Fatigue resistance of asphalt binders and the correlation with asphalt mixture behavior

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The prediction of asphalt pavements performance in relation to the main distresses has been proposed by different researchers, by means of laboratory characterization and field evaluation. With respect to fatigue, there are different approaches to determine what failure criterion to be considered, what testing conditions to be used and which specimens' geometry to be produced. Tests performed in asphalt binders and mixtures have been recommended to characterize the fatigue resistance, and correlations among the several scales are proposed in order to make it more practical and more precise to predict the performance of asphalt layers. In terms of laboratory fatigue characterization of asphalt mixtures, some of the most common tests are the four point bending beam, diametral compression, the push-pull tests, among others. The characterization of asphalt binders is also relevant, since fatigue is dependent on their rheological characteristics. Linear viscoelastic parameters of the binders, time sweep and amplitude sweep tests were used to rank three asphalt binders (one neat 30/45 penetration grade binder; one SBS-modified binder; and one highly modified asphalt, HiMA) in terms of fatigue behavior. HiMA showed the highest fatigue resistance. One dense hot mix asphalt (HMA) mixture (prepared with the AC 30/45 neat binder) was characterized in terms of different fatigue test methods and correlated with binder tests, comparing the two scales approaches. The fatigue life of the asphalt mixture followed in agreement with results from the asphalt binder.

Keywords: fatigue resistance; asphalt mixtures; asphalt binders; failure criteria

Introduction

The prediction of fatigue cracking performance of asphalt mixtures has been analyzed by means of different testing methods and test scale, such as the asphalt binder and the fine aggregates matrix (FAM). Since fatigue cracking is a distress highly dependent on the asphalt binder rheology and chemistry, their performance is a good indication of the fatigue resistance of asphalt mixtures.

In the late 1980s, American researchers developed the five-year Strategic Highway Research Program (SHRP) in order to put effort on the development of new techniques that could improve the performance of asphalt pavements. The project entitled ‘Binder Characterization and Evaluation’ had the main objective of providing a better understanding of asphalt binders in terms of their chemical and physical properties and to address their influence in the performance of asphalt pavements (Petersen et al., 1994). Another issue cited by the SHRP was that the traditional empirical tests could not truly capture the actual enhancement provided by the modification of asphalt binders by polymers or other materials (Gershkoff, Carswell, & Nicholls, 1997). Thus, SHRP implemented a new binder classification according to their Performance Grade (PG) by introducing rheological and performance-related tests. The methodology developed by SHRP considered stiffness-related properties to characterize the fatigue resistance of the asphalt binders. The so-called Superpave parameter, $|G^*|\times\sin\delta$, tested in aged specimens at a frequency of 10rad/s is currently specified in the PG methodology, and its value is limited to a maximum of 5,000kPa for low traffic highways and 6,000kPa for heavy/very heavy traffics (AASHTO M 332, 2014).

The Superpave parameter has many disadvantages and might not be capable of properly addressing the actual fatigue-related characteristics of asphalt materials. This parameter is obtained in the linear viscoelastic (LVE) region, so it does not account for their damage accumulation; also, other researchers have unsuccessfully tried to correlate it to the actual fatigue resistance of modified asphalt mixtures, such as Bahia et al., 2001. Those issues led to the development of new tests methods. Among the main existing laboratory tests that address the fatigue life of asphalt binders by means of the dynamic shear rheometer (DSR), the time sweep (TS) test, and the linear amplitude sweep (LAS) test have been widely studied in the past years (N. Tabatabaee & Tabatabaee, 2010; Pérez-Jiménez, Botella, & Miró, 2012; Willis et al., 2012; Bahia, Tabatabaee, Mandal, & Faheem, 2013; Nuñez, Domingos, & Faxina, 2014; Ameri, Jelodar, & Moniri, 2015; Safaei & Castorena, 2016; Wang, Zhang, Castorena, Zhang, & Kim, 2016).

The TS test can be a stress- or a strain-controlled test and consists in the application of a cyclic loading at a constant frequency. For the strain-controlled mode, performed in the present research, there are no standard frequency or strain amplitude values. In general, many authors tend to use 10rad/s and 10% of strain to accelerate the test, instead of having time-consuming testing in other conditions. It is important to ensure that the test is performed at strain levels outside the LVE region, especially because that asphalt materials have a nonlinear damage behavior (Clyne & Marasteanu, 2004). The LAS test (AASHTO TP 101, 2014) consists in the application of a cyclic loading divided into two parts. The first part corresponds to a frequency sweep from 0.2 to 30Hz at 0.1% of strain amplitude and the second part is an amplitude sweep from 0 to 30% with linear increment on the strain values at a constant frequency of 10Hz during 300 seconds. The first part of the test (frequency sweep at low strain amplitude) results in the rheological parameters of the specimen, including the relaxation modulus, which is further used in the calculation of accumulated damage.

A proper prediction of asphalt mixtures fatigue life by means of asphalt binder characterization is a complex task, but some researchers have tried different approaches. Previous studies have considered the strain distribution in asphalt mixtures to select the strain levels to be applied during the TS test. For example, Mannan, Islam, and Tarefder (2015) compared the results from four point beam tests performed in asphalt mixtures to the results from TS tests, by considering that strain levels found in asphalt binders are 100 times higher than the ones used for the asphalt mixtures characterization. Other authors have proposed different empirical correlations among the different strain and stress levels found on both materials (Underwood, 2011; Saboo & Kumar, 2016).

The present research has the main objective of comparing different fatigue resistance test methods and different approaches to characterize asphalt binders and asphalt mixtures. Correlations between the two scales are proposed. Three asphalt binders were tested in terms of the Superpave parameter, the TS and the LAS tests: one neat unmodified binder classified as 30/45 penetration grade by Brazilian standards, one SBS-modified binder, and one highly modified asphalt binder (HiMA). Asphalt mixture samples constituted by the unmodified binder were also tested in terms of fatigue resistance: diametral compression test (also known as indirect tensile test, ITT), four point bending beam test (4PBBT) and compression-tension test (also known as push-pull test).

Laboratory fatigue life characterization

Asphalt binders

The first Superpave specification's attempt to address fatigue resistance of asphalt binders was based on an experimental test site built in the 1950s in the state of California (US). Field monitoring data from the Zaca-Wigmore road test associated with laboratory test results were used as inputs for developing asphalt binder parameters that are considered in highway design projects, addressing their performance and durability (Petersen et al., 1994). The values of $|G^*|\times\sin\delta$ taken from different asphalt binders used in the construction of the test sections were compared to the percentage of cracked area. At first, the specification limited the value of $|G^*|\times\sin\delta$ in 3,000kPa obtained at the predicted annual average pavement temperature in the region of interest and at the frequency of 10rad/s (Petersen et al., 1994). This frequency value is based on an average truck speed of 80km/h (Stuark, Mogawer, & Romero, 2000). The failure criterion considered to control the maximum value of $|G^*|\times\sin\delta$ was 10% of fatigue cracking after approximately 9 to 10 years surveying the cracked area evolution (Finn, Yapp, Coplantz, & Durrani, 1990). Later, the Federal Highway Administration (FHWA) suggested increasing the limit to 5,000kPa and 6,000kPa, depending on the traffic level. The new limit values were included in AASHTO's specification for mixture design purposes (Gibson et al., 2012).

Few years after the Superpave's PG specification was initially proposed, a study by Bahia et al. (2001) concluded that the fatigue parameter could not address the modified binders' characteristics properly. This conclusion was based on 4PBBT tests performed in asphalt mixtures specimens that resulted in poor correlation between the number of cycles to failure (Nf) and the values of $|G^*|\times\sin\delta$. The failure criterion for the asphalt mixtures was 50% reduction in the initial flexural stiffness.

The lack of correlation between the Superpave fatigue parameter with the actual fatigue life of asphalt mixtures led to the development of new test methods to characterize asphalt binders in terms of fatigue resistance. Martono and Bahia (2008) conducted time sweep tests at three strain levels at 19°C and 10Hz. The authors considered 50% stiffness reduction as the failure criterion. The modified asphalt binders tested had a better resistance to fatigue cracking in comparison to the unmodified PG 70-22 binder, with the SBS-modified binder having the highest fatigue resistance among all. Tabatabaee and Tabatabaee (2010) performed the time sweep test using 10% strain level at loading frequencies of 15 and 1.59Hz (100 and 10rad/s), but discarded the 1.59Hz- tests because most binders did not fail in a reasonable amount of time. Testing temperatures were set at 5 and 30°C, but the first was discarded due to high stiffness values of the asphalt binders, which prevented the equipment to reach the target strain during the test. The authors compared the results from the time sweep tests (10% controlled-strain) performed in the asphalt binders to results of dissipated energy from indirect tensile strength tests performed in asphalt mixtures, and the correlation was found to be better than the correlation with the Superpave parameter.

The time sweep test might be time-consuming, especially if various strain levels are tested, and the results tend to present high variability. Due to these disadvantages, Johnson (2010) introduced an accelerated test known as the linear amplitude sweep (LAS). The author applied viscoelastic continuum damage concepts to characterize asphalt binders by means of the LAS test, providing a faster and more precise method from which it would be possible to correlate and to validate the results to asphalt mixtures behavior in laboratory, and the field performance. Other approaches have been considered to obtain the fatigue resistance of asphalt binders by means of the LAS test. One of them was studied by Hintz (2012) and is related to the fracture mechanics. The failure criterion proposed was the minimum value of crack growth rate before its rapid increase. This author found a good comparison ranking between the number of cycles to failure (from the time sweep test) to the crack length at failure (from the LAS test).

Asphalt mixtures

Regarding fatigue cracking characterization of asphalt mixtures, the commonly used laboratory tests can be divided in different methods, depending on the loading application, the failure criterion, and the specimen’s geometry, among others. Nuñez (2013) listed some of these tests: simple flexure, supported flexure, direct axial, diametral, triaxial, tests that consider the fracture mechanics principles, and accelerated pavement testing. Di Benedetto, La Roche, Pronk, and Lundström (2004) organized an interlaboratorial study that included several European countries with the main objective of analyzing the fatigue resistance characteristics of asphalt mixtures using eleven different test methods. The tests results based on the classical approach of fatigue cracking evaluation (number of cycles until 50% of stiffness) were highly influenced by the loading mode. The ones based on the continuum damage theory were capable of isolating the intrinsic characteristics of fatigue cracking resistance from the influence of the test methods.

Experimental testing

Asphalt binders

The present research is divided into two main laboratory studies: fatigue characterization of asphalt binders and fatigue characterization of asphalt mixture. In relation to the asphalt binders, three materials were tested by means of three different methods (the acquisition of the Superpave fatigue parameter $|G^*|\times\sin\delta$, the time sweep test, and the linear amplitude sweep test). Table 1 presents the empirical characterization of the materials tested: one neat 30/45 penetration grade asphalt cement (PG 58V-XX), one modified binder with 3.0% SBS (PG 82V-XX) and one highly modified asphalt with 7.5% SBS (HiMA, PG 82V-XX). Their characteristics meet the criteria required by the Brazilian standards. As expected, both modified materials are more viscous than the AC 30/45, and HiMA had 10% more elastic recovery than the SBS-modified binder.

Table 1. Empirical characterization of the asphalt binders.

Test procedure	Asphalt binder			Test standard
	30/45	SBS	HiMA	
Penetration (10^{-1}mm)	31	54	45	ASTM D 5/D 5M (2013)
Softening point (°C)	53.2	66.0	84.0	ASTM D 36/D 36M (2014)
Elastic recovery (%)	–	87.5	96.0	ASTM D 6084/D 6084M (2018)
Flash point (°C)	352	> 235	308	ASTM D 92 (2016)
Specific gravity	1.007	1.008	1.003	ASTM D 70 (2018)
Brookfield viscosity (cP):				ASTM D 4402/D 4402M (2015)
at 135°C	468	1,989	2,170	
at 150°C	226	805	997	
at 177°C	78	227	309	

The fatigue resistance tests were performed in the dynamic shear rheometer (DSR), by three different analyses. Firstly, the Superpave parameter |G*|×sinδ was obtained for aged specimens, at the frequency of 10rad/s, which is based on normal traffic speed from approximately 50 to 60mph (Bahia et al., 2001). There are two main reasons for limiting |G*|×sinδ to a maximum value. In order to resist early fatigue cracking, the asphalt binder should be elastic enough to rebound under traffic cyclic loading (lower phase angle) and not too stiff to avoid premature cracking (lower stiffness modulus). Shen, Airey, Carpenter, & Huang (2006) approached another explanation in their study by considering that a low amount of dissipated energy during load cycles is found in highly fatigue-resistant materials. Figure 1 presents the results at several testing temperatures and shows the maximum allowed value of 5,000kPa for standard traffic highways (lower than 10 million ESALs).

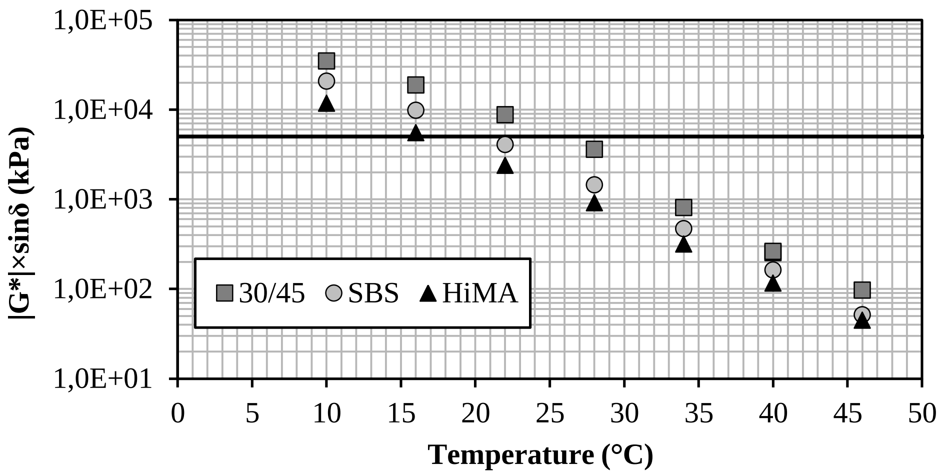


Figure 1. Superpave parameter |G*|×sinδ at different temperatures.

According to the results, the modified binders met the fatigue cracking parameter for 20°C or higher temperatures, but the unmodified binder would only meet the Superpave criterion for temperatures higher than 25°C, which is still satisfying, considering that the fatigue cracking occurs at intermediate temperatures. Considering the entire temperature range, the unmodified binder tends to be more susceptible to temperature changes (highest value of the fitting curve slope), while the HiMA has the lowest temperature susceptibility (lowest slope value). The behavior observed for the unmodified and the modified binders indicates that the parameter |G*|×sinδ might not be capable of properly distinguish asphalt binders, especially considering the modification. As previously reported by other studies, fatigue resistance cannot be predicted from LVE properties, because nonlinear behavior and damage should also be accounted.

For the present research, the fatigue tests were performed at 20°C, because this has been considered as an appropriate temperature in which cohesive fatigue cracking occurs in asphalt pavements. Also, higher testing temperatures could lead to the occurrence of other failure mechanisms during the tests. In addition, having one single temperature for all the tests proposed allows for the correlations among different tests.

The TS test procedure was performed at 20°C and 10Hz at different strain levels. The AC 30/45 binder was tested at 2, 4 and 6% strain, and the modified binders were tested at 6, 8 and 10% strain. These values were found to be outside the LVE region of the materials, which ensures the performance of nonlinear damage-induced tests. The strain amplitude values were chosen based on the LVE strain limits found for each material, which corresponds to the strain amplitude in which |G*| is more than 90% of the initial |G*| value. Bahia et al. (2001) consider that the frequency of 10Hz is very high; however, this value was still selected in order to reduce the testing time and to correlate the results with results from the 4PBBT performed in asphalt mixtures. Figure 2 shows the fatigue curves obtained after the TS test with the failure criterion based on 50% reduction in the initial stiffness (|G*|). Table 2 presents the parameters for the fatigue curves (Equation 1) for each material tested.

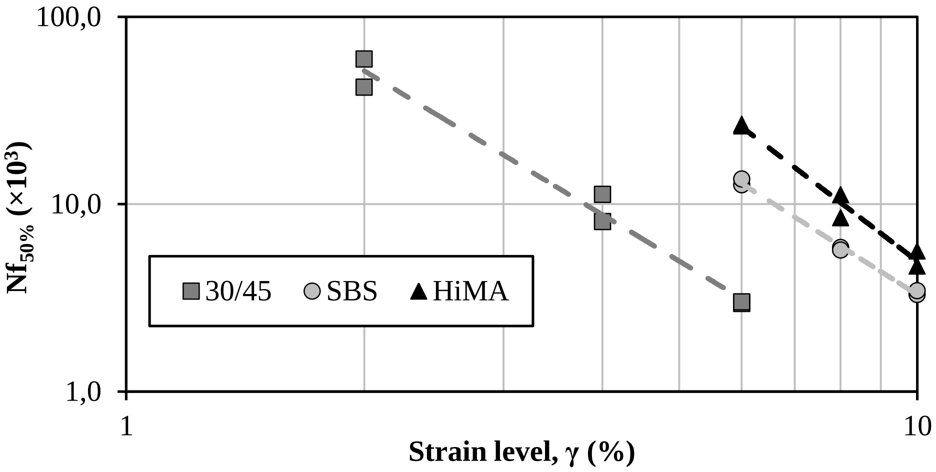


Figure 2. Fatigue behavior of the asphalt binders after TS tests.

$$N = A \times \left(\frac{1}{\gamma}\right)^{B} \quad (1)$$

Where Nf is the number of cycles to failure;
γ is the strain amplitude;
A and B are the fitting coefficients.

Table 2. Parameters of the fatigue curves for TS test.

Binder	Fatigue envelopes fitting coefficients	
	A	**B**
AC 30/45	$0.3{\times}10^6$	2.55
SBS-modified	$1.5{\times}10^6$	2.67
HiMA	$8.4{\times}10^6$	3.23

The parameter A is directly proportional to the fatigue resistance of the materials, and the parameter B is related to the susceptibility to changes on strain amplitudes. HiMA had a better fatigue cracking resistance (high values of A) and is the most susceptible to the strain amplitude, which could lead to better fatigue life at low strain levels in com to the other binders. Saboo and Kumar (2016), Anderson et al. (2001), and Ameri, Seif, Abbasi, and Khiavi (2017) found similar results for unmodified and SBS-modified asphalt binders.

Several researchers (Wang, Zhang, Castorena, Zhang, & Kim, 2016; Rowe & Bouldin, 2000; Safaei, Lee, Nascimento, Hintz, & Kim, 2014) have indicated the peak value of the normalized |G*| (Equation 2) as a better representative of the failure point of an asphalt material rather than using any percentage of the initial |G*| value. According to Wang, Zhang, Castorena, Zhang, and Kim (2016), this phenomenological failure parameter correlates well with the beginning of crack propagation when considered in asphalt mixtures characterization and it has been very promising for asphalt binders too. Figure 3a presents the evolution of normalized |G*| values with the increasing number of cycles (for 6% strain level), and Figure 3b provides a correlation between the Nf considered in this approach and the Nf obtained for the analysis that considers the reduction to 50% of initial |G*|. The comparison between these two failure criteria indicates that they both provide similar fatigue life since the results are very close to the equality line, except for the HiMA. This asphalt binder did not reach the peak value of normalized |G*|, which shows that the fatigue life of this asphalt binder would be much higher if the $|G^*|_{norm}$ criterion was considered. Therefore, the TS test should be carefully evaluated and finished after the peak of $|G^*|_{norm}$ is finally reached.

$$|G^*|_{norm} = N_i \times \left(\frac{|G_i^*|}{|G_0^*|}\right) \quad (2)$$

Where $|G^*|_{norm}$ is the normalized shear modulus;
N_i is the number of accumulated cycles at cycle i;
$|G_i^*|$ is the shear modulus at cycle i;
$|G_0^*|$ is the initial shear modulus.

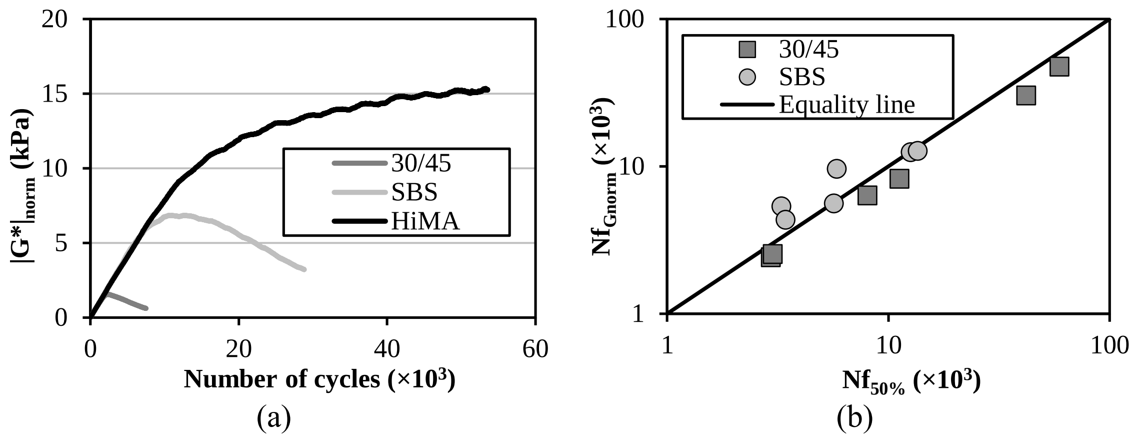


Figure 3. TS test results: (a) evolution of |G*|norm at 6% strain level, and (b) comparison between results from |G*|norm and 50% of initial |G*|.

The comparison between the number of cycles to failure according to 50% of the initial |G*| from the TS test and the Superpave parameter |G*|×sinδ was done. The fatigue life of an asphalt binder is dependent on the strain amplitude to which the material is subjected, therefore Figure 4a shows only the correlation considering 6% strain amplitude. In general, the lower the fatigue life, the higher the value of |G*|×sinδ is, which is expected, since the Superpave specification limits maximum values for the parameter.

Some researchers have used the dissipated energy approach to characterize asphalt binders in relation to fatigue cracking. The concept of dissipated energy ratio

(DER) was proposed by Ghuzlan and Carpenter (2000) and is calculated by Equation 3. Figure 4b presents the comparison between Nf values from two different approaches: considering 50% of decrease in the initial |G*| value and the point where the DER evolution is no longer linear. It is possible to see that the values are close to the equality line, which means that both criteria might indicate similar fatigue resistance to the asphalt binders.

$$DER = \frac{(DE_{n+1} - DE_n)}{DE_n} \quad (3)$$

Where DER is the dissipated energy ratio;
DE_n is the dissipated energy produced in load cycle n;
DE_{n+1} is the dissipated energy produced in load cycle n+1.

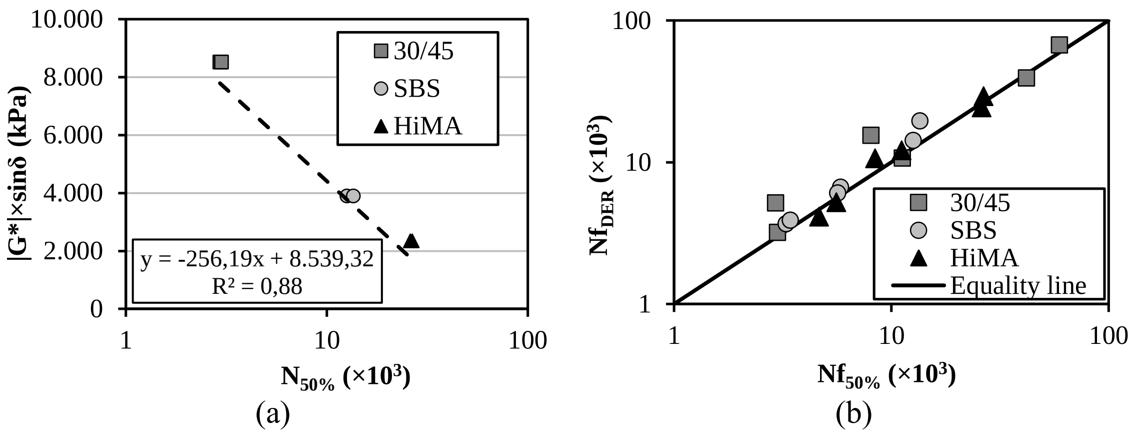
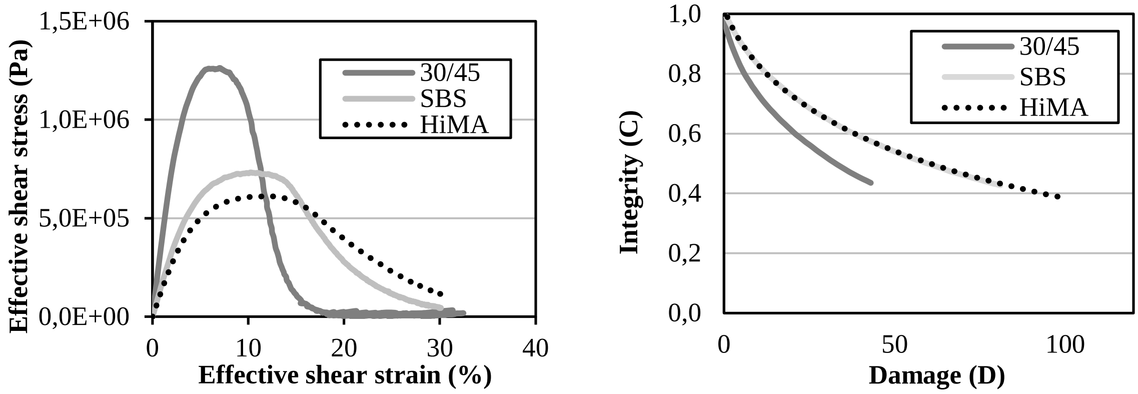


Figure 4. TS test results: (a) comparison with |G*|×sinδ at all strains tested, and (b) comparison between results from the dissipated energy approach and from the 50% of initial |G*| approach.

Another test method that has currently been performed in asphalt binders to predict their fatigue resistance is the LAS test. When the LAS test method was first introduced, the strain amplitude range went from 0 to 20%, but Hintz, Velasquez, Johnson, and Bahia (2011) concluded that some asphalt binders exhibit small damage levels under this condition, so they decide to extend the strain amplitudes to 30%. Then, Hintz and Bahia (2013) proposed to change the original stepwise amplitude sweep to continuous amplitude sweep, using small increments in loading amplitude at every cycle, should be used. This would resolve issues on the use of some rheometers that are not capable of increasing the strain amplitudes in sudden steps. Also, this new procedure eliminates crack tip formation on the specimens.

The LAS tests were performed at 20°C and the analyses of the results were based on the simplified viscoelastic continuum damage (S-VECD) theory. Figure 5a presents the change in effective shear stress with the effective shear strain. For the present research, the peak stress value was considered as the failure criterion, based on the provisional standard AASHTO TP 101 (2014). The AC 30/45 has a rapid increase in its shear stress in comparison to the modified binders, with a peak value of approximately 1.26×10^{6}Pa at the strain of 7.0%. The modified binders have a slower increase of their shear stress value, with their peak occurring in a stress value that is around 50% less than the value obtained for the unmodified binder. The SBS-modified binder has a peak shear stress value of 7.3×10^{5}Pa at 10.2% strain and the HiMA has a peak value of 6.1×10^{5}Pa at 11.6% of strain. Figure 5b shows the damage characteristic curves (material's integrity versus damage intensity, which were calculated according to AASHTO TP 101, 2014) for the three asphalt binders tested. These curves represent the decrease on the initial integrity of the materials as the damage increases. The integrity referred to in this paper is the value of |G*| at each cycle divided by the initial value of |G*|.



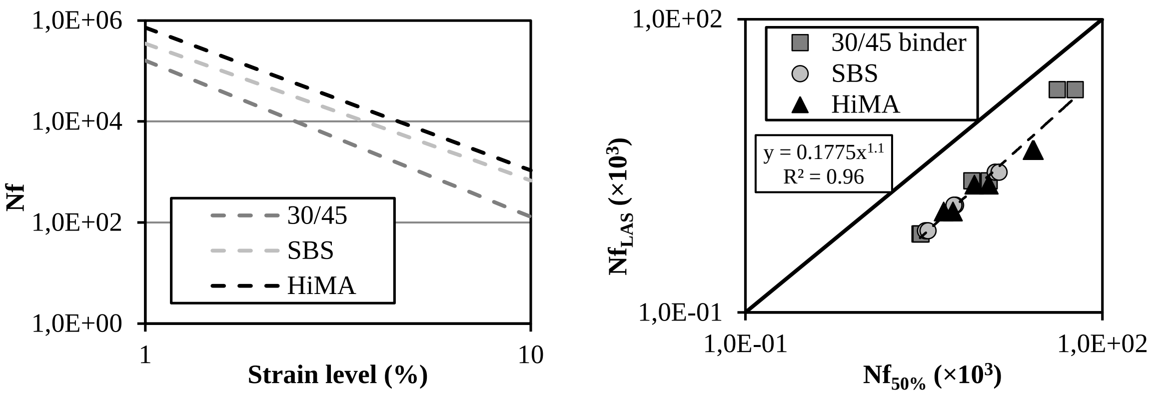
(a) (b)

Figure 5. LAS test: (a) stress-strain curves, and (b) damage characteristic curves.

As expected, the integrity of the AC 30/45 decreases more rapidly than the integrity of the modified binders (Figure 5b). The comparison between the SBS-modified binder and the HiMA indicates that they behave very similarly, with the HiMA having a softer curve at the end of the test. Table 3 presents the fitting coefficients of the fatigue curves for the three binders analyzed in terms of the S-VECD model. The parameters correspond to the strain levels in which each binder was tested at the time sweep tests. It is important to state that the higher the parameter A, the better is the material fatigue resistance. Figure 6a illustrates the fatigue curves, and Figure 6b shows a correlation between these results and the TS test results (50% of initial |G*| value).

Table 3. Parameters of the fatigue curves for LAS test.

Binder	**Fatigue curves coefficients**	
	A	**B**
AC 30/45	1.36×10^{5}	3.26
SBS-modified	3.38×10^{5}	2.83
HiMA	1.01×10^{6}	3.21



(a) (b)

Figure 6. LAS test: (a) fatigue curves, and (b) comparison between LAS test results and TS test results.

The fatigue curves (Figure 6a) indicate that the unmodified binder has a lower fatigue resistance if compared to the modified binders. The slopes are very similar for both modified materials but the unmodified binder has a more pronounced slope, which indicates that the fatigue resistance of this material is more affected by the strain levels it would be subjected to. The HiMA is the most resistant among the three binders analyzed, providing twice the number of cycles to failure if compared to the SBS-modified binder. The comparison between the results obtained by means of the LAS test and the results from the TS test shows that the LAS test tends to provide fatigue lives that are approximately 4.5 times lower than the fatigue life obtained from the TS test, but there is a clear correlation between the two tests.

Asphalt mixture

The second part of the present research is related to the characterization of one hot mix asphalt (HMA) constituted by the AC 30/45 that was previously characterized and presented in this paper. Due to limited time and testing materials, the two modified binders were not analyzed in terms of asphalt mixtures. Three tests were performed: diametral compression test (also known as indirect tensile test, ITT), 4PBB test and push-pull test (also known as tension-compression test). The dense 12.5mm HMA was constituted by granite aggregates and 4.4% optimum asphalt content. The gradation composition meets the Brazilian limits specification for asphalt concrete mixtures. Some of the HMA design parameters include the presence of 18% of flat/elongated aggregate particles and indirect tensile strength (ITS) of 2.0MPa at 20°C.

The laboratory specimens for the diametral compression test were tested at three different stress amplitudes at the temperature of 20°C. The stress values chosen were 30, 40, and 50% of the ITS value of the asphalt mixture studied. Lower stress values are normally suggested, but due to the extensive time needed to perform the tests at 10 or 20% stress amplitude, they were not considered in this research. The classical fatigue analysis defines the failure point as the number of cycles in which the specimen reaches complete failure (for stress-controlled tests), but in the present study the failure criterion was the point where the strain growth rate of the specimen was no longer linear. Figure 7 shows the fatigue curve. Three specimens for each stress condition were tested, and due to the inherit variability normally obtained for fatigue tests, average values were not calculated, instead all the results were plotted. The results presented a good value of R^2. It is important to state that in actual pavement structures, the stress amplitudes are normally lower than the ones applied in the test.

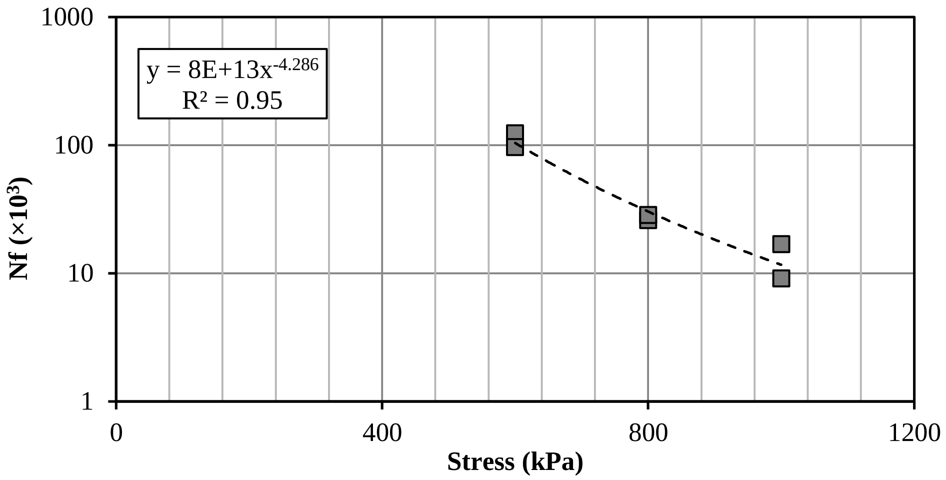


Figure 7. Fatigue life according to the ITT test.

The 4PBB tests were performed at 20°C in prismatic-shaped 380mm-long × 50mm-thick × 63mm-wide beam specimens (ASTM D 7460, 2010). Seven strain levels were selected (from 200 to 800με, with increments of 100με) based on the equipment capability. During the test, several variables were recorded for each loading cycle (loading amplitude, beam displacement, maximum tensile stress, maximum tensile strain, phase angle, and stiffness). The flexural beam stiffness (S) was calculated by means of Equation 4.

$$S_i = \frac{\sigma_i}{\varepsilon_i} \tag{4}$$

Where S_i is the flexural beam stiffness at cycle i;
σ_i is the maximum tensile stress at cycle i;
ε_i is the maximum tensile strain at cycle i.

The results were analyzed in terms of different approaches: classical fatigue life, which considers the decrease in the stiffness value, and peak value of normalized modulus. In terms of decreasing stiffness, there is a consensus that fatigue occurs at the point of 50% of the initial flexural stiffness. The normalized modulus is plotted against the number of cycles and its peak value is obtained by the maximum value of the polynomial-fit curve. Figure 8a presents the results for the laboratory in terms of four point bending beam fatigue test using the traditional analysis (number of cycles until decrease in stiffness values). The peak value of the normalized modulus was obtained through the exponential plot obtained in the curve $|E^*|_{norm}$ × number of cycles. Figure 8b presents the correlation between the results from the traditional fatigue life (50% of |E*|) and the results from the normalized modulus concept. The comparison between the two failure criteria shows that the fatigue life prediction is similar for both calculations, since the Nf values are very close to the equality line.

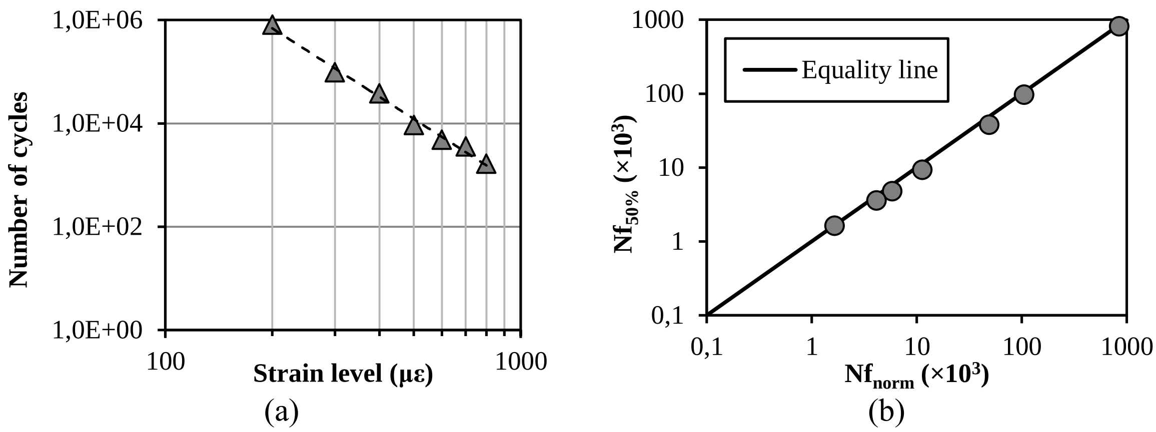


Figure 8. 4PBB test results: (a) 50% of the initial |E*| value, and (b) comparison with the peak value of $|E^*|_{norm}$.

The push-pull test was performed in order to characterize the fatigue life of the asphalt mixture in terms of the S-VECD model. Three specimens were tested by means of dynamic modulus and four specimens were tested at the temperature of 20°C for the fatigue test.

The fatigue damage characterization consisted in submitting the specimens to cyclic sinusoidal constant strain amplitude until failure (phase angle peak). The testing system collected the strain, the stress, the phase angle and the dynamic modulus throughout the test. The results were analyzed by means of the S-VECD model, and the damage characteristic curve (C × S) was plotted (Figure 9a), along with the failure envelop (Gr × Nf), presented in Figure 9b. The parameter Gr is based on the rate of change of total dissipated pseudostrain energy and is described in more details by Sabouri and Kim (2014).

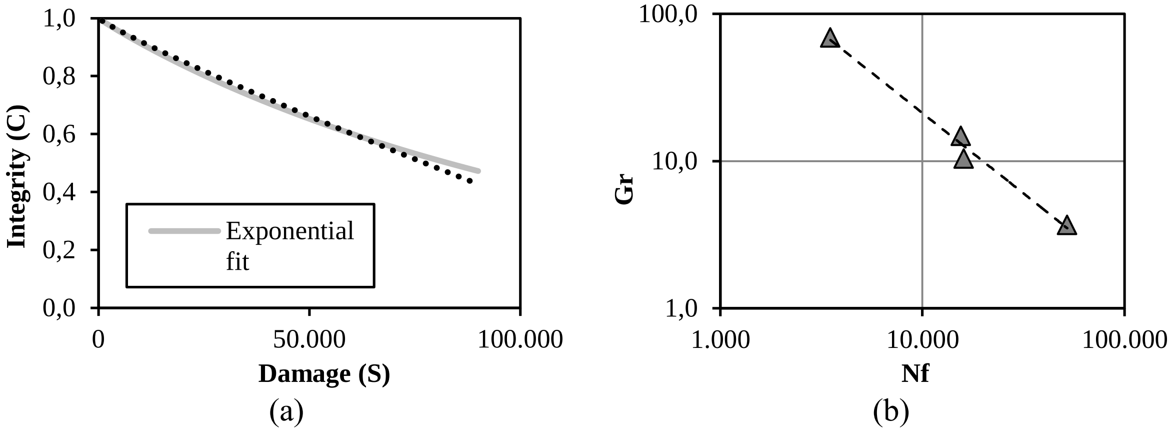


Figure 9. S-VECD results: (a) damage characteristics curve fittings, and (b) Gr curve.

After obtaining the LVE properties and the parameters needed as inputs for the S-VECD model, the fatigue life of the asphalt mixture was simulated according to the procedure presented by Nascimento (2015) combined with the Asphalt Institute model. Figure 10a presents the fatigue lives for three typical temperatures (15, 20 and 25°C) modeled at seven strain levels (200 to 800με) at the frequency of 10Hz. Figure 10b shows the correlation between the results obtained by the S-VECD model and the results from the 4PBBT test at 20°C.

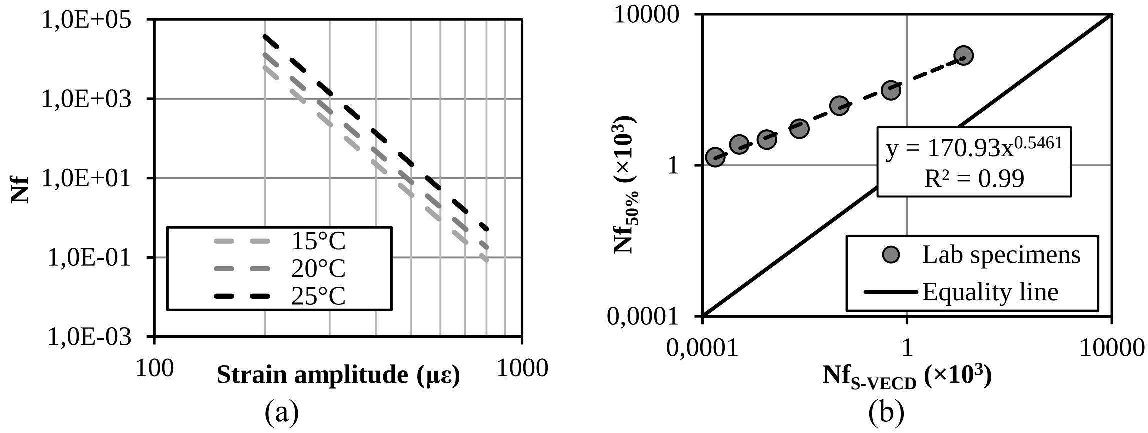


Figure 10. S-VECD simulation: (a) fatigue life at different temperatures, and (b) comparison with 50% of |E*| method (20°C).

Comparison between asphalt binder and asphalt mixture

Nascimento et al. (2014) proposed a new fatigue life criterion that can be obtained from the plot between strain amplitude and number of cycles to failure. Two typical strain amplitudes found on actual field constructions are considered (100 and 200με) for this criterion, and the area under the fatigue curve between those two points is calculated. The result is known as fatigue area factor (FAF) and is represented in Figure 11a. The higher the value of FAF is, the better fatigue resistance the asphalt mixture has. For asphalt binders, Underwood (2011) proposed the strain levels of 1.25 and 2.50% to be considered in the calculation of the FAF as this author considered that binders normally have a strain value that is about 122 times of the strain level of mixtures. For the present research, FAF_M and FAF_B, for asphalt mixtures and asphalt binders, respectively, were calculated in terms of the S-VECD results from the push-pull test and from the LAS test. Figure 11b shows the correlation between nine binders and nine mixtures in terms of FAF_M and FAF_B from the research done by Martins (2014) with the addition of the results from the present research.

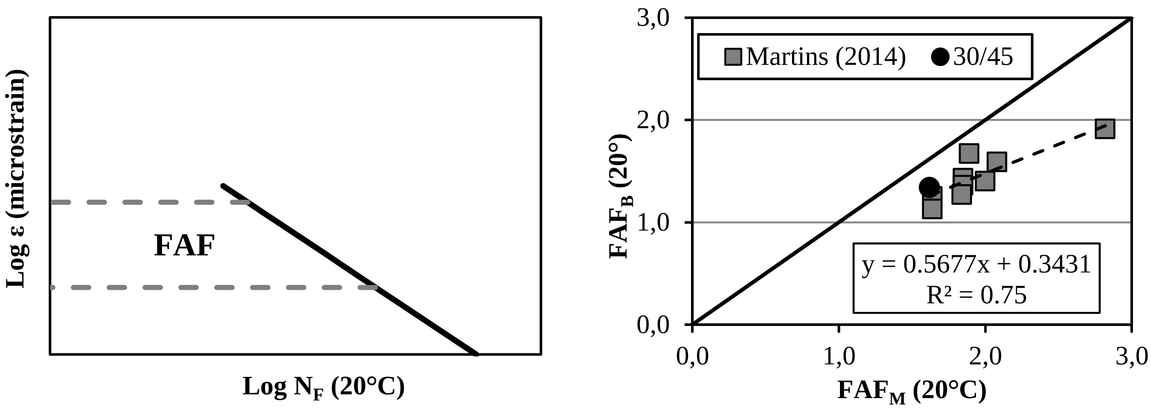


Figure 11. Fatigue area factor: (a) calculation of FAF (adapted from Nascimento, 2015), and (b) comparison between FAF_B and FAF_M.

Following the work done by Saboo and Kumar (2016), there was an attempt of correlating the fatigue results from the LAS test to the fatigue life of asphalt mixtures tested by means of the 4PBB test (using the failure criterion of 50% of initial |E*|). These authors assumed that the strain amplitude to which the asphalt binders in an actual pavement are subjected to is approximately 50 times the strain amplitude found in the asphalt mixtures. Figure 12 presents the correlation between the results from each scale. Strain levels of 2, 4 and 6% were considered for the asphalt binder, which correspond to strain levels of 400, 800 and 1,200με for the asphalt mixture. Note that the value of 1,200με was extrapolated from the fatigue curves obtained in the tests. The comparison indicates that the fatigue life of the asphalt mixture studied in the present research could be predicted by the fatigue life of its asphalt binder. The results fall close to the equality line, and the linear equation fits well when correlating the results obtained for both scales.

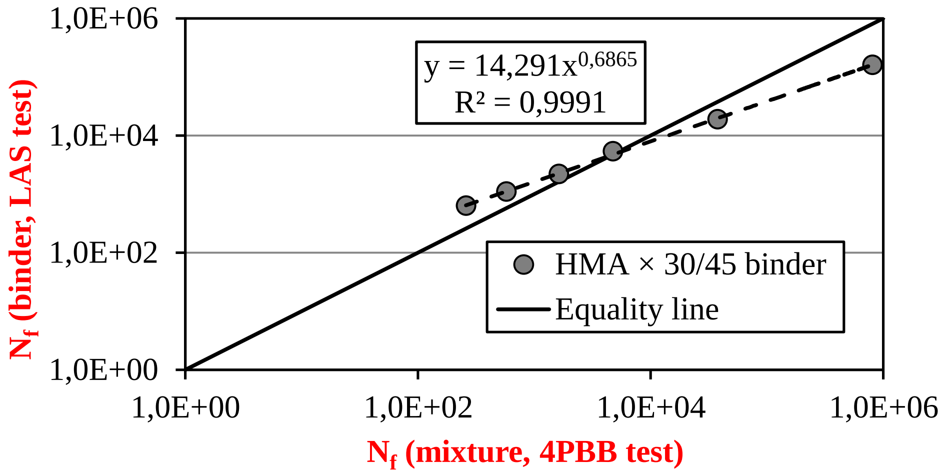


Figure 12. Comparison between asphalt binder and asphalt mixture fatigue lives from LAS test and 4PPB test, respectively.

Summary and conclusions

The present research evaluated three different asphalt binders (one neat 30/45 penetration grade binder; one SBS-modified binder; and one highly modified asphalt, HiMA) in relation to their fatigue resistance by means of different methods and analysis approaches. One dense hot mix asphalt (HMA) prepared with the AC 30/45 was also evaluated in terms of fatigue resistance by means of different test methods and analyses. Then, the results from the two scales were compared, and the main aspects are concluded below:

- The modified asphalt binders resulted in higher fatigue lives in comparison to the neat material, and the HiMA provided the best fatigue resistance;
- The parameter |G*|×sinδ presented a good correlation with time sweep (TS) test results;
- The two approaches used to analyze the TS test data (dissipated energy ratio and 50% reduction in the initial value of stiffness) resulted in similar values of fatigue life (Nf);

- The results from the simplified viscoelastic continuum damage (S-VECD) analysis performed for the linear amplitude sweep (LAS) test were, in general, 4.5 times lower than the traditional method of the TS test;
- The consideration of the peak normalized modulus (Nf_{norm}) provides similar results in comparison to the 50% stiffness reduction approach for the asphalt mixture characterization;
- The S-VECD modeling using results from the push-pull test resulted in lower fatigue lives, but can provide the fundamental properties of the material tested;
- For the materials tested in this research, there is a good agreement between the fatigue life of the asphalt mixture and the fatigue life of the asphalt binder studied, considering that the binder is submitted to 50 times the strain found in the mixes. Other materials should be tested in order to validate this proposition.

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