Evaluation of Fatigue Behavior of Aged Asphalt Mixtures Using the Simplified Viscoelastic Continuum Damage Model

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Abstract Aging of asphalt mixtures might play an important role in pavement structural behavior. That should be evaluated using mechanical models. This work aims at identifying the effects of aging on linear viscoelastic and damage behavior of asphalt mixtures, properties that influence the fatigue life of asphalt pavements. That is performed by characterizing a Hot Mix Asphalt (HMA) at four different aging states. The aged materials were obtained by heating loose asphalt mixture in oven at two different temperatures (85 and 135 °C) and aging times (2 and 45 days). Prony series were fitted to complex modulus results. For damage characterization, the Simplified Viscoelastic Continuum Damage (S-VECD) model was adopted. Damage characteristic curves and G^R versus N_f failure envelopes were obtained from controlled crosshead tension-compression test results at 19 °C. It was concluded that aging produces materials that fail for less evolved damage states. However, depending on pavement conditions and layer geometry, and considering the HMA hardening, aging does not necessarily reduce the fatigue life.

Keywords Asphalt mixtures · Aging · Fatigue modeling · S-VECD

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1 Introduction

Asphalt pavement analysis adopts asphalt mixture properties obtained from specimens fabricated without long-term aging. Nevertheless, asphalt mixtures are known to age as time passes. Although Rolling Thin Film Oven (RTFO) and Pressure Aging Vessel (PAV) tests are currently used for comparing unaged and aged asphalt binders, there is still no recommended method for considering changes in the constitutive behavior of asphalt mixtures due to aging. This work focuses in evaluating the change in fatigue life that asphalt mixtures can present upon aging.

2 Literature Review

Park et al. (1996) presented an application of Schapery's work potential theory that would later produce the S-VECD model, which describes the damage behavior of asphalt mixtures. AASHTO TP 107 (2014) presents test procedures and the calculation process that ends up with the damage characteristic curve (*C* vs. *S* curves) for a given material. Such curve relates material integrity (*C*) to damage accumulation (*S*), which is a function of the loading history (Underwood et al. 2012). Some of the fatigue failure criteria presented in the literature define a maximum acceptable percentage loss in modulus, usually 50 %. This criterion does not consider differences between the capabilities of materials to undergo damage. Other criteria are based on energy dissipation or on the phase angle trend, which is generally associated to the coalescence of microcracks into macrocracks (failure). In experiments, those criteria are observed to be mode-dependent, thus, not accessing material properties. Contributions by Sabouri and Kim (2014) allowed the combination of the phase angle drop criterion with a pseudo strain energy-based variable, producing a mode-independent failure criterion for fatigue. That variable is the averaged rate of release of the pseudo strain energy (per cycle), G^R, throughout the entire history of the test. Its relation with the number of cycles to failure (G^R vs. N_f curve) for a given asphalt mixture was found to be linear in log-log axis.

In order to simulate asphalt mixtures aging in the laboratory, one can use ovens, either with compacted samples (Walubita 2006; Baek et al. 2012) or with loose samples, prior to compaction (Partl et al. 2012, RILEM TC206 procedure). The main advantage of aging compacted samples is that compaction problems will not be observed after aging. However, this procedure leads to a heterogeneous aging of the sample. The main advantage in loose mixture aging is that a more homogeneous aged mixture is obtained, even though it is noticed that compaction is influenced by the aging state of the material (Babadopulos 2014).

3 Materials and Methods

The Brazilian asphalt mixture investigated in the present research is a dense asphalt concrete with 12.5 mm nominal maximum aggregate size with a PG 64-22 (AC 50/70) binder. For the designed air void content (4.0 %), the required binder content was 6.0 % (by weight of the total mixture). The materials tested are the reference unaged mixture (Age Zero), and that very mixture but subjected to different aging levels. They are named Age X, Y °C, where X denotes the number of days of loose mixture aging in the oven and Y the aging temperature. Specimen fabrication (100 mm diameter) was set to stop at a height of 150 mm with samples of 2630 g of asphalt mixture, targeting a 4 % air void content. The obtained mean air void contents were 4.3 % for Age Zero, 4.5 % for Age 2, 85 °C, 4.7 % for Age 2, 135 °C, and 6.0 % for Age 45, 85 °C. AASHTO T 342 (2011) was the protocol adopted for stiffness characterization. Controlled crosshead harmonic uniaxial fatigue tests were conducted using nine HMA samples per aging condition. The results were used to fit the S-VECD model parameters, after verifying that the damage curves collapsed for the different loading conditions (different strain amplitudes). This procedure was conducted according to AASHTO TP 107 and the G^R based failure criterion was also obtained. Three specimens were tested at each of the three different target strain levels (around 200, 350, and 500 μm/m).

4 Results and Discussion

With respect to stiffness characterization, results showed that the norm of complex modulus ($|E^*|$) gradually increases with aging. Log-log plots of $|E^*|$ master curves (in which the percentage increase in $|E^*|$ with aging is observed) showed that stiffness is mainly affected by aging at low reduced frequencies (or high temperatures), as observed by other authors (Glover et al. 2008). In those frequencies binder properties influence more the bulk response of the mixture. Characterization of E^* allowed the fitting of Prony series (which gives the material relaxation spectra) with 11 elements (Babadopulos 2014). The damage parameter α is directly obtained from the relaxation spectra ($\alpha = 1 + 1/m$, where m denotes the maximum absolute log-log derivative of the relaxation modulus) and it is an input for the S-VECD characterization. Its results for Age 0; Age 2, 85 °C; Age 2, 135 °C; and Age 45, 85 °C were 2.993, 3.089, 3.101, and 3.126, respectively. Figure 1 and Table 1 summarize the obtained damage characteristic curves description (plotted until their respective mean values of the material integrity at failure).

The first trend observed regarding aging is that the damage characteristic curves present higher values of material integrity (C) for the same values of damage accumulation (S). An increase in the material integrity at failure is also observed as aging progresses. This means that the material is failing for less evolved damaged conditions (less damage tolerance). When it comes to failure criteria, good

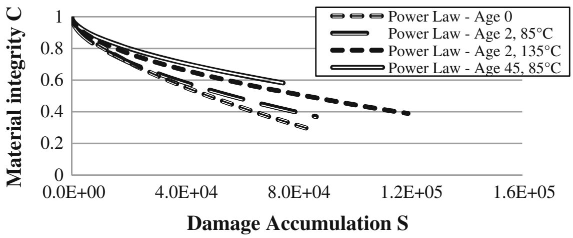

Fig. 1 Damage characteristic curves for the investigated aging states

Table 1 Power law ($C = 1 - C_{11} \cdot S^{C_{12}}$) fitting coefficients for C versus S curves

	Age zero	Age 2, 85 °C	Age 2, 135 °C	Age 45, 85 °C
C_{11}	5.41E−04	1.33E−03	1.04E−03	7.50E−04
C_{12}	6.33E−01	5.42E−01	5.45E−01	5.63E−01

Table 2 Fitting coefficients for G^R versus N_f curves

	Age zero	Age 2, 85 °C	Age 2, 135 °C	Age 45, 85 °C
Multiplier	4.93E+07	1.45E+07	7.60E+07	6.05E+06
Exponent	−1.52	−1.37	−1.51	−1.28
R^2	0.98	0.93	0.98	0.82

agreement between the model proposed by Sabouri and Kim (2014) (linear G^R vs. N_f in log-log axis) to relate averaged rate of release of the pseudo strain energy and fatigue life was observed (R^2 higher than 0.93) for early ages and acceptable agreement for Age 45, 85 °C (R^2 equals to 0.82). Results are summarized in Table 2.

With the calibrated damage models, material level simulations of fatigue behavior for the unaged and for the aged states were performed. The procedure applied by Nascimento et al. (2014) was used, i.e., failure was considered when the simulated G^R at a given cycle matched the one predicted by the fitted G^R versus N_f curve (coefficients in Table 2). A constant strain amplitude solicitation at 10 Hz was simulated at three different temperatures, in order to highlight the model capability of capturing temperature dependency of the fatigue behavior. Consequently, fatigue curves are obtained for three different values of dynamic modulus for each mixture. For the simulations at each temperature, five different strain levels were selected, chosen to achieve 120,200; 60,200; 20,000; 5000; and 1000 loading cycles at failure. The obtained data relate the number of cycles at failure with both the strain level (Whöler curves) and the dynamic modulus, making it possible to fit models for mechanistic-empirical (M-E) design methods (Eq. 1). The obtained parameters from the fitting (Eq. 1) for the tested materials are presented in Table 3. For easier visualization, only the fatigue life simulation results for Age Zero and Age 45, 85 °C were plotted in Figs. 2a–c.

Table 3 Mechanistic-empirical model parameters from fitting using the S-VECD model

	Age Zero	Age 2, 85 °C	Age 2, 135 °C	Age 45, 85 °C
K_1	2.95E+10	1.50E+08	3.96E+13	1.50E+08
K_2	4.44	6.25	5.45	6.25
K_3	−3.14	−3.66	−4.07	−3.66

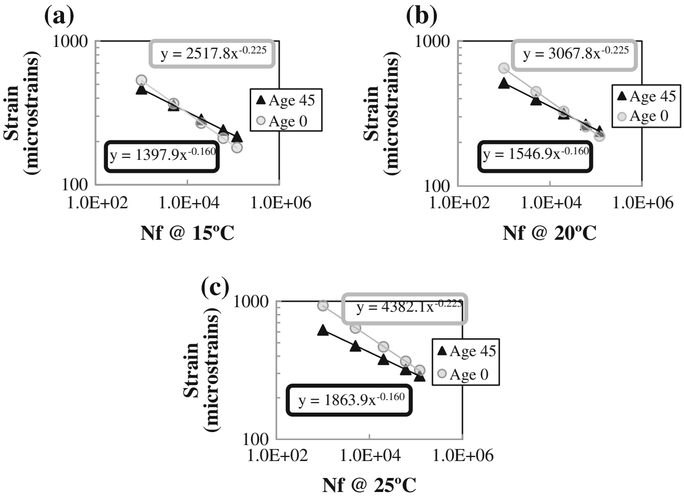

Fig. 2 Constant strain amplitude fatigue simulations for age zero and age 45, 85 °C

From manipulation of Eq. 1 and observation of results presented in Figs. 2a–c, it is noticed that the influence of temperature in fatigue behavior is accounted for by the stiffness term. The powers of the x-variable did not change for the different simulations, i.e., the slopes in the log-log space do not change with temperature, because they depend only on the value of $1/K_2$. It is actually the position of the Whöler curves in the y-axis that is changed by temperature, and this change is driven by dynamic modulus variation with temperature (from Time-Temperature Superposition Principle) and the model parameters K_2 and K_3 in Eq. 1. It can be shown that the change in the position of the Whöler curves in the y-axis is driven by the factor $(K_3/K_2) \cdot \log|E^*|$.

$$N_f = K_1 \cdot \left(\frac{1}{\varepsilon_t}\right)^{K_2} \cdot |E^*|^{K_3} \tag{1}$$

At 15 °C, within the simulated strain levels (210–470 μm/m), unaged and aged mixtures presented very similar results. Maximum difference between the predicted number of cycles to failure was approximately 30 %, for strains around 210 μm/m (a relatively low difference for fatigue results). At 25ºC, within the simulated strain levels (316–620 μm/m), maximum difference between the number of cycles to failure was approximately 80 %, for strain levels around 620 μm/m (from 6000 for Age Zero to 1000 for Age 45, 85 °C). For strain levels around 320 μm/m, the change was of approximately 120,000–60,000, representing a loss of 50 % in fatigue life. One should not forget that the layers thicknesses and stiffness play an important role in the fatigue life of the mixture on the pavement, driving the strain level within the asphalt layers. The aged material could perform better than the unaged one, depending on how the stiffness increase due to aging (inducing a decrease in the strain level in the aged pavement).

5 Conclusions

This work presented the S-VECD characterization of an asphalt mixture at different aging levels and some fatigue simulations. Results showed how the damage characteristic curve (*C* vs. *S* curves) changes with aging. The *C* versus *S* curves were observed to present higher values of material integrity (*C*) for the same values of damage accumulation (*S*) as aging evolves. That fact could mislead to the conclusion that a more resistant material was produced, as *C* is higher. The values of *C* at failure were higher as the aging state has grown, i.e., the material failed for a less evolved damage state. This contributes for a decrease in the fatigue life. However, from the results and simulations, aging does not necessarily reduce fatigue life in asphalt pavements. The consequence of aging can be either positive or negative depending on loading conditions, layers geometry and mixture properties.

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