Damage Theory Applied to Fatigue Tests in Gap-Graded Asphalt Mixtures with 4th Generation Rubberized Asphalt

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ABSTRACT

Damage to flexible pavements due to stress and strain caused by traffic and environmental factors is manifested in most cases in the form of fatigue cracking. Recent researches have adopted less empirical and more mechanistic criteria for the evaluation of materials used in flexible pavements. Application of the Continuum Damage Theory (CDT) to evaluate the evolution of internal damage in Hot Mix Asphalt (HMA) is investigated in this paper. The CDT leads to the formulation of a characteristic curve relating normalized pseudo-stiffness and the internal damage variable, and this curve is supposed to be unique for each material. New materials, also called 4th generation rubberized asphalt, such as Reacted and Activated Rubber - RAR and Pelletized Asphalt-rubber, were developed with the purpose to simplify the manufacturing process (as in the asphalt mixture obtained by the dry process) and to enhance the performance of the asphalt mixture (as the asphalt mixture obtained by the wet process). The uniqueness of the characteristic curve was investigated in this paper by performing fatigue tests in which prismatic samples of HMA were subjected to cyclic bending loads under strain controlled tests. Asphalt mixtures with gap gradation with 4th generation asphalt-rubber were tested. The results of all the tests showed the existence of unique curves independent of loading mode, amplitude or frequency within the studied range. This property may be implemented in numerical codes to simulate the behaviour of flexible pavements under a variety of field conditions, using a well formulated mechanistic approach.

Keywords: Fatigue, Damage, Asphalt Rubber.

1. INTRODUCTION

Damage to flexible pavements due to stress and strain caused by traffic and environmental factors is manifested in most cases in the form of fatigue cracking. Fatigue resistance is the ability to withstand repeated loads without cracking and is associated with stiffness of the material [1]. The fatigue characteristics of asphalt are therefore important for the structural design of pavements and they have been investigated using either the phenomenological or mechanistic approach. In the phenomenological approach, the initial strain or stress, and the fatigue life, have been shown to have a power law relationship [2]. Fatigue tests are conducted at various initial stress/strain levels, and the relationship between strain versus number of cycles to failure is the basis for assessing fatigue performance.

The dissipated energy [1; 3], the fracture mechanics and the continuum damage mechanics methods may be categorized into a mechanistic approach to study the characteristics of asphalt concrete. Fracture mechanics theories, either linear or non-linear, may be used to track the evolution of existing cracks during numerical analyses. This approach has been trailed by many researchers [4-6] in the pavement community, but it has the intrinsic shortcoming of not being able to forecast the initiation of cracks.

The application of the Continuum Damage Theory (CDT) provides an alternative approach for the study of damage initiation and propagation in asphalt mixes. Based on the original works of Schapery (1984, 1990) and Lee (1996), models were developed for Characteristic Curves of hot asphalt mixes subjected to different amplitudes of stress/strain [7-9]. The results showed that these curves were independent of load level, and the evolution of damage was traced by means of an internal damage variable. Other authors reported that the Characteristic Curves are also independent on load frequency and test temperature if the time-temperature superposition principle is applied [10; 11].

Cracking can be reduced using modified asphalt binder with the incorporation of ground scrap tyre rubber to produce rubberized asphalt via the wet process [12; 13]. This process results in a highly viscous material with enhanced engineering properties, but requires a specific equipment that is typically installed at the job site, or close to the supplying asphalt plant and its manufacture requires high temperature and long mixing time. New materials such as Reacted and Activated Rubber - RAR and Pellet rubber were developed with the purpose to simplify the manufacturing process (as in the asphalt mixture obtained by the dry process) and to enhance the performance of the asphalt mixture (as the asphalt mixture obtained by the wet process). The RAR, as an asphalt rubber binder, is composed of plain soft bitumen, fine crumb rubber, and an Activated Mineral Binder Stabilizer (AMBS) at optimized proportions. RAR is produced by a short-time hot blending and activation in a specially designed process to form a dried granulated activated rubber [14]. Pellets are produced by mixing crumb rubber and other polymers into the binder and after meeting some specifications, mineral fillers, fibers or other solid components can be added to the pelletized mix [15].

The present research analyzed the fatigue resistance of a gap-graded mixtures produced with addition of Pellet and RAR using four point bending tests (4PB) conducted on prismatic samples. These analyzes were carried out according to the work described by Mello et al. (2010) [16] and the tests were performed according to AASHTO T 321-03 [17] and interpreted within the framework of the Continuum Damage Theory.

2. THEORETICAL FRAMEWORK

Continuum Damage Theory ignores specific micro-scale behaviours and instead characterizes a material using macro-scale observations. The methodology for applying CDT model consists of three concepts:

- The elastic-viscoelastic correspondence principle;
- The definition of a Pseudo-Energy Density Function; and
- The definition of a Damage Evolution Law.

Schapery (1984) suggested that constitutive equations for certain viscoelastic media are identical to those for the elastic cases, but stresses and strains are not necessarily physical quantities in the viscoelastic body [7]. Instead they are pseudo variables in the form of convolution integrals. The pseudo-strain, for instance, is defined as:

$$\varepsilon^R = \frac{1}{E_R}.\int_0^t E(t-\tau)\frac{d\varepsilon}{d\tau}d\tau \quad (1)$$

in which ε^R is the pseudo-strain, E_R is a reference stiffness modulus, ε is the actual strain, $E(t)$ is the relaxation modulus, t is real time and τ is an auxiliary time integration variable.

For the case of bending fatigue tests under harmonic load, the pseudo-strain can be computed as:

$$\varepsilon_0^R = \frac{1}{E_R}\left[\varepsilon_0.|S^*|.\sin(\omega t + \theta + \varphi)\right] \quad (2)$$

in which ε_0 is the imposed strain amplitude, $|S^*|$ is the norm of the complex flexural stiffness, ω is the frequency, θ is a regression constant and φ is the phase angle. Eq. (2) is similar to an expression used by Lee (1996) [9], but here the dynamic flexural stiffness $|S^*|$ is used instead of the uniaxial dynamic modulus $|E^*|$.

The Pseudo-Energy Density Function, may be computed with the following expression for tests subjected to harmonic loads with constant strain amplitude [9]:

$$W^R = \frac{I}{2}.C.\left(\varepsilon^R\right)^2 \quad (3)$$

in which W^R is the pseudo-energy density, I is the initial pseudo-stiffness, C is the normalized pseudo-stiffness via dividing the pseudo stiffness by I and ε^R is the pseudo-strain. The pseudo-stiffness is defined as the relationship between the stress (σ) and pseudo-strain (ε^R).

For the general case, W^R is supposed to vary with ε^R and a series of internal damage variables D_s, i.e. these internal damage variables must have their own evolution laws. Park et al. (1996) suggested the following expression for viscoelastic materials [18]:

$$\frac{dD_s}{dt} = \left(-\frac{\partial W^R}{\partial D_S}\right)^{\alpha_S} \quad (4)$$

in which D_s represents a damage variable, the over dot means time rate, D_s is a material constant for each damage variable, and s is the number of damage variables adopted in the model. Summation over repeated indices is not implied in Eq. (4). Here only one internal variable D and one parameter are used to characterize the damage.

Lee (1996) proposed an expression to compute the damage parameter from the results of harmonic tension tests [9]. Daniel (2001) proposed a similar expression, but corrected the time intervals to account only for the time period during which the sample is under tension in haversine loading tests [10]. For bending tests with harmonic loading, as the ones used in this paper, the tension time corresponds to ½ of the total cycle time. Therefore, the expression to obtain the damage parameter from 4PB tests is given by:

$$D = \sum_{i=1}^{N}\left[\frac{I}{2}.(\varepsilon^R)^2.(C_{i-1}-C_i)\right]^{\frac{\alpha}{1+\alpha}}.(t_i - t_{i-1})^{\frac{1}{1+\alpha}} \quad (5)$$

in which C_i and C_{i-1} are the pseudo-strains for two consecutive data acquisition times t_i and t_{i-1}. The parameter α is believed to be a viscoelastic property of the material. Some definitions and correlations can be in related work, but there are still uncertainties determination. The first definition presented in the literature, relates the value of α to the viscoelastic properties of material, in particular, the parameter defined in curves of creep or relaxation tests. It was recommended to correlate α to the slope, *m* in the central part of the dynamic modulus master curve [10]. After determination of the internal damage variable *D* and the parameter *α*, the characteristic curve may be modelled. A simple model was proposed by Lee (1996), as follows [9]:

$$C = C_0 - C_1 D^{C_2} \tag{6}$$

in which C_i are coefficients determined experimentally. By relating of damage parameter and so-called pseudo-stiffness parameter of the material during the performance of a fatigue test, one can observe the evolution of the damage inside it, the C-D curves.

3. MATERIALS AND TESTS METHODS

Four different types of asphalt-rubber mixtures of gap-graded gradation with different 4th generation asphalt-rubber compositions added to the CAP 50/70 binder were produced. The asphalt-rubber blend in which Pellet was used was designated MAB-P, with addition of this material in 30% of binder mass. The asphalt-rubber blends produced with RAR were named MAB-R25 (with addition of 25% RAR in binder mass) and MAB-R30-1, MAB-R30-2 and MAB-R30-3 (with addition of 30% RAR by binder mass). Details of the methodology used during the production of prismatic samples can be found in Nunes (2017) [19].

The 4PB equipment software allows the test configuration according to EN 12967-24 [20], which allows the execution of a pre-test to obtain the dynamic modulus of the sample. Thus, at least three prismatic samples for each mixture were tested under the frequency values of 0.1; 0.2; 0.5; 1; 2; 5; 10; 15; 20; 25 Hz and temperatures of 5, 15, 25 and 35 °C for the determination of the dynamic modulus ($|E^*|$) and phase angle (φ). The imposed deformation was 50με in order to avoid premature damage and represents the external fibers response of the beam to the load. The sampling rate was determined by the application of sinusoidal pulses, with 200 repetitions per loading cycle. This step provided information to obtain the master curve of the studied mixtures that were adjusted according to the sigmoidal model. With the dynamic modulus, the relaxation and creep modulus can be obtained through some existing forms of conversions. Schapery & Park (1999) present some approximate formulations that allow the interconversion between the viscoelastic properties [21].

The viscoelastic material properties were estimated through the relaxation modulus calculation. The relaxation modulus values were calculated for each mixture type using the exact inter-conversion method. This approach requires the storage modulus E' to allow simple inter-conversion between the frequency and time domains. Through the Prony series, it is possible to obtain the relaxation modulus using a Weichert model, with the elements in parallel. The Prony series function can be expressed using:

$$E(t) = E_\infty + \sum_{i=1}^{N} E_i exp^{\frac{-t}{\rho_i}} \tag{7}$$

in which $E\infty$ is the equilibrium relaxation modulus, E_i and ρ_i are the the number of terms of the series of Prony.

The fatigue test was performed according to AASHTO T 321 [17] protocol, using mode of loading set to controlled deformation, and the shape of the sinusoidal pulse varied from 300 to 1000 με at 5 °C; 12.5 °C and 20 °C. In the case of beams the deformation does not appear uniformly along the section and the evolution of the damage progressively occurs from the outer edges toward the center of the sample [9-11]. In this paper, the characteristic curves of the mixtures studied aim to endorse the study of Mello et al. (2010) [16] in the validation for the application of the theory of continuous damage in tests of flexural fatigue.

4. RESULTS

Figure 1 shows the evolution of the damage parameter with the number of cycles for different imposed deformation values (in με) for MAB-R30-2 mixture. The curves of cumulative damage versus the number of load cycles show a non-linear damage evolution. The damage rate is higher for the initial cycles of test, then it decreases and becomes almost constant to finally increase again (more obvious in some tests than others), which is indicative of a last stage of failure of the sample. Similar results are obtained for mixtures MAB-P, MAB-R25 and the mixtures MAB-R30-1, MAB-R30-2 and MAB-R30-3, the last three tests in different temperatures. The same tendency is observed, i.e., non-linear damage evolution and faster damage accumulation for higher strain amplitudes. In C-D curves obtained for the mixtures modified with 30% of RAR tested at different temperatures, it was not possible to observe the influence of the test temperature on the evolution of the damage. These results showed similar damage increase rates for the same strain levels.

For the calculation of the damage parameter, the previous determination of the value of α is necessary. In this work, the variable α will be determined iteratively, with the aid of the characteristic curve to be determined. With the damage evolution and pseudo-stiffness data throughout all the tests on the beams, an α parameter is determined such that all the curves are superimposed on each other, assuming that such a parameter is a property of the material [9,10,22]. Figure 2 shows the results for the mixtures MAB-P and MAB-R25, for example, subjected to different strain amplitudes, at the temperature of 20°C. A fitting for the Characteristic Curve model, as represented by Eq. (6), is also shown in the same figure. The results were obtained for the seven different strain amplitudes and, nonetheless, all curves of normalized pseudo-stiffness factor versus the damage parameter are practically coincident. Although the results in Figure 2 were obtained from fatigue tests on beam samples under cyclic bending, they agree with the results obtained by other researchers who used uniaxial fatigue tests under tension on cylindrical samples [9-11; 22]. The fitting for Characteristic Curve model obtained in the others mixtures (MAB-R30-1, MAB-R30-2 and MAB-R30-3) also showed good adherence to the model.

Table 1 shows the values of parameter *α* and the parameters of the characteristic curves obtained for all mixtures. The α values obtained for the different mixtures reaffirm the similar behavior of the parameter k_2, of the traditional model of fatigue, according to the studies carried out in [19].

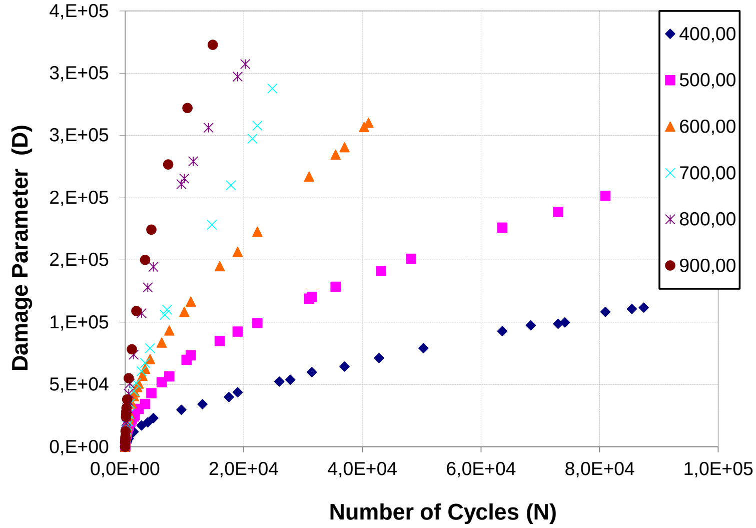
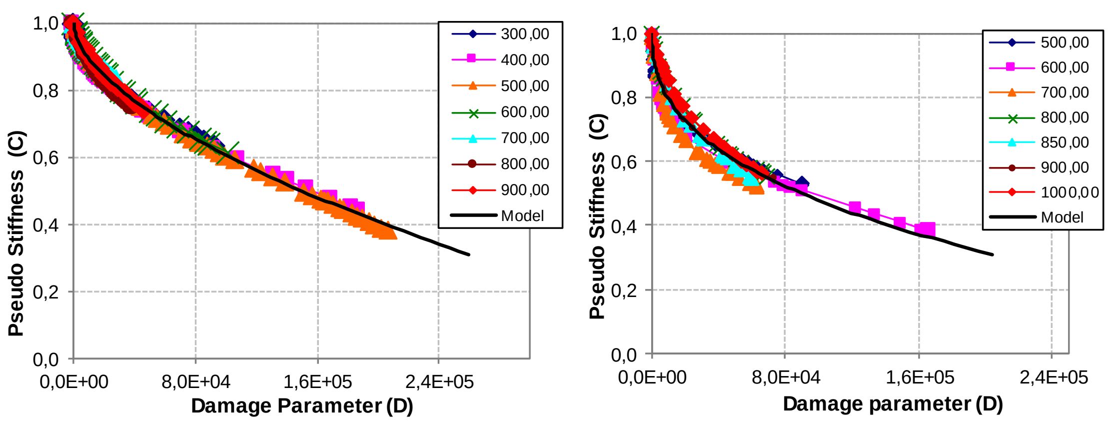


FIGURE 1 Evolution of the damage parameter for different strain amplitudes (MAB-R30-2, Temp.=20°C; 10 Hz).



(a) (b)

FIGURE 2 Characteristic curves for different strain amplitudes (a) mix MAB-P, Temp. = 20°C; 10 Hz (b) mix MAB-R25, Temp. = 20°C; 10 Hz.

TABLE 1 Coefficients of the characteristic curves for all mixtures.

Mixture	Temperature	C_0	C_1	C_2	α	k_2
MAB-P	20°C	0.99	4.36E-04	0.59	1.91	4.32
MAB-R25	20°C	1.03	7.44E-03	0.37	1.79	5.54
MAB-R30-1	20°C	1.03	3.88E-03	0.42	2.31	5.96
MAB-R30-2	5°C	1.00	1.02E-04	0.67	2.08	3.59
MAB-R30-3	12.5°C	1.01	3.04E-04	0.59	2.30	3.75

Notice that coefficient C_0 is very close to unity as expected. Coefficient C_1 is closely related to the negative slope of the characteristic curves. Coefficient C_2 is related to the non-linearity of the characteristic curves and it increases for lower temperatures.

These behavior of the C-D curves parameters were not similar to the data obtained by Mello et al. (2010) [16]. However, the need for a greater number of flexural fatigue tests for the mixture produced is emphasized, in order to obtain more consistent results, reducing the variability. In addition, it is necessary the numerical simulation stage will allow the analysis of evolution of the damage, according to the characteristic curves, which relate the parameter of damage with the degree of cracking existing inside the material.

5. CONCLUSIONS

The evolution of internal damage in hot mix asphalt (HMA) can be properly evaluated using the framework of the Continuum Damage Theory (CDT) to determine its characteristic curve. The uniqueness of this curve was investigated in this paper by performing fatigue tests in which prismatic samples of HMA were subjected to cyclic bending loads under strain controlled tests. Asphalt mixtures with gap gradation using different 4^{th} asphalt-rubber modified binders were tested and evaluated.

The characteristic curves proved to be unique for a wide range of strain amplitudes for all compositions asphalt-rubber mixes investigated. Tests with different temperatures for the same composition (MAB-R30-1, MAB-R30-2 and MAB-R30-3) and the same temperature for different materials (MAB-P, MAB-R25 e MAB-R30-1) showed α parameter with the similar behavior of the parameter k2. The C-D curves allows the development of models from numerical tools in the study of the evolution of the damage inside the mixture, which cannot be done when analyzing based on the traditional models of fatigue. Thus, in order to obtain conclusions about the damage evolution in the mixtures produced and on the 4th asphalt-rubber materials, numerical analyzes involving the use of the C-D curves are necessary. In this way, it will facilitate the understanding and definition of solutions capable of assisting in the development of projects closer to reality.

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