FINITE ELEMENT SIMULATION OF FATIGUE DAMAGE TESTS ON HETEROGENEOUS ASPHALT MIXTURES

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ABSTRACT

This paper presents a finite element methodology to simulate, using linear viscoelasticity and continuum damage theories, the fatigue test on asphalt mixtures, considering their inherent heterogeneities. The test consists of applying sinusoidal solicitation and reading the mechanical response, evaluating the damage evolution, characterized by the material stiffness loss. The studied materials are a Fine Aggregate Matrix (FAM) and a Hot Mix Asphalt (HMA) composed of coarse aggregate, air voids, and FAM. The inputs are the aggregate gradation curve and the material properties within the mixture: aggregate Young's modulus, FAM relaxation modulus, FAM integrity curve (C *vs.* S curve) and FAM failure envelope ($\boldsymbol{G^R}$*vs.* $\boldsymbol{N_f}$) curve. The number of loading cycles ($\boldsymbol{N_f}$) that produces material failure is evaluated based on the criterion of the rate of change of the released Pseudo-Strain Energy (PSE) per cycle ($\boldsymbol{G^R}$ *vs.* $\boldsymbol{N_f}$ curve). The simulation results are compared with actual experimental results obtained in laboratory tests on HMA.

Keywords: Asphalt Mixtures; Linear Viscoelasticity; Continuum Damage Mechanics; Heterogeneities.

1. INTRODUCTION

According to Nascimento (2015), cracking damage is the main distress in Brazilian roadways. The literature presents basically two approaches to model the damage phenomena in asphalt mixtures: micromechanical models and models based on continuum damage mechanics. These models describe the behavior of the material subjected to loads identifying and quantifying the parameters that influence the resistance to fatigue damage in asphalt mixtures.

Continuum Damage Mechanics (CDM) ignores specific microscale behaviors and attempts to characterize the material considering the overall effect of microstructural changes on observable properties. This theory considers the quantification of damage effects using two variables: (i) a damage parameter and (ii) the effective stiffness. The damage parameter, generally, is an internal variable that quantifies any microstructural change that results in stiffness decrease (Kim *et al.*, 2009; Nascimento, 2015). A basic consideration of CDM approaches is that any stiffness decrease is related to damage (Park and Schapery, 1997; Nascimento, 2015). For elastic materials, stiffness decrease can be observed on the slopes of stress *vs.* strain curves, whereas for viscoelastic materials it can be observed on stress *vs.* pseudo-strain curves, since the used CDM formulation for viscoelastic materials typically uses secant pseudo-stiffness to quantify damage (Baek, 2010).

This work aims at developping a computational methodology to simulate fatigue tests in asphalt mixtures (considered as heterogeneous), from its grading curve, air voids content and mechanical properties of its constituents (aggregate Young's modulus, Fine Aggregate Matrix - FAM - relaxation modulus, and FAM integrity curve). Air voids are considered as non-resistant, while stiffness evolution is simulated using material properties. The number of loading cycles at failure is evaluated according to a failure criterion based on G^R *vs.* N_f curve.

2. THEORETICAL BACKGROUND

The Elastic-Viscoelastic Correspondence Principle (EVCP) is based on the observation that viscoelastic relations, written in another mathematical domain, resemble to elastic relationships that can be used as a reference to the solution of the original viscoelastic problem. The stress-strain relationships in linear viscoelastic materials can be written by similar linear elasticity relations using Schapery's (1984) EVCP, based on pseudo-variables (Kim, 2009). The pseudo-variables can be, for example, pseudo-strains, which are the values of linear viscoelastic stress (calculated for a linear viscoelastic regime) divided by a reference modulus (E_R) for a given strain input (Baek, 2010). Using this correspondence principle, the viscoelastic response is obtained from the corresponding elastic response solving a convolution integral, which can be numerically evaluated.

Using EVCP based on pseudo-variables, the strains, ε, can be replaced by pseudo-strains, ε^R, to represent the viscoelastic material behavior (Kim, 2009). However, it was observed experimentally (Park, 1994) that the damage evolution law in elastic materials cannot be applied to viscoelastic materials by simply using the elastic-viscoelastic correspondence principle, and replacing strains, ε, by pseudo-strains, ε^R (Kim, 2009). The damage evolution law in viscoelastic materials must consider that both the forces available to make the damage (represented by S) grow and those that oppose its growth are dependent on the rate of change of damage over time (Kim, 2009). Thus, an expression similar to a power law describing growth of micro cracks in viscoelastic materials was proposed (Kim, 2009), as in Equation (1).

$$\dot{S} = \left(-\frac{\partial W^R}{\partial S}\right)^{\alpha} \tag{1}$$

where, $W^R = W^R(\varepsilon^R, S) -$ pseudo-strain energy density function;

$\dot{S} = \frac{\partial S}{\partial t} -$ rate of change of the internal state variable, S, over time;

$\alpha -$ constant related to material's relaxation rate.

Using the EVCP, the damage evolution law for viscoelastic materials can be written in an incremental form as presented in Equation (2).

$$S_{n+1} = S_n + \left[\frac{1}{2}\, C_{11}\, C_{12}\, S_n^{(C_{12}-1)}\right]^{\alpha} \Delta t \tag{2}$$

where, n and $n+1$ are steps associated to instants t_n and t_{n+1}, respectively;

S_n and S_{n+1} are parameters that quantify damage at steps n e $n+1$;

C_{11} and C_{12} are regression constants from damage characteristic curves - cf. Equation (3) - obtained from fatigue damage tests on the material.

In this work, the material integrity curve is given by Equation (3).

$$C(S) = 1 - C_{11}\, S^{C_{12}} \tag{3}$$

2. METHODOLOGY

A finite element program was developed for simulation of damage evolution in viscoelastic materials based on material properties from the *Simplified Viscoelastic Continuum Damage* (*S-VECD) Model* (Underwood *et al.,* 2012). The program uses the failure criterion proposed by Sabouri and Kim (2014), which is based on the failure envelope ($G^R\ vs. N_f$ curve) (rate of change of the released Pseudo-Strain Energy (PSE) *vs.* cycle at failure). The program, denominated AEDC, has the following parameters:

Input: (1) Virtual Sample (VS) geometry (node coordinates and elements connectivity); (2) aggregate's Young's modulus and Poisson's ratio (3) FAM's Relaxation modulus, C_{11} and C_{12}

parameters of the integrity curve, A (multiplier) and B (exponent) parameters of FAM $G^R\ vs. N_f$ curve; (4) Intensity and periodic function of prescribed displacements, or intensity and periodic function of prescribed loads; (5) Frequency and analyzed time of solicitation;

Output: (1) Damage evolution *vs.* number of cycles; (2) Material integrity (C) *vs.* damage parameter (S); (3) G^R *vs.* number of cycles; (4) Number of loading cycles that produces failure in the simulated specimen and damage and integrity values associated to that cycle.

The following procedure clarifies the methodology. The program: (1) Generates the mesh that models the VS, according to design parameters and aggregate gradation; (2) Calculates nodal displacements of the mesh subjected to loads or to displacements prescribed in the peaks (and valleys) of sinusoidal loading; (3) Calculates, in the peaks (and valleys) of loading, the stress, strain, damage, integrity and released PSE at each element's integration points; (4) Calculates, in the peaks (and valleys) of loading, the arithmetic averages of stress, strain, damage, integrity, released PSE at element's integration points; (5) Calculates the volume weighted averages of arithmetic means of item 4 parameters, obtaining the homogenized responses on VS (or on selected elements); (6) Draws damage *vs.* cycle curve, integrity *vs.* damage curve, G^R *vs.* cycle curve, obtained in the simulation; (7) Calculates intersection of G^R *vs.* N (simulated) curve with G^R *vs.* N_f (experimental) curve, obtaining the number of cycles associated with structural failure on VS.

3. MATERIALS, RESULTS AND DISCUSSIONS

In order to validate the formulation, the Hot Mix Asphalt (HMA) studied by Freire *et al.* (2017), whose characteristics are presented in Table 1, was analyzed. Aggregates with diameter smaller than 2.0mm were considered to belong to FAM. The FAM Prony series constants for reference temperature 20°C can be found in Freire *et al.* (2017). As the mentioned constants refer to the shear modulus (G), these values were used to obtain Prony series constants for the longitudinal modulus (E), considering the Poisson's ratio equal to zero and a linear viscoelastic isotropic FAM. The FAM dynamic modulus at 25°C and 10Hz is 3.47 x 10^6 kPa. The HMA dynamic modulus at 25°C and 10Hz is 9.58 x 10^6 kPa. The HMA air void content is 4.0%, and the aggregate Young's modulus is 6.85 x 10^7 kPa. Table 2 shows C_{11} and C_{12} of the $C\ vs. S$ curve, and α values for FAM and for HMA. It also shows parameters A and B of the $G^R\ vs. N_f$ curve, for FAM and for HMA (Freire *et al.,* 2017).

Table 1 – % of aggregates and FAM in the mixture on VS

Misture	# 12.7mm	# 9.5mm	# 4.8mm	# 2.0mm	FAM
Freire *et al.* (2017)	2.00	9.50	27.50	15.10	45.90
GCPV	2.10	9.88	24.66	13.70	49.66

Table 2 – Parameters for $C(S) = 1 - C_{11}\ S^{C_{12}}$ and for $G^R = A\ N_f^B$ (Freire *et al.,* 2017)

	C_{11}	C_{12}	α	A	B
FAM	$1.91\ x10^{-6}$	$6.20\ x\ 10^{-1}$	2.33	$2.00\ x\ 10^9$	-1.24
HMA	$1.68\ x\ 10^{-4}$	$7.36\ x\ 10^{-1}$	3.06	$1.25\ x\ 10^9$	-1.66

In the verification step, a VS composed only of FAM was submitted to a controlled displacement that provides a shear strain amplitude (peak-to-peak) of $700\mu\varepsilon$ in a plane stress model. This shear strain amplitude would correspond to normal strain amplitude of 350με. The mesh used, consisting of 16 quadratic (Q8) elements, is shown in Figure 1, with deformed VS configuration at the end of the last cycle. Table 3 shows the experimental value of N_f and the values of N_f, S_f and C_f obtained from the simulation. The experimental N_f value was obtained with Equation (4), where the constants k_1, k_2, k_3 were calculated with the fatigue test results with shear loading (Freire *et al*., 2017):

$$N_f = k_1 \left(\frac{1}{\varepsilon_t}\right)^{k_2} |E^*|^{k_3} \quad (4)$$

where, $k_1 = 1.87;\ k_2 = 5.59;\ k_3 = 6.03;\ \varepsilon_t = \frac{\gamma}{2} = 350\mu\varepsilon$ and $|E^*| = 3.47\ x\ 10^6$ kPa, for VS temperature of 25°C.

The large difference observed between experimental and simulated N_f values can be attributed to tests (torsion) and simulation (pure shear) loading differences, as it will be shown in the simulation of HMA homogeneous tension-compression tests. Torsion produces a heterogeneous state of stresses, having maximum stresses at the edges and zero stress at the center of the specimen. The simulation uses $C\ vs. S$ and $G^R\ vs. N_f$ curves' coefficients from experimental results, but the loading is more severe than the one in the actual test. On the other hand, pure shear produces a homogeneous stress state, producing uniform damage in the VS.

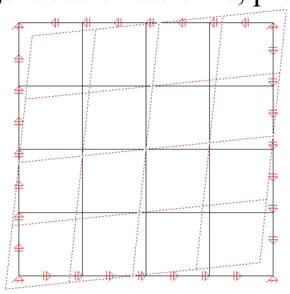


Figure 1 – FAM subjected to pure shear: mesh and deformed configuration

Table 3 – Experimental N_f (from torsion tests) and simulated cycle, damage and integrity of VS at failure for VS of homogeneous FAM (for pure shear simulation)

Experimental - Equation (4)			Simulated – $\gamma_{max}\ (peak - to - peak) = 700\mu\varepsilon$			
Frequency	VS	N_f	Time	N_f	S_f	C_f
10.0 Hz	25°C	$3.08\ x\ 10^{25}$	401 seg.	$6.10\ x\ 10^{12}$	44979	0.998

The fatigue simulation test in normal strain was performed in VS with 75mm of radius and 150mm of height. Using the mesh in Figures 2a and 2b, the numbers of cycles where there is structural failure was calculated considering a frequency of 10Hz with sinusoidal axial displacement with amplitude of $\delta = 0.0525$mm at the upper face of VS in the axisymmetric model. The bottom face is restrained. The applied displacement amplitude provides 350με axial strain amplitude (peak-to-peak), commonly used in fatigue tests. The mesh in Figure 2a contains 253 nodes and 72 Q8 elements. The mesh in Figure 2b contains 1994 nodes and 2910 elements. Figure 2c shows the damage distribution in the VS considering the heterogeneities.

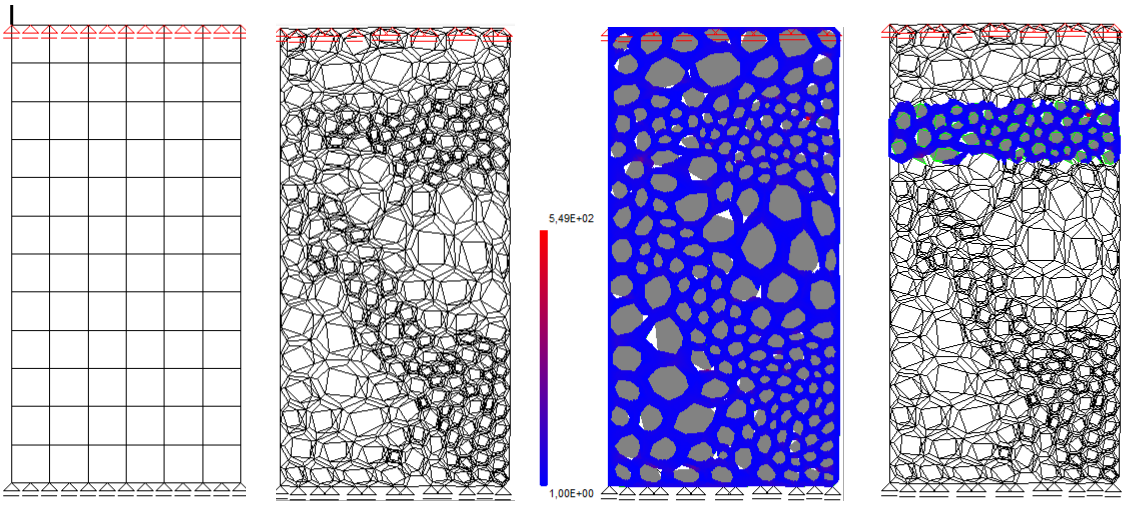
Table 4 shows the experimental N_f value and the simulated N_f, S_f and C_f values obtained for the homogeneous HMA for 25°C. The experimental N_f value was obtained with Equation (4), where constants k_1, k_2, k_3 were calculated with the fatigue results from controlled axial displacement tests in a UTM-25 (Freire *et al*., 2017), where: $k_1 = 1.25167\ x\ 10^7$; $k_2 = 4.18$; $k_3 = -2.59$; $\varepsilon_t = 350\ x10^{-6}$ e $|E^*| = 9.58\ x\ 10^6$ kPa, for VS at 25°C. Table 5 shows N_f, S_f and C_f values obtained in heterogeneous HMA simulation. In this case, the entire VS volume was considered for the homogenization results (according to Step 5 of the presented algorithm, cf. Section 2 "Methodology").

Table 4 – Experimental N_f (from tension-compression tests) and simulated cycle, damage and integrity at failure for VS of homogeneous HMA (from tension-compression simulation)

Experimental - Equation (4)			Simulated – $\varepsilon_{max}\,(peak - to - peak) = 350\mu\varepsilon$			
Frequency	VS	N_f	Time	N_f	S_f	C_f
10.0 Hz	25°C	2897	201 seg.	2619	105810	0.163

Table 5 – Cycle, damage and integrity at failure for VS of heterogeneous HMA

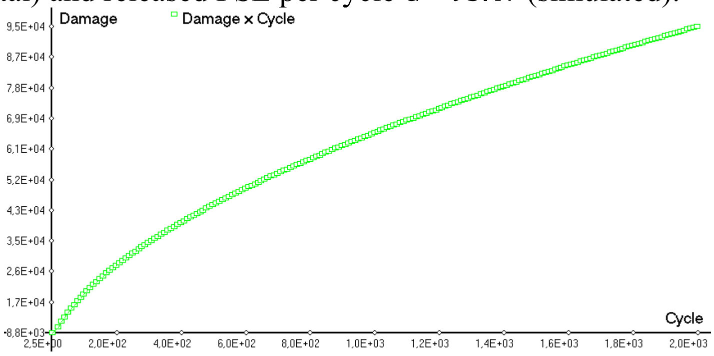
Simulated – $\varepsilon_{max}\,(peak - to - peak) = 350\mu\varepsilon$					
Frequency	VS	Time	N_f	S_f	C_f
10.0 Hz	25°C	401 seg.	$1.45\,x\,10^{15}$	$1.70\,x\,10^{7}$	0.942



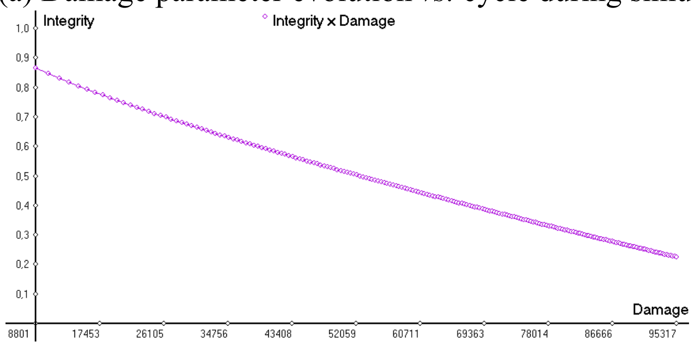
(a) Homogeneous (b) Heterogeneous (c) Damage distribution (d) Selected region

Figure 2 – Meshes in the HMA simulation submitted to controlled axial displacement

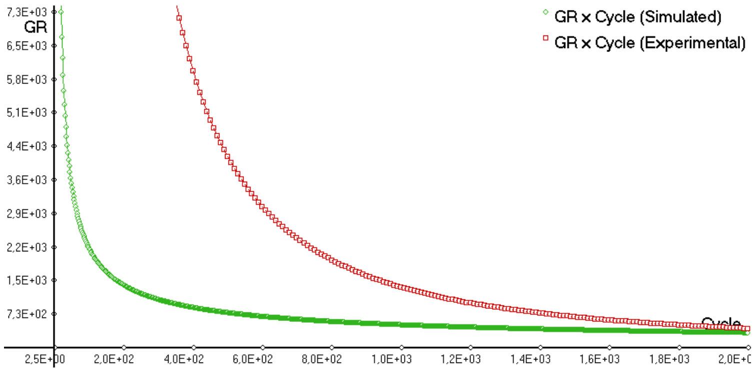
Figures 3a, 3b, 3c show, respectively: damage parameter (S) evolution *vs.* cycle; material integrity (C) *vs.* damage parameter during simulation; and failure envelope $G^R\,vs.\,N_f$ (experimental) and released PSE per cycle $G^R\,vs.\,N$ (simulated).



(a) Damage parameter evolution *vs.* cycle during simulation



(b) Material integrity *vs.* damage parameter during simulation



(c) $G^R\ vs. N_f$ (experimental) curve and $G^R\ vs. N$ curve during simulation

Figure 3 – Curves in simulation considering HMA homogeneous

Another HMA heterogeneous simulation was performed with the same mesh as in Figure 2b, but this time considering only the selected region shown in Figure 2d for homogenization results (according to Step 5 of the presented algorithm, cf. Section 2 "Methodology") and for N_f, S_f and C_f calculation. Table 6 shows N_f, S_f and C_f values obtained in this simulation.

Table 6 – Cycle, damage and integrity at failure for VS of heterogeneous HMA considering the selected region (cf. Figure 2d) for homogenization results and for N_f, S_f and C_f calculation

Simulated – $\varepsilon_{max}\ (peak - to - peak) = 350\mu\varepsilon$					
Frequency	VS	Time	N_f	S_f	C_f
10.0 Hz	25°C	401 seg.	$1.57\ x\ 10^{15}$	$2.61\ x\ 10^{7}$	0.924

The analyzed region was selected by visual inspection, presumably where there is a higher concentration of structural damage. The N_f value (greater than that in Table 5) contradicts this hypothesis. However, values of S_f and C_f confirm it. Concentration points of damage around aggregates in the selected region are shown in Figure 2d. This demonstrates that damage is not uniformly distributed in the VS. The damage concentration can be attributed to stress concentrations in FAM-aggregate contact region, due to stiffness differences between the materials and also because of the air voids presence. The large difference observed in results obtained in the homogeneous HMA simulation and in the heterogeneous HMA simulation is due to the results homogenization process. The heterogeneous HMA VS presents, overall, low damage index, although it presents high concentration of local damage.

4. CONCLUSIONS

A computational methodology was presented and a finite element program was developed to analyze damage evolution in asphalt mixtures, considering their inherent heterogeneities. The program was used to simulate fatigue tests in virtual samples, using as input the mixture grading curve and properties of the constituents (FAM, aggregates and air voids). Thus, it estimated the damage and the corresponding integrity, and the number of cycles at failure, according to the failure criterion based on G^R *vs.* N_f experimental curve. The program coherently simulates the damage behavior of heterogeneous mixtures submitted to loading. However, the fatigue life estimated using homogenized parameters (as for a homogenous HMA) were not able to predict experimental failure. As a future perspective, the authors should establish a criterion that defines structural collapse from local failure within the VS, making it possible to estimate fatigue life of asphalt mixtures specimens, and in the long-term, also in the field, considering heterogeneities.

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