Asphalt mixture performance and testing

DISCUSSION ON THE PROCEDURE TO BUILD THE CHARACTERISTIC CURVES OF FINE AGGREGATE MATRICES

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Abstract

An existing viscoelastic continuum damage (VECD) model, which accounts for the effects of rate-dependent damage growth, has been successfully applied to represent the reduction of the material integrity as a function of damage accumulation (characteristic curve) of asphalt concrete mixtures. A common problem experienced by researchers when applying the VECD model to characterize the damage of fine aggregate matrices (FAMs) is that the inherent heterogeneity of asphalt mixtures can lead to different linear-viscoelastic properties and characteristic curves of replicates of some FAMs. In this study, two or three replicates of ten FAMs were tested and some FAMs have shown results reinforcing such findings of the literature. An adjustment of the characteristic curves by using the average of the linear-viscoelastic properties of the replicates of these FAMs is presented, as a proposed procedure to build a unique material characteristic curve that is able to differentiate each FAM. In most cases, the procedure made it possible to obtain superposed characteristic curves. However, it was observed that a higher number of replicates may be needed for some materials, once that the application of the proposed procedure was not enough to generate similar characteristic curves among the replicates of some of the FAMs. The results also showed that it is possible to obtain a unique characteristic curve of replicates even when they are tested at different stress levels.

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1. INTRODUCTION

Mechanistic approaches have been employed to investigate the complex phenomenon of fatigue behavior of asphalt concrete mixtures. This approach can account for some relevant factors that influence the fatigue life of a viscoelastic material that models such as stress/strain vs. cycles to failure cannot. Mechanistic models based on the continuum mechanics approach have been successfully employed to predict the fatigue life of asphalt concrete samples subjected to fatigue tests [1-3]. According to the viscoelastic continuum damage (VECD) theory, a damaged body presenting internal micro cracks is assumed to be an undamaged body with a reduced stiffness, and the micro cracks are uniformly distributed within the body. Additionally, according to the theory, the time-dependency of viscoelastic materials can be eliminated by means of correspondence principles, which transform physical variables (stress, strain and stiffness) in pseudo variables (pseudo stress, pseudo strain, and pseudo stiffness) [4,5].

The material damage evolution is described as a function C(S), in which a reduction of the pseudo stiffness (C) is related to an internal state variable (S). Each material presents damage behavior which is independent of the loading amplitude or loading mode, so a single function C(S) represents the material damage behavior. However, due to the great variability intrinsic to asphalt mixtures, replicates of the same mixture can present different viscoelastic properties. Such properties are determinant for the calculation of the C(S) function of each sample, leading to different C vs. S curves (C values plotted against S values) [1,2, 6].

Studies about the fatigue phenomenon in asphalt mixtures have been developed by using the fine aggregate matrix (FAM) approach. FAM represents an intermediate scale between the asphalt mastic and the full asphalt mixture, and its internal structure is more homogeneous than the internal structure of the full HMA mixture. Studies using FAM samples are able to provide a more realistic characterization of the fatigue response of full asphalt mixtures than the one provided by tests performed on the mastic. The fine aggregate matrix represents the fine portion of the HMA mixture, which is comprised by fine aggregates, minerals fillers, bitumen and air voids. The fatigue response of FAMs can be assessed by measuring the changes in the material microstructure. This is done by performing damage tests on samples and building the characteristics curves (C vs. S curves) of the materials. Such a procedure is based on the premise that the changes of the material microstructure represent the beginning of the fatigue process [3].

This paper presents results from fingerprint and damage tests performed to predict the fatigue behavior of FAMs of different compositions. Although literature references indicate that each material presents a single characteristic curve, which is independent of loading conditions, laboratory tests sometimes result in different characteristic curves for samples of a same FAM [7,8]. Material heterogeneity is supposed to be the reason for such results. The method adopted in this study takes into account the average of the linear properties of the samples to build the material characteristic curves, in an attempt to handle the material variability.

2. LITERATURE REVIEW

2.1. Fine Aggregate Matrix – FAM

Fatigue process of asphalt mixtures is substantially influenced by properties of the mastic (combination of bitumen, filler, and entrapped air), as the changes of the material microstructure initiate on the fine portion of the mixture by means of adhesive micro cracks (cracking between aggregates and bitumen) and cohesive micro cracks (cracking of the bitumen). The micro cracks coalesce, generating a crack propagation process that result in the formation of macro cracks until the complete degradation of the material [3].

Based on the premise that the changes of material microstructure are the beginning of the fatigue process, researchers [9-10] started to study the fatigue behavior of asphalt mixtures using the FAM approach, and developed a protocol to evaluate the FAM properties. The protocol consists of performing oscillatory tests on cylindrical samples, by following two steps: (i) low strain tests, in order to identify the viscoelastic properties of the material; and ii) high strain tests, to evaluate the damage evolution process on the material [3]. Studies that correlated the results of tests performed on FAM samples with the results of tests performed on full mixture samples indicate that the FAM scale can provide reasonable information to predict the full mixture behavior [11,12].

The main assumption in studies with FAM mixtures is that they are able to reproduce the internal structure of the fine portion of the full HMA mixture. Another important assumption is that the physic-chemical interactions between aggregate and bitumen are replicated in the FAM specimen. Another advantage of utilizing FAM samples in fatigue testing is that the reduced size of the samples requires a smaller amount of material compared with the amount required to produce samples of full asphalt mixtures, demanding a reduced laboratory work to prepare the samples.

2.2. Viscoelastic Continuum Damage Theory – VECD

The constitutive equation for elastic materials (Hooke's Law: $\sigma=E\varepsilon$) postulates a linear relationship between stress and strain. The same relationship that describes the behavior of elastic materials can be used to describe the behavior of viscoelastic materials. However, in viscoelastic materials, such behavior is influenced by time, and the stress and the strain are not necessarily physical quantities, but pseudo variables: pseudo stress (σ^R) and pseudo strain (ε^R). An artifice proposed by Schapery [4] in order to eliminate the time dependent effects was to transform the stress-strain relationships of viscoelastic media into a pseudo domain that corresponds to a hypothetical elastic material, suggesting that the constitutive equation for elastic media can be applied to viscoelastic media, by means of correspondence principles.

According to the correspondence principle, $\sigma^R=\sigma$, where σ (Equation 1) is the time dependent stress applied to a viscoelastic material, and the pseudo strain, ε^R, is given by Equation 2, where ε is the time-dependent strain in a viscoelastic material, G(t) is the linear viscoelastic relaxation modulus of the material and E^R is the modulus of a hypothetical elastic material. A constitutive equation for viscoelastic materials is given by Equation 3 [4,5].

$$\sigma = \int_0^t G(t-\tau)\frac{d\varepsilon}{d\tau}d\tau \tag{1}$$

$$\varepsilon^R = \frac{1}{E_R}\int_0^t G(t-\tau)\frac{d\varepsilon}{d\tau}d\tau \tag{2}$$

$$\sigma=E\varepsilon^R \tag{3}$$

Studies pointed out that the fatigue damage of asphalt mixtures can be evaluated by means of the VECD theory, which is independent of type, mode, amplitude or frequency of loading [1,2,6]. Lee and Kim [1] conducted uniaxial tensile cyclic loading tests on asphalt concrete samples, with different loading amplitudes, under controlled-strain and controlled-stress loading modes and concluded that the pseudo stiffness, C, is a function of the material internal state, S. The constitutive equation for viscoelastic materials with growing damage could be rewritten as $\sigma=IC(S)\varepsilon^R$, in which I is the initial pseudo stiffness used to minimize the sample to sample variation. After mathematical adjustments, the internal state variable can be calculated by Equation 4, in which α is the damage evolution rate, with $\alpha=1/m$, where m is the relaxation rate. The function C(S) (Equation 5) is built by cross plotting the C values, obtained from the constitutive equation, against the S values (Equation 4), and by performing a regression on the data, in which C_0, C_1, and C_2 are the regression coefficients.

$$S \cong \sum_{i=1}^{N}\left[\frac{I}{2}(\varepsilon^R)^2(C_{i-1}-C_i)\right]^{\alpha/(1+\alpha)}(t_i-t_{i-1})^{1/(1+\alpha)} \tag{4}$$

$$C(S)=C_0-C_1(S)^{C_2} \tag{5}$$

2.3. Linear Viscoelasticity

Viscoelastic materials under dynamic loading conditions provide frequency-domain dynamic properties, such as (i) phase angle, $\emptyset(\omega)$, that represents the gap between the stress and strain due to the time-dependency of the viscoelastic materials, (ii) storage shear modulus, $G'(\omega)$, that represents the elastic characteristics of the material and (iii) loss shear modulus, $G''(\omega)$, that represents the viscous behavior of the material. The combined form of storage shear modulus and loss shear modulus results in Equation 6 for the phase angle, in Equation 7 for the dynamic shear modulus, $|G^*(\omega)|$, and in Equation 8 for the complex shear modulus, $G^*(\omega)$, where ω is the angular frequency, τ_{max} is the maximum shear stress in each cycle, γ_{max} is the applied cyclic shear strain amplitude, and i is equal to $\sqrt{-1}$.

$$\emptyset(\omega)=\tan^{-1}\left[\frac{G''(\omega)}{G'(\omega)}\right] \tag{6}$$

$$\left|G^*(\omega)\right|=\frac{\tau_{max}}{\gamma_{max}}=\sqrt{[G'(\omega)]^2+[G''(\omega)]^2} \tag{7}$$

$$G^*(\omega) = G'(\omega)+iG''(\omega) \tag{8}$$

3. TEST METHODS

The tests were performed according to the protocol developed by Kim and researchers [3,9,10]. First, a stress sweep test is performed in order to obtain the linear viscoelastic range of each FAM. One sample is used in this step, which is discarded right after the test. The next step is a fingerprint test, which is performed to obtain the linear viscoelastic properties of each FAM. Subsequently, the same FAM sample is submitted a fatigue test in order to cause damage and the behavior of the materials is monitored. The tests will be detailed in the following sections.

3.1. Linear Viscoelasticity Range

Ideally, the linear viscoelastic dynamic shear modulus, $|G^*|LVE$, is equal to the dynamic shear modulus value that is measured by applying a small level of strain or stress within the linear viscoelastic range of the material [13]. In the absence of a procedure for FAMs, researchers have been considered different criteria in order to obtain the dynamic modulus within the linear viscoelastic region of each material. Oscillatory tests with stress ranging from 5 to 450 kPa, at 1 Hz and 25°C, were carried out in this study, and the linear-viscoelastic region was defined as the range of stresses under which the materials present a deviation of 10% of their initial stiffness. Test results indicated the stress of 15 kPa as an appropriate value to keep the tests within the linear-viscoelastic region for all tested FAMs.

3.2. Linear Viscoelasticity Properties

A fingerprint test was performed at 15 kPa to obtain the dynamic shear modulus ($|G^*|$) and phase angle (δ) of the materials, at different frequencies. The following frequencies were used: 30, 26, 22, 18, 14, 10, 6, 4, 2, 1, 0.5, 0.2, 0.1, 0.05 and 0.01 Hz. Such data were used to estimate the relaxation rates (m) of the materials, based on their relaxation curves. The first step is to calculate the storage modulus values, $G'(\omega) = |G^*(\omega)|\cos\delta(\omega)$, and plot the $G'(\omega)$ vs. angular frequency curve. After that, the viscoelastic Maxwell model was adjusted to the curve, by means of Prony series. The data were converted from the frequency domain to the time domain, by using a Laplace Transform, and the shear modulus, G, as a function of time was obtained. The G(t) vs. time curve was plotted and a power law ($G=G_0+G_1.t^{-m}$) was adjusted to the data in order to estimate the relaxation rate m.

3.3. Damage Tests

Oscillatory tests under controlled stress at a frequency of 1 Hz and a temperature of 25 °C were performed in the dynamic shear rheometer (DHR 2000 and MCR 302) in order to evaluate the damage evolution of the FAMs. The stress used in the tests ranged from 100 to 350 kPa. The pseudostiffness (C) and the accumulated damage (S) values were calculated by means of the Equations 4 and 5. Characteristic curves, C vs. S, were built according to the model proposed by Lee and Kim [1].

4. MATERIALS

Aggregate particles passing sieve #10 (2.00 mm) were used to prepare the FAM samples. The FAM aggregate gradation is derived from a dense aggregate gradation (grade C) typically used in road construction in Brazil, which complies with the specification of the Brazilian Department of Terrestrial Infrastructure (DNIT 031/2004-ES). Four FAMs were prepared with one asphalt cement (AC), graded as PG 64-22, supplied by Replan/Petrobras, one bitumen modified with polyphosphoric acid (PPA), named AC+PPA, one bitumen modified with styrene-butadiene-styrene copolymer (SBS), named AC+SBS, and one bitumen modified with crumb rubber (AC+rubber). All the modified bitumen were prepared in the laboratory by using the neat bitumen as base material. The bitumen contents of the FAMs prepared with the base AC, the AC+PPA, the AC+SBS and the AC+rubber are, respectively: 7.4%, 7.8%, 7.7% and 9.3%. Detailed information on the preparation of the samples can be found in Ng et al. [14].

The same neat bitumen used in the production of the modified bitumen and a shale-oil residue, which worked as a rejuvenating agent, were used to produce the FAMs containing Reclaimed Asphalt Pavements (RAP). Table 1 presents the composition of these FAMs. The RAP bitumen content was obtained by an extraction method, and it was found to be equal to 7.1%. An extra amount of virgin bitumen was added to all FAMs in order to reach a bitumen content of 8%. Such a bitumen content was estimated by means of the specific surface method [15] to cover all fine aggregates present in the FAM. Detailed information on the preparation of the specimens can be found in Klug [7].

All the aforementioned FAMs were produced using mineral aggregates derived from basalt rock, supplied by the Bandeirantes Quarry, located at the City of Sao Carlos, State of Sao Paulo, Brazil. The RAP used in the production of the FAMs was obtained from roads around the City of Sao Carlos. The FAMs designated as Helvio Basso and TQ Superior were produced with materials used in the construction of field trials in the city of Santa Maria, in the State of Rio Grande do Sul, Brazil. The mineral aggregates are derived from basaltic rock, supplied by the Della Pasqua

Quary (Helvio Basso) and the Brita Pinhal Quary (TQ Superior), both located at the city of Itaara, in the State of Rio Grande do Sul, Brazil. The bitumen used in these field trials are both unmodified bitumen graded as PG 64-16.

Table 1. Composition of FAMs containing RAP

FAM	virgin bitumen (V.B.) PG 64-22 (%)	rejuvenating agent (R.A.) shale oil residue (%)	observation
20%RAP+PG64	0.18[(1)]+6.40[(2)]=6.58	-	20% RAP
40%RAP+PG64	0.36[(1)]+4.8[(2)]=5.16	-	40% RAP
20%RAP+50/50(V.B./R.A.)	0.09[(1)]/6.40[(2)]	0.09	20% RAP
40%RAP+50/50(V.B./R.A.)	0.18[(1)]/4.80[(2)]	0.18	40% RAP

[(1)]virgin bitumen added to adjust the RAP bitumen content; [(2)]virgin bitumen to cover the virgin mineral aggregate

5. RESULTS

5.1. Linear Viscoelastic Properties

Table 2 presents the viscoelastic properties of the materials, including $|G^*|_{LVE}$ and the relaxation rate of the materials. The air voids of the samples and the stress applied in the time sweep tests are also presented for reference. It was observed that different samples of a same FAM can present different values of m and $|G^*|_{LVE}$, even when the samples present similar air voids. The samples designated as TQ SUPERIOR, AC+SBS and AC+rubber are examples of this fact. On the other hand, the FAM designated as 40%RAP+50/50 presents very different air voids and very similar values of $|G^*|_{LVE}$ and m. Other FAMs, such as those designated as 20%RAP+50/50 and Helvio Basso present distinct values for both air voids and linear viscoelastic properties. Based on these results, one can conclude that the control of air voids in the production of the FAM samples seems to be not enough to guarantee low variabilities in the linear-viscoelastic properties. Other factors are supposed to be affecting the variability, such as particle arrangement, which can not be totally controlled during the production of the samples. This hypothesis seems to be valid when shear tests are used, once that part of the applied stress is consumed to brake the friction between aggregate particles.

Table 2. Viscoelastic properties of the materials

FAM designation	sample #	air voids (%)	stress (kPa)	$\lvert G^*\rvert_{LVE}$ (Pa)		relaxation rate (m)	
				individual	average	individual	average
Neat bitumen	1	4.7	350	1.03E+09	8.31E+08	0.45	0.45
	2	4.9	350	6.31E+08		0.45	
AC+PPA	1	3.0	400	9.77E+08	9.65E+08	0.44	0.42
	2	3.7	400	9.53E+08		0.39	
AC+SBS	1	2.1	400	1.28E+09	9.17E+08	0.49	0.47
	2	1.9	400	8.40E+08		0.45	
AC+RUBBER	1	2.9	300	3.93E+08	5.39E+08	0.35	0.37
	2	3.0	300	6.48E+08		0.40	
20%RAP+PG64	1	1.2	150	1.00E+09	8.54E+08	0.35	0.35
	2	1.2	250	7.08E+08		0.36	
40%RAP+PG64	1	2.3	300	1.36E+09	1.54E+09	0.21	0.19
	2	2.5	350	1.72E+09		0.18	
20%RAP+50/50	1	4.1	150	1.04E+09	9.83E+08	0.35	0.38
	2	3.3	100	9.27E+08		0.41	
40%RAP+50/50	1	4.8	300	1.89E+09	1.84E+09	0.27	0.28
	2	7.2	300	1.78E+09		0.29	
Helvio Basso	1	1.5	250	1.05E+09	1.02E+09	0.26	0.27
	2	2.0	200	9.59E+08		0.31	
	3	1.1	250	1.05E+09		0.25	
TQ Superior	1	2.3	250	1.52E+09	1.56E+09	0.19	0.15
	2	2.4	250	1.30E+09		0.13	
	3	2.4	250	1.87E+09		0.16	

5.2. Damage Properties

The characteristic curves of the materials were built by applying the VECD model proposed by Lee and Kim [1]. Results obtained from tests with FAMs have been showing that the heterogeneity in the material properties for two replicates may result in different characteristic curves [7,8]. In order to overcome this issue and to predict an accurate damage behavior of the FAM mixtures, the average of the sample properties was considered in the model. By adopting such a procedure, it was possible to obtain a unique characteristic curve representing the material damage behavior.

Figure 1 to 3 presents the individual C vs. S curves, which are represented by the full line curves, and the adjustment of the C vs. S curve based on the average of the linear viscoelastic properties (|G*|LVE and m) represented by the dashed line curves. Figure 1 shows the individual and the adjusted C vs. S curves for the FAMs prepared with neat and the modified bitumens The stress level, around 300 to 400 kPa, was the same for the two replicas of each FAM (Table 2). It can be observed that each sample presents a C vs. S curve that is different from each other. Out of the four FAMs, for those prepared with AC+PPA and AC+SBS was observed a good fit of the characteristic curves after the adjustment, resulting in a single C vs. S curve for the two replicas. However, the FAMs prepared with the neat bitumen and the AC+rubber did not match after the adjustment. The results obtained for the FAMs prepared with the neat bitumen and the AC+rubber point out that for some materials two replicates can not be enough to obtain a good adjustment.

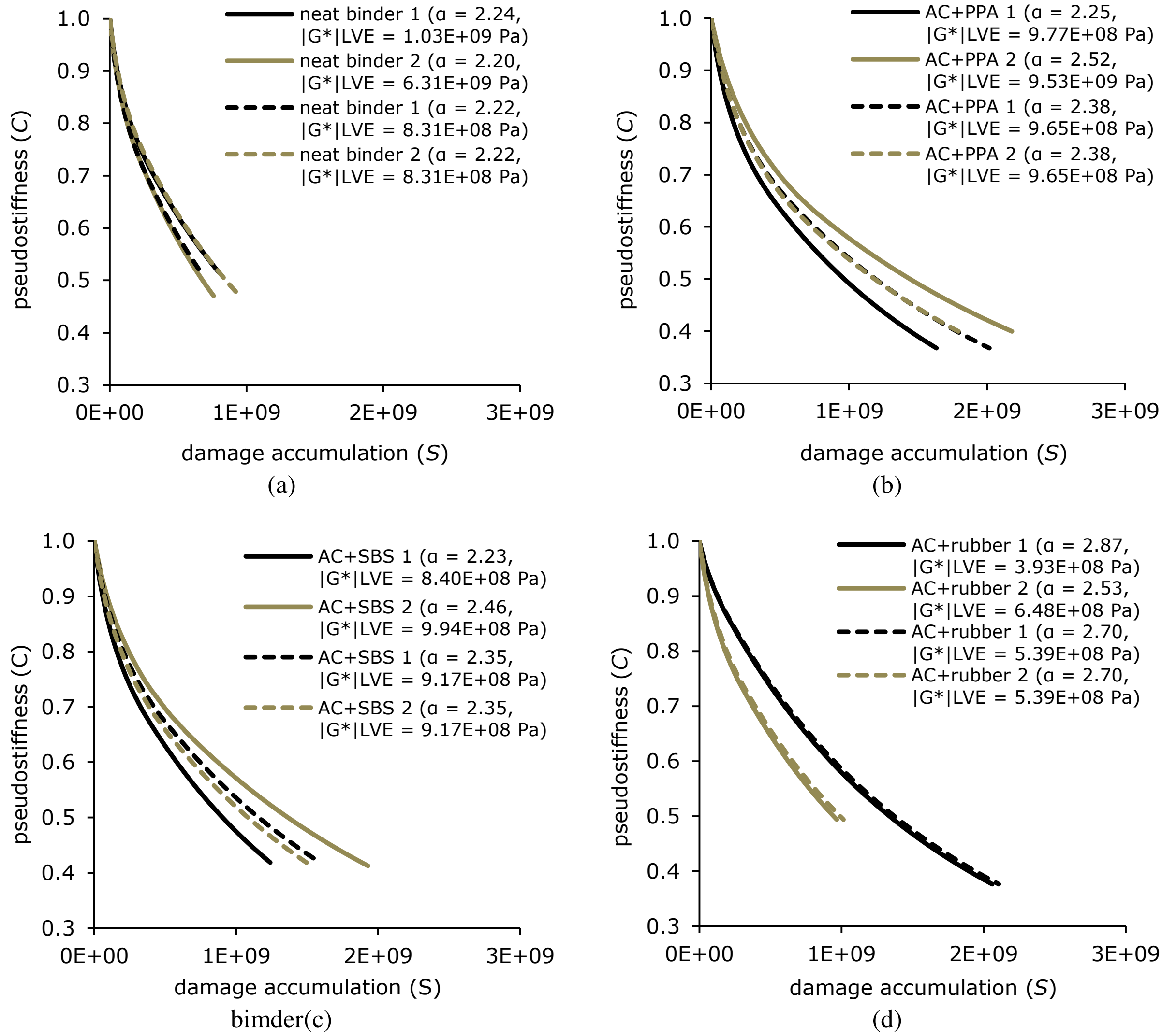


Figure 1. Individual and adjusted C vs. S curves for FAMs prepared with (a) neat AC, (b) AC+PPA, (c) AC+SBS, and (d) AC+rubber

On the other hand, Figure 2 shows that the adjustment of the characteristic curves (dashed line curves) for the FAMs containing RAP resulted in better fits, even when the stress applied in the damage test to two replicas are different. This was the case of the following FAMs: 20%RAP+PG64, 40%RAP+PG64, and 20%RAP+50/50. Such a conclusion matches the findings of previous studies conducted by Park and researchers [1,2,6]et al. (1996), Lee and

Kim (1998), and Daniel and Kim (2000), who observed that each material (HMA mixtures in these cases) presents a unique characteristic curve, which is independent of the mode or amplitude of load. Regarding the FAM designated as 40%RAP+50/50, one can see that the curves show a more uniform shape as compared to the curves of the other three materials. This seems to have some relationship with the stress level employed in the damage tests, once that the FAMs designated as 40%RAP+50/50 were tested at 350 kPa (both replicas), whereas the other three FAMs were tested at much lower stress levels (100 to 250 kPa) with replicas tested at different stress levels.

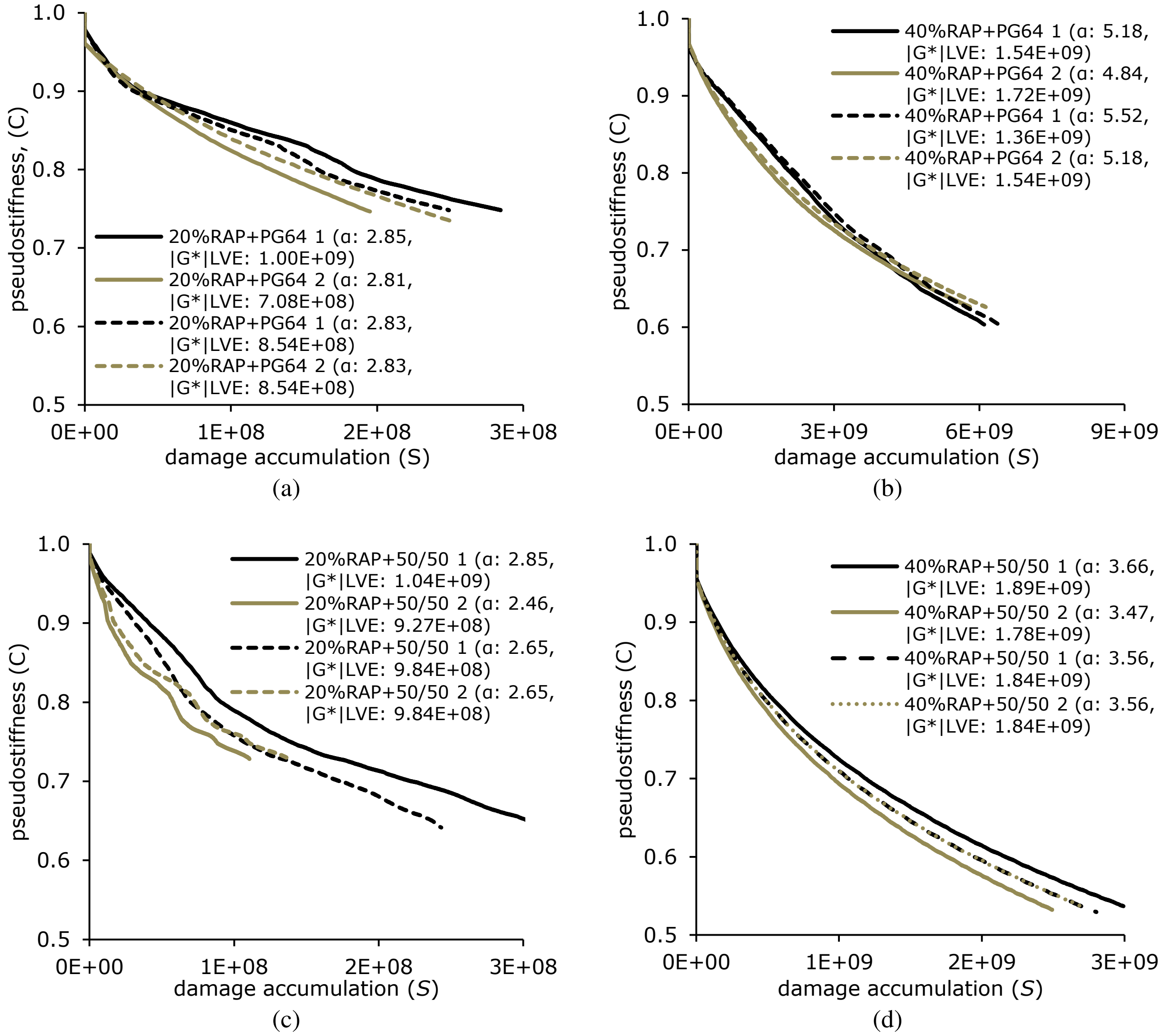


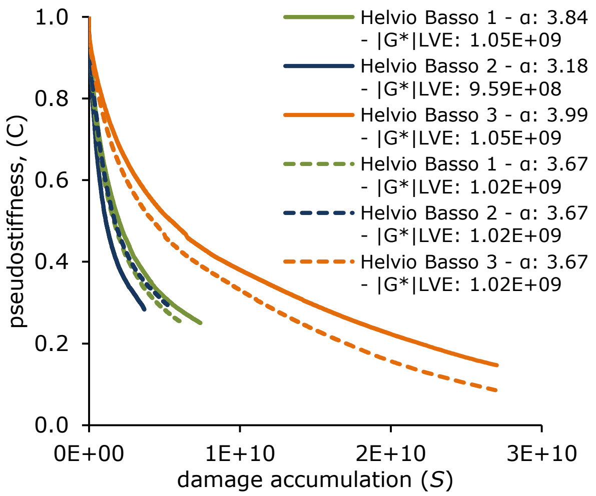
Figure 2. Individual and adjusted C vs. S curves for the FAMs prepared with RAP

Figure 3 presents the individual C vs. S curves for the FAMs Helvio Basso and TQ Superior, and the adjustment of the curves by considering the average properties. Three replicates of each FAM were tested. The FAM Helvio Basso presented three distinct characteristic curves for samples 1, 2 and 3. Samples 1 and 3 were tested at the same stress level of 250 kPa, and sample 2 was tested at 200 kPa. By using the average of the linear viscoelastic properties, the curves of samples 1 and 2 matched and the curve of sample 3 got closer to the other two. For the FAM TQ Superior, Figure 3 shows superposition only for the curves of samples 2 and 3. After the adjustment, the curve of sample 1 also got closer to the curves of samples 2 and 3. For this material, the stress level applied to the three replicates was 250 kPa. The results obtained for these two materials reinforce the adequacy of the adjustments using the average linear-viscoelastic properties.

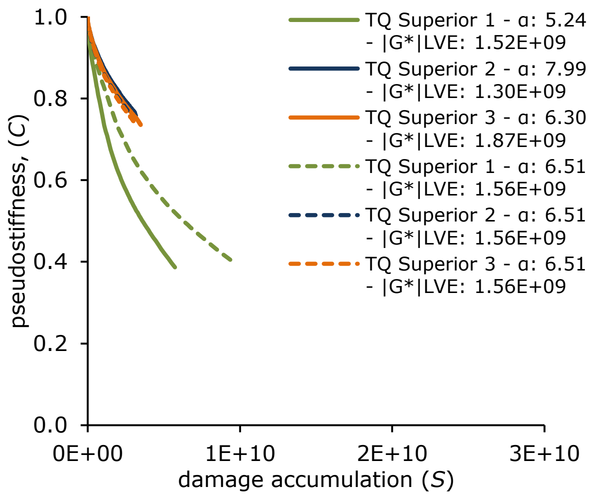
6. CONCLUSIONS

This paper addressed a common problem experienced by researchers when applying the VECD theory to build the characteristic curves of fine aggregate matrices (FAMs). Extensive laboratory testing has been showing that there are some materials whose replicates present different linear-viscoelastic properties and characteristic curves, even when the air voids of the samples and all the other test conditions are similar. Some FAMs tested in this experiment have shown results reinforcing such findings. An adjustment of the characteristic curves of replicates of ten FAMs of different compositions is presented in this study, as a proposed procedure to build a unique material characteristic curve that is able to differentiate the FAMs produced with different materials. The adjustment of the C vs. S curves was done by using the average of the linear-viscoelastic properties of the materials.

In most cases, it was possible to obtain superposed C vs. S curves after applying this procedure. However, it was observed that, for some materials, testing of only two replicates was not enough to generate a unique characteristic curve, even when the proposed procedure was applied. A higher number of replicates may be needed for some materials, even when the air voids are strictly controlled, once that results from this study showed that the control of air voids is not enough to generate similar characteristic curves among replicates. The results of this study also showed that it is possible to obtain a unique characteristic curve of replicates even when they are tested at different stress levels. It was also observed that for some materials testing at higher stresses (around 350 kPa) is a good practice to generate C vs. S curves with a more uniform shape.



(a)



(b)

Figure 3. Individual and adjusted C vs. S curves for (a) FAM Helvio Basso and (b) FAM TQ Superior

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