THE USE OF LINEAR AMPLITUDE SWEEP TESTS TO CHARACTERIZE FATIGUE DAMAGE IN FINE AGGREGATE MATRICES

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ABSTRACT

Fatigue cracking is a major distress found in asphalt pavements. This distress is caused by vehicle traffic and is directly affected by variation in climatic conditions to which the asphalt mixture is subjected. Distresses such as fatigue and rutting are related to small-scale phenomena. This study aims to characterize the fatigue damage of the fine part of hot mixes asphalt (HMAs), consisting of asphalt cement (ACs), fine aggregates and fillers, called fine aggregates matrices (FAM). In order to conduct the characterization, FAMs, samples were prepared to represent realistically the fine part of their correspondent HMA's. The FAM fatigue damage characterization was performed using a traditional method (time sweep tests) and the linear amplitude sweep (LAS) tests. The LAS is based on the viscoelastic continuum damage (VECD) mechanics theory. The results showed that the LAS results were similar to those obtained using the traditional methodology (maximum error of 15%).

Keywords: Asphalt Mixtures, Fine Aggregates Matrix, Fatigue Damage, Linear Amplitude Sweep Tests.

BACKGROUND

Fatigue damage (formation and propagation of micro and macro cracks under cyclic loading) is a major pavement distress which occurs commonly in asphalt mixtures. This distress is caused by traffic and by the constant change in temperature conditions of the asphalt mixture. Asphalt pavements are most sensible to fatigue damage when subjected to intermediate temperatures (10 to 25°C). In that range of temperatures, pavements bearing capacity is reduced, leading to high stresses and strains in the asphalt layer (HUANG, 2004).

During fatigue process, material's behavior interpretation is a difficult task. This is a frequent process in asphalt materials and may be basically explained by two distinct theories: (i) fracture mechanics, and (ii) continuum damage mechanics. The first one concentrates on the phenomena occurring in the microcracks scale in order to represent overall material behavior, while the second one represents globally the microscale phenomena using the state variables concept.

Johnson (2010) applied continuum damage mechanics to a viscoelastic media (Viscoelastic Continuum Damage – VECD) to analyze fatigue damage in asphalt cements (AC's) using the linear amplitude sweep (LAS) tests. In the LAS tests procedure presented in that work, 20 strain amplitudes were applied, between 0.1 e 20%, which were increased linearly after each 100 load cycles application. Tests with constant amplitudes (time sweep) usually take from hours to days to be performed. Using LAS tests, the same characterization could be performed in a few minutes.

Hintz et al. (2011) proposed changes in the test used by Johnson (2010). According to those authors, some AC's presented lower amount of damage at the end of the tests. In order to avoid that, the number of strain amplitudes was increased from 20 to 30, and the strain applied ranged from 0.1% to 30%. Using the new procedure, satisfactory amounts of damage were observed on the tested AC's samples. The tested AC's reached a minimum level of fatigue damage and the test analysis could be performed in less than 15 minutes each. Using those tests, researchers were capable of predicting laboratory fatigue life of AC's for different strain levels.

Continuum damage model for fatigue characterization in asphalt materials (Johnson, 2010)

The dissipated energy during a loading cycle for a viscoelastic material is given by the area of the hysteresis loop (Equation 1):

$$W = \pi \times I_D \times \gamma_0^2 \times |G^*| \times sen\delta \tag{1}$$

Where $\boldsymbol{I_D}$ is the initial numerical value of the undamaged shearing dynamic modulus (in MPa), divided by 1MPa, $\boldsymbol{\gamma_0}$ is the shearing strain amplitude, $|G^*|$ is the shearing dynamic modulus during the loading cycle (MPa), and $\boldsymbol{\gamma}$ is the phase angle during that loading cycle. The dynamic modulus is the norm of the complex modulus G^* which can be decomposed in two distinct parts, one real and one imaginary as $G^* = G' + i.G'' = |G^*| \cos\delta + i.\mathrm{sen}\,\delta$. G' is known as storage modulus while G'' is known as loss modulus. The dissipated energy is used as energy potential (W) in Schapery's equation (Equation 2) for the thermodynamic evolution of damage in a viscoelastic media (SCHAPERY, 1969):

$$\frac{\boldsymbol{dD}}{\boldsymbol{dt}} = \left(-\frac{\boldsymbol{\partial W}}{\boldsymbol{\partial D}}\right)^{\alpha} \tag{2}$$

Where D is the state variable related to damage; $\frac{d}{dt}$ is the time rate; $\alpha = 1 + 1/m$ is used to obtain better fitting of data in cyclic loading (LEE and KIM, 1998a); m is the exponent in a power law for the shearing relaxation modulus $G(t)$ and can be understood as a material's logarithmic rate of relaxation (power law: $\mathrm{G(t)} = \mathrm{G_0} + \mathrm{G_1 t^m}$).

Johnson (2010) used the approximated method presented by Schapery and Park (1999) to interconvert storage modulus $\mathrm{G'(\omega)}$ and relaxation modulus $\mathrm{G(t)}$ in order to calculate $\boldsymbol{m}$ by the slope of the curve $\log[\mathrm{G'(\omega)}]$ versus $\log(\omega)$.

The quantity $\frac{\mathrm{dD}}{\mathrm{dt}}$ can be understood as the available force to produce damage. It is, then, possible, to calculate the damage variable using a Riemann sum as follows (Equation 3):

$$\boldsymbol{D(t) \cong \sum_{i=1}^{N} \left[\pi I_D \gamma_0^2 (|G^*|_{i-1} sen\delta_{i-1} - |G^*|_i sen\delta_i)\right]^{\frac{\alpha}{\alpha+1}} (t_i - t_{i-1})^{\frac{1}{1+\alpha}}} \tag{3}$$

In order to calculate $\boldsymbol{\frac{\partial W}{\partial D}}$, it is necessary to assume a mathematical fitting for $\left|\mathrm{G}^*\right| \mathrm{sen}\,\delta$, varying over the loading cycles (damage evolution), such as the one presented in Equation 4.

$$\boldsymbol{|G^*| sen\delta = C_0 - C_1 (D)^{C_2}} \tag{4}$$

Where $\boldsymbol{C_0}$, $\mathrm{C_1}$ e $\mathrm{C_2}$ are the coefficients used in the fitting process.

It is possible, then, to calculate $\frac{\partial \mathrm{W}}{\partial \mathrm{D}}$ as follows (Equation 5).

$$\boldsymbol{\frac{\partial W}{\partial D} = -\pi I_D C_1 C_2 (D)^{C_2 - 1} \gamma_0^2} \tag{5}$$

Using this procedure, Schapery's equation can be applied in order to calculate the quantity of loading repetitions necessary to reach an arbitrary value for the damage variable. Assuming the cumulated damage value when the material reaches the failure criterion as being $\mathrm{D_f}$, one can calculate the number of cycles necessary to failure, $\mathrm{N_f}$, as in Equation 6.

$$\boldsymbol{N_f = \frac{f(D_f)^k}{k(\pi I_D C_1 C_2)^\alpha} \gamma_0^{-2\alpha}} \tag{6}$$

Where $\mathrm{k} = 1 + (1\text{-}\mathrm{C_2})\alpha$ and f is the loading frequency in Hz.

Equation (6) can be written in a simplified manner, grouping terms as shown in Equations 7, 8 and 9.

$$\boldsymbol{A = \frac{f(D_f)^k}{k(\pi I_D C_1 C_2)^\alpha}} \tag{7}$$

$$\boldsymbol{B = 2\alpha} \tag{8}$$

$$N_f = A\gamma_0^{-B} \tag{9}$$

By means of the previous procedure, it is theoretically possible to obtain fatigue parameters (A and B) for viscoelastic materials. Using these parameters, it is possible to estimate the number of loading cycles (N_f) necessary to lead the material to failure for any given strain amplitude (γ_0) and frequency (f). In order to obtain the fatigue parameters, it is only necessary to perform sinusoidal loading tests, in controlled strain mode, with constant frequency and growing strain amplitudes, in sufficient number and magnitude to produce damage in the sample in enough quantity to reach the adopted failure criterion.

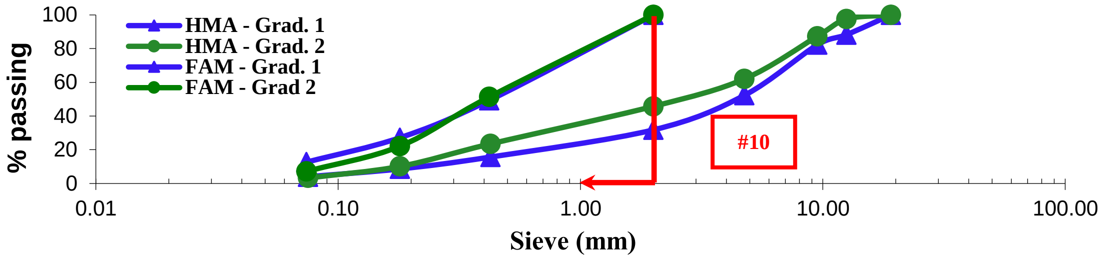
The limitation in predicting fatigue in field conditions with this kind of model is evident because of the lack of aging consideration. In the field, the material is continuously subjected to oxygen reaction and to loss of volatiles. In addition, it is necessary to note that second order contributions to stress and strain were not taken in account, as if it was valid the small deformations hypothesis (HINTZ et al., 2011). Although this is not true for AC's (strains at the end of the tests are of the order of 30%). Performing tests in FAM samples could lead to small deformations in the fatigue tests. This mixture (FAM) can be used to characterize the fine portion of hot mix asphalt (HMA), because these mixtures' structure is more homogeneous and play an important role in the HMA's cracks formation and propagation (MASAD et al., 2006).

EXPERIMENTAL INFORMATION

In this paper, three different HMA's and its correspondent FAM were studied. Two HMA's were designed using pure AC of 50/70 penetration grade (PG 70-28), produced by Petrobras/Lubnor. Another HMA was designed using the same base AC modified by 4% in mass of ethylenvinilacetate copolymer (EVA).

The mixtures studied in this paper are dense graded asphalt concrete of nominal maximum aggregate size of 12.5mm designed using 100 gyrations. Two different aggregate gradations were used, obtained by mixing aggregates from different sources: (i) Gradation 1 used only granitic aggregates; and (ii) Gradation 2 used phonolitic coarse aggregates and gnaissic fine aggregates mixed with sand.

Figure 1 – Aggregate gradations



FAM were designed using the methodology proposed by Coutinho et al. (2011). FAM 1 is constituted by aggregate gradation 1 and 9.6% of pure AC, FAM 2 by gradation 2 and 8.2% of AC and FAM 3 by gradation 1 and 9,8% of modified AC. FAM test specimens of 50mm height and 12mm diameter were prepared. Approximately 10 FAM samples are obtained by coring a 100mm diameter and 90mm high specimen compacted using a Superpave gyratory compactor (SGC). To obtain the desired height (50mm) for the FAM sample and also to assure uniformity, the ends of the 100mm SGC sample were sawed off before coring. More details about the FAM preparation procedure can be found in Coutinho (2012).

Fatigue damage characterization for FAM

Fatigue damage characterization for FAM was performed using two distinct methods. The first one is the linear amplitude sweep, applying the VECD theory (JOHNSON, 2010; HINTZ et al., 2011), which is being adapted to fatigue analysis in FAM. The second one is the traditional time sweep, where both kinds of control mode were tested: strain controlled and stress controlled tests.

Fatigue tests: linear amplitude sweep

Tests with FAM were performed in a Dynamic Shear Rheometer (DSR). Before each LAS test, a frequency sweep was performed. This pretest is performed in order to obtain linear viscoelastic properties, e.g. the value of $\alpha = 1 + 1/m$, where $\boldsymbol{m}$ is the slope of the curve $\boldsymbol{log}[\boldsymbol{G}'(\boldsymbol{\omega})]$ versus $\boldsymbol{log}(\boldsymbol{\omega})$. The frequency sweep is performed in the same temperature of the fatigue tests. The same frequencies used by Johnson (2010) (0.02 a 30Hz) were applied, with a strain level equal to 0.0065%, which can be associated to the FAM linear viscoelastic limit (CASTELO BRANCO, 2008).

After the frequency sweep tests, LAS tests were performed. Different strain amplitudes were applied, at constant frequency (10Hz), until the material reached the failure criterion. It is to be noted that, since FAM have very different characteristics when compared to AC (modulus, resistance), amplitude strains applied in tests with FAM were not the same as in tests with AC. For FAM, amplitude strains ranged from

0.0065% to 0.08%. For the present paper, the chosen failure criterion was a drop of 50% in the initial dynamic modulus value ($|G*|$).

From the resulting strain and stress values from the LAS test, and from the curve $\boldsymbol{log}[\boldsymbol{G}'(\boldsymbol{\omega})]$ versus $\boldsymbol{log}(\boldsymbol{\omega})$, the continuum damage model was fitted, following the procedure previously presented in this paper. After the tests for each FAM sample, model parameters A and B and the number of cycles to failure ($\mathrm{N_f}$) for different frequencies and strain amplitudes. All the fitting procedure was performed using Excel tools, such as *Solver*.

Fatigue tests: time sweep

Time sweeps tests were also performed using a DSR in order to evaluate the FAM samples. It consists in the application of a constant frequency (10Hz for this work) and a constant strain amplitude. The test was finished when the failure criterion or a limitation of time (24h) is reached. The failure criterion considered in this paper was 50% loss of dynamic modulus (with respect to the initial undamaged dynamic modulus $|G*|_{\text{Initial}}$).

During the tests, FAM samples were subjected to a torsion sinusoidal loading. All tests were performed at 25°C and using the same strain amplitudes for all the tested mixtures. Although lower temperatures would be more adequate to study FAM fatigue properties, this temperature was chosen because of the DSR loading capacity limitations. In order to determine the value of $|G*|_{\text{Initial}}$, each sample was subjected to a previous test, where a frequency sweep test was performed from 0.02 to 30Hz and with strain amplitudes lower than 0.0065%.

Results of the fatigue characterization in FAM

Results of fatigue tests: LAS test

For FAM samples studied in the present work, LAS tests were performed as follows: (i) frequency sweep tests under controlled strain (0.0065%) mode of load at 25°C and using frequencies ranging from 0.02 to 30Hz; (ii) LAS tests applying 150 different strain amplitudes ranging from 0.0065% to 0.08% (150 loading application cycles for each strain amplitude), at frequency of 10Hz and test temperature of 25°C. Following this methodology, the analysis of the three studied FAM were performed and the results are shown in Table 2.

Table 2. LAS test results and coefficients of VECD model

FAM	$\|G*\|_{Initial}$ (MPa)	$\|G*\|_{Final}$ (MPa)	%Loss of $\|G*\|$	C_0	C_1	C_2	m	α
1	1.14	0.47	59	785.00	236.89	0.30	0.42	3.37
2	1.58	0.76	52	887.50	253.18	0.37	0.36	3.78

3	1.45	0.69	52	725.67	233.16	0.36	0.29	4.43

Table 2 shows that the value of $|G^*|$ in linear viscoelastic zone at 25°C and load frequency of 10Hz ranged from 1.14 to 1.58 MPa. Karki (2010) presented values between 0.8 and 1.2 MPa. This indicates that the values found in this work are in the same range of the ones found in the literature.

The first step of the fitting method is the calculation of α. After obtaining α, C_0 was estimated (Equation (4)). C_0 results are listed in Table 2 as well as the values of C_1 and C_2. These values were calculated fitting the damage model parameters (Equation (4)) to experimental data. This fitting is performed using the least squares method, executed by Excel's *Solver*.

With the values of C_0, C_1, and C_2 parameters A and B have been calculated using Equations (7) and (8) (Table 3). From the values of A and B, it was estimated the number of load cycles (N_f) required to failure (50% loss of stiffness) of the material for any strain amplitude (γ_0) (Equation (9)). Thus, considering the strain amplitude of 0.043% (amplitude used in the time sweep test under controlled strain) values of N_f were calculated for FAM 1, 2 and 3 (Table 3).

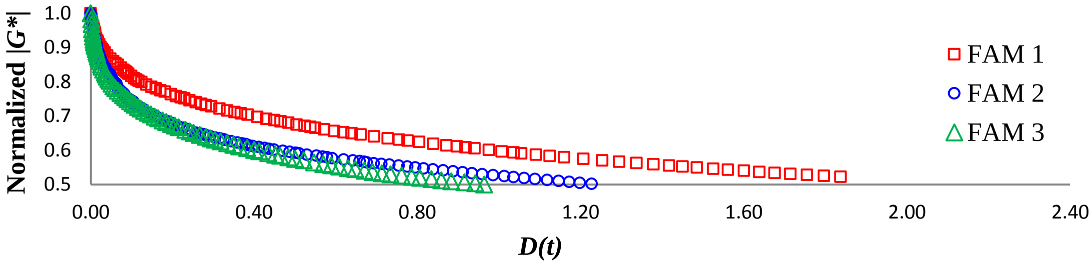
Table 3. Fatigue parameters of LAS test and the fatigue life (N_f) obtained from this test

FAM	A	B	γ_0 (%)	N_f
1	4.02×10^{-17}	-6.73	0.043	9.77×10^{5}
2	2.04×10^{-20}	-7.56	0.043	2.78×10^{5}
3	3.17×10^{-25}	-8.85	0.043	2.55×10^{5}

N_f results presented in Table 3 show that among the studied FAM, FAM 1 is the one which has the largest fatigue life (N_f), more than three times larger than the other FAM (under controlled strain) fatigue lives. FAM 2 and 3 have similar fatigue resistance, N_f for FAM 2 being only 8% higher than N_f for FAM 3.

Figure 2 shows the curves of normalized $|G^*|$ versus damage accumulation $[D(t)]$. Theoretically, the relationship shown in Figure 2 represents the material's capability to resist damage. According to Figure 2, FAM 2 and 3 show a greater loss of stiffness ($|G^*|$) with respect to the same damage accumulation if compared to FAM 1. This behavior was expected, considering that FAM 1 showed greater fatigue resistance.

Figure 2. Experimental data for the FAM 1, 2 and 3



Results of fatigue tests: time sweep test

The time sweep tests for the FAM were performed using a loading frequency of 10Hz, temperature of 25°C and, strain amplitude of 0.043%. The values of strain amplitudes used in these tests were obtained empirically according to DSR torque limitations, in such a way that all FAM could be tested with the same loading amplitudes. The time sweep tests duration was set up to 24 hours or until it reaches the failure criterion (50% loss of $|G^*|$ for controlled strain mode of loading and complete failure for controlled stress mode of loading). The results of these tests can be seen in Table 4.

Table 4. Results of time sweep test

FAM	N_f (mean)	Standard deviation	Coefficient of Variation – CV (%)
1	8.6×10^5*	4.2×10^2	0
2	2.9×10^5	1.4×10^4	5
3	2.5×10^5	2.3×10^4	9

According to Table 4, the results of the time sweep tests presented low variability among the samples (CV lower than 15%). This shows that these tests have good repeatability in FAM. It is important to note that FAM 1 did not reach the failure criterion during the test period (24 hours). Time sweep tests with this mixture yield a loss of stiffness of only 46% in dynamic modulus. Results from time sweep tests under controlled strain were compared with the results from LAS tests for FAM, since this test is also performed with the same mode of loading.

Table 5 shows the comparison between the results of fatigue life ($\mathrm{N_f}$) obtained by time sweep tests under controlled strain and by the LAS test followed by VECD model fit. These results showed that the method presented satisfactory results for fatigue analysis in FAM presenting similar results (maximum error of 15%) to the ones obtained by the traditional method (time sweep tests performed under controlled strain). This indicates that the LAS method to predict the fatigue life ($\mathrm{N_f}$) can also be used for FAM samples, making this fatigue analysis faster. LAS tests adapted for FAM samples take about 40min to be performed, while time sweep tests can require more than 1,440min (24 hours). Also, time sweep tests are generally conducted only for one loading frequency and one strain amplitude, while the LAS tests results can be used to estimate the material behavior for various combinations of loading frequency and strain amplitudes.

Table 5. Comparison of results from time sweep test under controlled strain and LAS test

FAM	N_f (Time sweep)	N_f (LAS)	Error (%)
1	8.6×10^5*	9.8×10^5	15
2	2.9×10^5	2.8×10^5	5
3	2.5×10^5	2.5×10^5	3

* The material has not reached the failure criterion

It can be seen in Table 5, from the time sweep test results, that FAM 1 shows higher fatigue resistance ($\mathrm{N_f}$ more than 300% greater) if compared to FAM 3. These two FAM have the same mineral skeleton and different binders (FAM 1 was designed with conventional binder and FAM 3 was designed with modified binder).This is due to the fact that the modifier increases the mixture stiffness. Since the test was performed at controlled strain, higher stress amplitudes were applied for the FAM 3.

In order to analyze the influence of the mineral aggregates in fatigue damage for the FAM evaluated in this paper, results found for FAM 1 and 2 (FAM with different mineral skeletons and the same binder) can be compared. FAM 1 presented greater fatigue resistance when compared to FAM 2, showing that the FAM with the aggregates contained in Gradation 1 exhibit lower susceptibility to fatigue damage.

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