coded according to Safaei and Castorena [26], since it was the only study that presented |G*| range recommendations for LAS tests. Table 5 shows that at 10°C the 30/45 binder showed |G*| values greater than 60 MPa. This suggests that adhesion loss may have occurred at binder-plate interface, due to the binder's high stiffness, which would explain the inconsistent data observed in Figure 2. On the other hand, the HPMB shows lower |G*|, which characterizes cohesive cracking, because the polymer network imparts greater elasticity and stiffness reduction. These characteristics (low |G*| values) were already reported herein by means of the master curves. At the highest temperature tested (30°C), both binders presented |G*| values lower than 12 MPa, which indicates that plastic flow may be the dominant failure mechanism at this condition.

It is worth mentioning that even though the 30/45 binder and the HPMB are completely different materials in terms of rheological properties, both binders fail due to co-

Table 5: Relationship between |G*|, test temperature and failure mechanism (based on [26])

Asphalt binder	Replicate	|G*| @ 10Hz (MPa)				
		10°C	15°C	20°C	25°C	30°C
30/45	1	88	55	41	14	7
	2	92	57	40	14	7
HPMB	1	40	22	14	5	3
	2	39	21	13	5	3

Caption: ■ = plastic flow; ■ = cohesive cracking; ■ = adhesion loss

Table 6: LAS fatigue model parameters A and B

Temperature	30/45		HPMB	
(°C)	A	B	A	B
10	-	-	3.814E+05	−3.579
15	1.354E+05	−3.427	6.305E+05	−3.118
20	1.621E+05	−3.005	1.236E+06	−3.019
25	1.805E+05	−2.596	1.275E+06	−2.724
30	1.308E+05	−2.422	1.754E+06	−2.690

hesive fatigue cracking at 15 and 20°C. This could be the reason for most studies to adopt the temperature of 20°C for fatigue testing. Conversely, the arbitrary selection of a test temperature might lead to inconsistent conclusions. Different types of asphalt binders and modifiers should be evaluated in order to validate 20°C as LAS test temperature, ensuring that cohesive cracking is observed rather than plastic flow or adhesion loss. For the HPMB, the test temperature of 20°C and the 30% applied strain specified at the current test protocol proved to be adequate. It was possible to identify the peak stress on the stress-strain curve, but lower values of strain amplitude could have provided the failure point for the two materials tested.

If all the references provided in Table 4 are considered, the temperature of 20°C should be selected for the 30/45 binder, and the temperatures of 10 and 15°C should be chosen for the HPMB in terms of fatigue characterization. This is an important issue to be addressed, because it shows that two binders with different composition and stiffness do not necessarily need to be tested at the same temperature for comparison purposes. The authors believe that the consideration of the |G*| value in the beginning of the LAS fatigue tests, which corresponds to the undamaged material ($|G^\star|_{LVE}$), might be significant in characterizing the fatigue behavior of asphalt binders.

Finally, Figure 3 shows the fatigue curves for both asphalt binders. The curves were plotted by using the mean values of the A and B parameters (Equation 1) at each test condition, which are presented in Table 6. It can be seen that the HPMB showed higher resistance to fatigue than
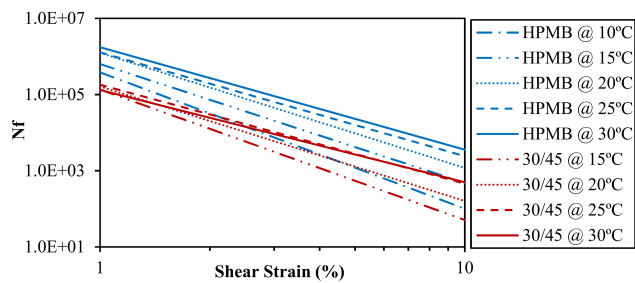
Figure 3: Fatigue curves

the 30/45 for all tested temperatures, since the A parameter was greater for this binder at all temperatures. Regarding the B parameter, there is a clear tendency towards higher absolute values for lower temperatures, which indicates that both asphalt binders tested are more susceptible to strain variation at low temperatures.

The increase in temperature enhances resistance to fatigue damage, since a greater number of cycles is required before failure. Thus, seeing that the current LAS test protocol does not specify a testing temperature, conducting the test at higher temperatures would give the wrong perception that the asphalt binder is more resistant to fatigue damage, overestimating its performance, while at lower temperatures its performance may be underestimated. Therefore, the standardization of a test temperature would provide similar test conditions in order to evaluate the fatigue resistance of different types of asphalt binders. In addition, the consideration of |G*| values of each binder coupled with the LAS test might represent the
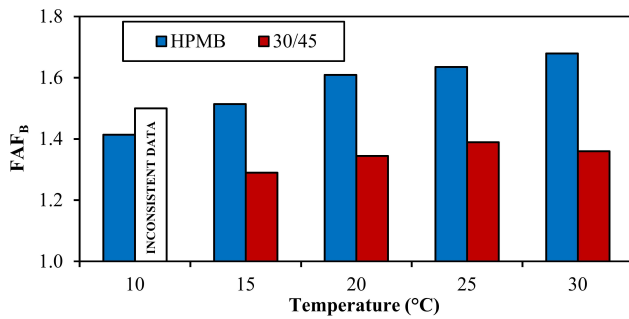
Figure 4: Fatigue area factor results

(a)

(b)

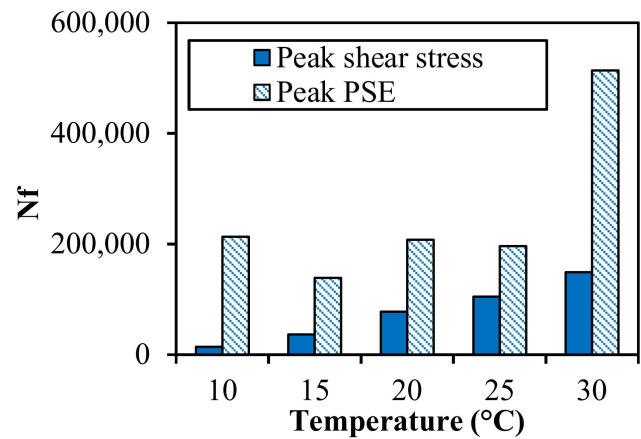**Figure 5:** Results from two failure criteria: (a) HPMB and (b) AC 30/45

failure mechanism of fatigue cracking in asphalt binders. This would be beneficial for the selection of the most suitable asphalt binder type, diminishing pavement distresses in its early-life service.

Nascimento [11] proposed a correlation between asphalt binders and asphalt mixtures based on a parameter referred to as fatigue area factor (FAF), which is the area limited by the fatigue curve, in log-log scale, between two previously selected strain amplitudes. For asphalt binders, the amplitudes recommended are 1.25 and 2.5%. Figure 4 shows the FAF_B values obtained for the materials tested in this research. Higher values of FAF indicate better resistance to fatigue cracking.

The results indicate that the higher the temperature, the less susceptible to strain variation is the binder, but after 25°C the 30/45 binder decreases its FAF_B value, which indicates worse fatigue cracking resistance at this temperature. In addition, at each temperature tested, the fatigue resistance is higher for the HPMB material, as we have shown on the fatigue life curves.

In terms of alternative failure criteria, several researchers have studied different approaches to analyze asphalt binders fatigue damage. In relation to the LAS test, Safaei and Castorena [26] proposed the stored pseudostrain energy (PSE) as a good indication of damage accumulation during fatigue tests (Equation 2). The increase of stored PSE indicates that the specimen remains able to store additional energy as the loading cycles and increasing amplitude continue during the test. The peak of stored PSE corresponds to the point where there is a rapid decrease in the material's integrity, where the failure could be defined. Figure 5 presents the correlation between N_f values at 2.5% strain for the two failure criteria presented: peak stored PSE and peak shear stress. The 2.5% strain was proposed by Johnson *et al.* [48] and Shamborovskyy [49] for being an adequate strain amplitude value for asphalt binder characterization.

$$W_s^R = \frac{1}{2} C \left(\gamma_p^R \right)^2 \qquad (2)$$
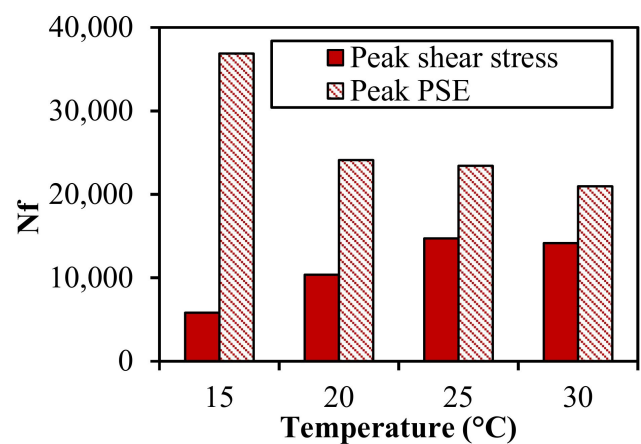
Where
W_s^R: Stored pseudostrain energy;
C: Material's integrity;
γ_p^R: Pseudostrain.

The results for the two criteria presented have different tendencies for each asphalt binder tested. The peak PSE provided fatigue life values that were not in accordance with what was found for the peak shear stress criterion. For the HPMB, the lowest fatigue life was found at 15°C and the temperature of 30°C provided a fatigue life that was almost three times higher than what was found at 25°C. For the 30/45 binder, the best fatigue life was found at 15°C, which is the opposite of what was found for the peak shear stress criterion. The differences found for the two criteria might be explained by the fact that the peak PSE is calculated instead of simply obtained during the test. It is not possible to imply which criterion should be considered for the LAS test and further investigation should be done for other asphalt binders. However, the most adequate crite-
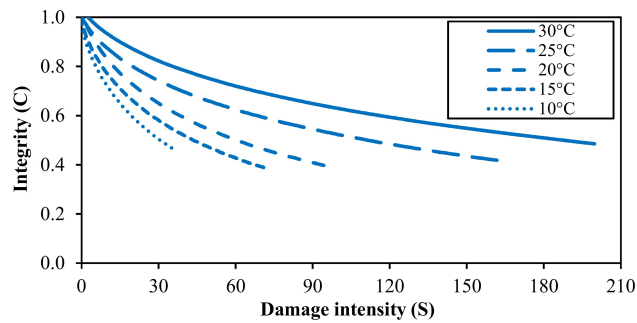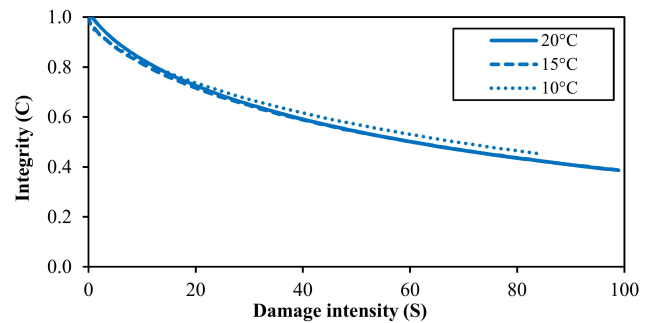
(a)
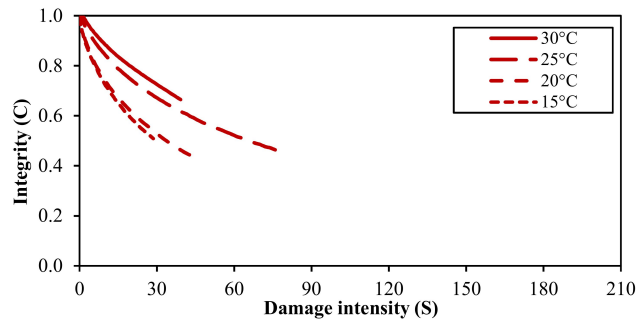
(b)

Figure 6: Damage characteristic curves: (a) HPMB and (b) AC 30/45

(a)

(b)

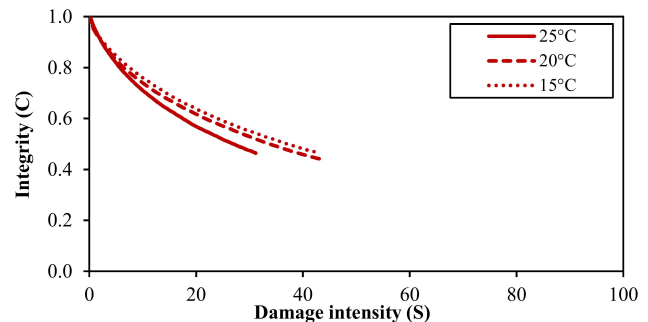**Figure 7:** Shifted damage characteristic curves: (a) HPMB and (b) AC 30/45

rion should provide results that truly identify the fatigue life of the asphalt binders and have better correlation with asphalt mixtures fatigue resistance and field performance.

The LAS test results are used in the calculation of the data needed to obtain the damage characteristic curves (C × S) of the asphalt binders tested. This curve is the plot of the integrity (C) and the damage (S) of the specimens at each loading cycle. In theory, this curve is supposed to be independent of the mode of loading and the temperature used during the tests [8, 48, 49], but this is not the case for asphalt binders tested in terms of the LAS test, since the temperature has a clear effect on the results, as shown in Figure 6. The main explanation for this might be other phenomena occurring during the test that are not related to fatigue cracking and are dependent on the testing temperature. This means that the LAS test is not a true fatigue test, as previously stated by Hintz and Bahia [52].

The C × S curves of the two binders tested did not collapse into one single curve for the different testing temperatures, which shows that the LAS test is not capable of providing the fundamental properties of the materials because it is influenced by the temperature (Safaei and Castorena [26]; Wang *et al.* [53]). Higher temperatures led to shallower curves, *i.e.*, lower decrease rate in the integrity as the damage accumulated, but for the 30/45 binder two

groups of temperature (15 and 20°C; and 25 and 30°C) resulted in similar behavior.

Following the proposition of Safaei and Castorena [26], time-temperature superposition was applied to the C × S curves by using shift factors from the frequency sweep step. In this process, only the temperatures that resulted in cohesive fatigue cracking during the test were considered (10, 15 and 20°C for the HPMB and 15, 20 and 25°C for the 30/45 binder). The reference temperature for shifting was 20°C. Figure 7 presents the results collapsed into one single curve.

The collapsed curves indicate that the LAS test coupled with the S-VECD protocol can properly characterize the fatigue resistance of asphalt binders independent of the testing temperature if the time-temperature superposition is applied. For the HPMB, the curves were better fitted in comparison with the 30/45 binder. Regarding the dispersion of the C × S curves, Singh and Swamy [54] did a probabilistic characterization of the damage characteristic curves for asphalt mixtures and stated that specimen variation and the testing procedures might lead to scattered results.

Therefore, the analysis presented herein indicates that the use of the collapsed C × S curve (independent of the testing temperature) might be helpful for predicting

binder's fatigue resistance if the suggested |G⋆| in the LVE region proposed by Safaei and Castorena [26] does truly indicate binder cohesive fatigue cracking. However, as mentioned before, the LAS test cannot be considered a true fatigue test, seeing that the C × S curves are different from each other for varying temperatures before the time-temperature superposition is applied. It is suggested that other fatigue tests (*e.g.* time sweep) should be conducted in order to confirm if the collapsed C x S curves and the recommended |G⋆| range proposed by Safaei and Castorena [26] do indeed indicate the occurrence of true fatigue cracking on asphalt binders.

5 Conclusions

Since the asphalt pavement undergoes different temperatures throughout the year, fatigue damage does not occur in a specific temperature, but in a temperature range. Thus, we present the evaluation of temperature influence in fatigue life of two asphalt binders: a neat binder (penetration grade 30/45) and a highly polymer-modified binder (HPMB). Five test temperatures were selected (10, 15, 20, 25 and 30°C) and the following conclusions can be drawn:

- The HPMB presented better performance than the 30/45 binder at all tested temperatures. The continuous polymeric network imparts elasticity to the asphalt binder, allowing higher strain levels to be supported prior to failure;
- At 10°C, the 30/45 binder presented higher stiffness, which led to loss of adhesion between the specimen and the rheometer plate. At 30°C, both asphalt binders tested had low stiffness values, and this might indicate failure by means of plastic flow instead of fatigue cracking. On the other hand, the temperature of 20°C, commonly used in fatigue tests, was adequate for the materials tested, since both binders failed under the fatigue mechanism. Several researchers do not provide a definitive reason for selecting the testing temperatures, so it is important to evaluate the failure mechanism occurring at each test so that the results are more reliable;
- The strain level (30%) specified at the current LAS test protocol proved to be adequate for the HPMB, even for the highest temperatures considered in this paper (30°C). However, seeing that the different types of asphalt binders in the market, fatigue tests should be continuously evaluated in order to validate the current strain level proposed;

- The arbitrary selection of higher temperatures might indicate better resistance to fatigue cracking, and lower temperatures might underestimate it. Therefore, it is important to select a temperature in which the asphalt binder fails under fatigue, and this temperature is not the same for different materials. The observation of the |G⋆| in the LVE region can be an important tool for this selection;
- The testing temperature to be considered in LAS tests has a major influence on the results, however it is possible to characterize the asphalt binders at one single temperature and then predict the results for other temperatures based on the shift factors from the LVE characterization of the materials. For highly modified asphalt binders, 15°C seems to be adequate, and for conventional asphalt binders 20°C seems to be more appropriate. Other temperatures might induce other mechanisms rather than cohesive fatigue cracking during the test. Despite that, the authors suggest that additional testing should be conducted in order to confirm if the collapsed damage characteristic curves and the |G⋆| in the LVE region does indicate true fatigue cracking.

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