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EVALUATION OF THE EFFECT OF DEFLECTION WAVEFORM ON FATIGUE PERFORMANCE OF ASPHALT MIXTURE IN THE FOUR POINT BENDING BEAM TEST

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1 **EVALUATION OF THE EFFECT OF DEFLECTION WAVEFORM ON FATIGUE**
2 **PERFORMANCE OF ASPHALT MIXTURE IN THE FOUR POINT BENDING**
3 **BEAM TEST**

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Abstract

An experimental study was conducted to determine the effect of deflection waveform on four-point flexural fatigue test results for hot mix asphalt. This paper reports how the waveform affects the fatigue resistance of an asphalt mixture and, consequently, the fatigue models of the material. The mix was tested at different strain levels under both haversine and sinusoidal deflection-controlled modes. The findings indicate that haversine displacement control testing results in a sinusoidal strain response of half the intended amplitude. This outcome was attributed to the viscoelastic nature of asphalt mixes. In the deflection controlled haversine test permanent deformations lead to a new equilibrium neutral position of the beam and the force output follows a sinusoidal waveform. This produce erroneous fatigue results since the test assumptions do not match the actual test conditions. It is recommended to use a sinusoidal waveform in order to obtain consistent results.

Keywords: Asphalt mixture; Fatigue performance; Deflection waveform; Fatigue models; Pavement design.

1 INTRODUCTION

The study of mechanisms or phenomena that result in loss of structural and functional integrity of pavements is extremely important to design safe, durable, and resistant structures. When it comes to flexible pavements in countries with tropical climate, the appearance of defects is usually related to two main causes: material fatigue and permanent deformation (Melo 2014).

Asphalt mixtures are subjected, in short intervals of time, to the repeated loads of vehicle traffic over highways. This repeated load applied to the material's surface results in the progressive loss of its stiffness at long term and contributes to the emergence of microcracks in the asphalt's layer. The accumulation and evolution of these microcracks result in damage attributed to the fatigue phenomenon (Di Benedetto et al. 2004; Beskou et al. 2016; Aarabi and Tabatabaei 2018).

According to the ASTM E1823 (2013), fatigue can be defined as: "the process of progressive and localized permanent structural change occurring in a material subjected to certain conditions that generate fluctuating stress and strain at some point or points and that may culminate in cracks or in a complete fracture after a sufficient number of fluctuations." Understanding this mechanism and how to control its deleterious effects on flexible pavements contribute to the design of structures that can bear the load to which they will be subjected throughout the project's lifespan (Pintarelli 2017).

According to Melo (2014), it is substantial to know the characteristics of the materials used on pavement construction through laboratory tests, that enable researchers to adequately determine its properties, in order to achieve reliable data, similar and closer to the field situation.

Therefore, vis-à-vis the fatigue characterization of asphalt mixtures, it is currently possible to use several devices designed to evaluate their resistance. Among them, the Four Point Bending Apparatus is one of the devices most employed throughout the world. This machine

applies a load consisting of two vertical forces spaced apart by a third one, with the span of a beam. It bends the prismatic specimen either upwards or downwards, and measures the maximum load applied and the maximum displacement in the medium point of the beam (Melo 2014). In this type of test, the fatigue occurs in the central zone of the beam, with constant bending moment and null shear stress. Hence, the beam rupture tends to happen without shear stress.

In Europe, the standardization of this test is established by EN 12697-24 (2012a), in Australia by AG:PT/T233 (2006) of the Austroads Guide and in the USA by ASTM D7460 (2010b) and AASHTO T321 (2017). Both American documents were developed based on the results obtained from researches made in the program SHRP A-003A (Tayebali et al. 1994). The differences between all standards are mainly related to the format of the wave load applied during the test and to the failure criteria adopted. The European procedure and the American AASHTO standard recommend the use of the sinusoidal loading, in which the prismatic specimen is bended both upward and downward in relation to its neutral axis, with constant displacement amplitudes, alternating over time. The Australian and American ASTM standards recommend the use of the haversine loading, in which the equipment applies a one-way range displacement, bending the specimen in one direction only, in relation to its neutral axis.

The general formula of the wave formats can be expressed according to Equation 1. When $\delta = \frac{\pi}{2}$ and $A = D$, the wave has a haversine shape, while $\delta = 0$ and $D = 0$ represent a sinusoidal wave (Mamlouk et al. 2012).

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$$97 \quad y(t) = A \cdot \sin(2\pi ft + \delta) + D \quad (1)$$

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99 where t = time; A = half of peak-to-peak oscillation; f = loading frequency; δ = initial phase
100 angle; D = center amplitude.

101

102 In this context, several papers about the fatigue resistance of asphalt mixtures have been
103 developed using the haversine waves in laboratory tests (Mamlouk et al. 2012; Hernández et
104 al. 2013; Cooper Jr. et al. 2013; Huang et al. 2015). On the other hand, a wide range of studies
105 have been using the sinusoidal waves (Eberhardsteiner and Blab 2017; Goli et al. 2017;
106 Varma et al. 2016; Rasouli et al. 2018; Melo and Trichês 2017; Almeida et al. 2018; Melo et
107 al. 2018), revealing a disagreement among the researchers about the ideal waveform to be
108 employed in the test. Therefore, caution is advised while comparing fatigue models obtained
109 through standard procedures that were conducted under different loading. This means that a
110 relevant mismatch can be found between the results, especially when they are used to
111 estimate the fatigue failure of the asphalt surface course on a pavement structure.

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113 This paper presents the results of a comparative study about the impact of the applied
114 waveform—sinusoidal or haversine—in the elaboration of asphalt mixtures' fatigue models.
115 Also, the effects of the load format on the fatigue failure prediction of asphalt surface layers
116 were investigated.

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118 **2 MATERIALS AND METHODS**

119 **2.1 Materials**

2.2.1 Mineral Aggregates and Granulometric Composition

The mineral aggregates selected on this study come from a metamorphic rock formation, of the gneiss type, resulting from the deformation of arcogenic deposits and granites. The main properties of mineral aggregates, vis-à-vis its acceptance or rejection in the formulation of asphalt mixes, are shown in Table 1. It can be noticed that all properties fulfill the Superpave specification requirements.

The granulometric formulation of the asphalt mixture was composed of 20% of coarse aggregate 3/4" (19.1 mm), 25% of fine aggregate 3/8" (9.5 mm), 53.5% of stone dust, and 1.5% of hydrated lime. The gradation curve was defined to fit the Asphalt Institute mixture type IV-B. Considering that: coarse aggregate corresponds to the fraction that passes through a 19.1 mm sieve and is retained by a No. 4 ASTM sieve; fine aggregate represents the fraction that passes through a No. 4 ASTM sieve and is retained by a No. 200 ASTM sieve; and, powdered material passes through a No. 200 ASTM sieve; the mixture is a composite from 39.6% of coarse aggregate, 53.2% of fine aggregate and 7.2% of powdered material. Figure 1 presents the granulometric composition formulated.

The lime used in this study was of the type CH-1, dolomitic, and hydrated, classified as type II, according to AASHTO M303 (AASHTO 2014). The lime has the following physical and chemical properties: 26.2% of loss on ignition, 3.6% of insoluble residue, 3% of carbon dioxide (CO₂), 40.9% of calcium oxide (CaO), 29% of magnesium oxide (MgO), 94.7% of total non-volatile oxides (CaO + MgO), and 3.7% of total non-hydrated oxides (provided by the manufacturer Pinocal Indústria e Comércio de Cal Ltda.).

2.2.2 Asphalt Binder

The asphalt binder selected was of a modified type, with the addition of 20% of crumb tire rubber (terminal blend). The binder was obtained from Petrobras. The main properties of the binder are presented in Table 2.

2.2.3 Design of the Asphalt Mixture

The dosing procedure of the asphalt mixture was carried out according to the recommendations of ASTM D6926 (ASTM 2016) and ASTM D6927 (ASTM 2015c). It was prepared for high-volume traffic and according to the Marshall methodology, in which an energy level corresponding to 75 blows per face was applied to the specimens. The asphalt mixture was designed to satisfy the following volumetric criteria: air voids percentage between 3 and 5%; VFA (voids filled with asphalt) between 65 and 78%; stability greater than 8006 N; VMA (voids in mineral aggregate) greater than 13%; dust to effective binder ratio between 0.8-1.2; and, flow value between 8-14 (0.25 mm). For the production of the mixture in laboratory, a mechanical mixer was employed. The materials were heated up to the temperatures recommended by ASTM D6114/D6114M (ASTM 2009). In this sense, the asphalt binder was heated to a temperature of 170 °C and the aggregates were heated to 177 °C. Considering the recommendations of AASHTO R30 (AASHTO 2015), after the mechanical homogenization of the mixture, and before its compaction, it was stored in an oven for two hours at the compaction temperature (155°C).

The design led to a mixture with asphalt binder content of 6.1%, theoretical maximum density of 2.501 g/cm³ (ASTM D2041) (ASTM 2011), apparent specific gravity of 2.390 g/cm³ (ASTM D2726) (ASTM 2017), air voids percentage of 4.2%, VMA of 14.1%, VFA of 71.57%, stability of 11444 N, flow value of 13.4 (0.25 mm) and dust to effective binder ratio of 1.18. All volumetric requirements established were met.

2.2.4 Slabs Compaction and Specimens Obtainment

After dosing the asphalt mixture in the laboratory, six slabs with the dimensions of 60 cm x 40 cm x 9 cm were compacted in order to subsequently provide prismatic samples for complex modulus and fatigue resistance tests. The compaction of the slabs was carried out on an IFSTTAR (*Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux*) compaction table. The procedure followed the french specification AFNOR NF P 98-250-2 (AFNOR 1997), for heavy traffic. After the slabs' stripping, they were sawn, with the assistance of a cutting saw, resulting in five prismatic specimens per slab, with the following dimensions: 5.08 cm x 6.35 cm x 38.1 cm (± 0.1 mm). This process is shown in Figure 2. Thirty specimens were obtained in this process. However, after a screening process, vis-à-vis the samples' dimensions and air void volume, 26 specimens were selected, from which 2 were used for the complex modulus tests, while the remaining 24 were used in fatigue tests. Therefore, two groups with 12 specimens were created for the fatigue tests, one through sinusoidal loading and the other through haversine loading.

2.2 Methodology

First, the viscoelastic linear characterization of the mixture was obtained through complex modulus tests. The next step was to carry out tests of the fatigue resistance on material. For both steps, the Four Point Bending Apparatus was used. After the experimental stage, a numerical simulation regarding a hypothetical pavement structure was carried out. This step was conducted to evaluate the service life of an asphalt layer, regarding its fatigue rupture, according to the fatigue models obtained for both waveforms evaluated in this report. The simulation considered the viscoelastic linear behavior of the asphalt mixture and the load dynamic. In the following sections the method steps will be detailed.

2.2.1 Characterization of the Asphalt Mixture Rheological Behavior

This phase's purpose was to obtain the rheological aspects of the asphalt mixture that describe its behavior in the field of linear viscoelasticity. The selected rheological parameters (E_∞ ; E_0 ; τ ; k ; h ; δ ; A_0 ; A_1 ; A_2) compose the mathematical and rheological model of Huet & Sayegh (H&S) (Huet 1963), represented by Equation 2, alternatively calculated by Equations 3, 4, and 5. The Huet & Sayegh model was used in the numerical simulation of the pavement structure as a requisite to determine the service life estimative of an asphalt surface course.

$$E^*(i\omega\tau(\theta)) = E_0 + \frac{E_\infty - E_0}{1 + \delta(i\omega\tau(\theta))^{-k} + (i\omega\tau(\theta))^{-h}} \quad (2)$$

$$E^*(i\omega\tau(\theta)) = \sqrt{E_1(i\omega\tau(\theta))^2 + E_2(i\omega\tau(\theta))^2} \quad (3)$$

$$E_1(i\omega\tau(\theta)) = E_o + \frac{\frac{1 + \delta(i\omega\tau(\theta))^{-k} \cos\left(\frac{\pi}{2}\right) + (i\omega\tau(\theta))^{-h} \cos\left(\frac{\pi}{2}\right)}{E_\infty - E_o}}{\left(\frac{1 + \delta(i\omega\tau(\theta))^{-k} \cos\left(\frac{\pi}{2}\right) + (i\omega\tau(\theta))^{-h} \cos\left(\frac{\pi}{2}\right)}{E_\infty - E_o}\right)^2 + \left(\frac{\delta(i\omega\tau(\theta))^{-k} \sin\left(\frac{\pi}{2}\right) + (i\omega\tau(\theta))^{-h} \sin\left(\frac{\pi}{2}\right)}{E_\infty - E_o}\right)^2} \quad (4)$$

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$$E_2(i\omega\tau(\theta)) = \frac{\frac{\delta(i\omega\tau(\theta))^{-k} \sin\left(\frac{\pi}{2}\right) + (i\omega\tau(\theta))^{-h} \sin\left(\frac{\pi}{2}\right)}{E_\infty - E_o}}{\left(\frac{1 + \delta(i\omega\tau(\theta))^{-k} \cos\left(\frac{\pi}{2}\right) + (i\omega\tau(\theta))^{-h} \cos\left(\frac{\pi}{2}\right)}{E_\infty - E_o}\right)^2 + \left(\frac{\delta(i\omega\tau(\theta))^{-k} \sin\left(\frac{\pi}{2}\right) + (i\omega\tau(\theta))^{-h} \sin\left(\frac{\pi}{2}\right)}{E_\infty - E_o}\right)^2} \quad (5)$$

218

219 where E^* = complex modulus; E_1 = real component; E_2 = imaginary component; E_∞ =
 220 infinite complex modulus; E_0 = static modulus; i = complex number defined by $i^2 = -1$; τ =
 221 relaxation time of shock absorbers, parameter in terms of time, that is, compared to a delay
 222 time and that varies over temperature (θ), $\tau(\theta) = e^{(A_0 + A_1\theta + A_2\theta^2)}$; ω = angular loading
 223 frequency, $\omega = 2\pi f$; f = loading frequency; k, h = parameters of parabolic elements, situated
 224 on the interval $0 < k < h < 1$; δ = dimensionless constant; A_0, A_1 and A_2 = scale parameters.

225

226 The parameters (E_∞ ; E_0 ; τ ; k ; h ; δ ; A_0 ; A_1 ; A_2) of the H&S mathematical and rheological
 227 model were obtained by the following process:

228

229 1°) The complex modulus (E^*) and the phase angles (δ) of the asphalt mixtures were
 230 determined through the Four Point Bending Apparatus at different frequencies (0.1; 0.2; 0.5;
 231 1; 2; 5; 10; and, 20 Hz) and temperatures (0; 5; 10; 15; 20; 25; and 30 °C), according to the
 232 European standard EN 12697-26 (EN 2012b). The tests were conducted under the controlled
 233 deformation of 50 $\mu\text{m/m}$ (sinusoidal loading);

2°) For each frequency and temperature pair tested, an elastic (E_1) and a viscous component (E_2) of the complex modulus were calculated;

3°) The Cole-Cole plot of the asphalt mixture was built considering the complex modulus' real (E_1) and viscous component (E_2), obtained for the entire frequency and temperature scan. This complex plan (Cole-Cole) characterizes the asphalt mixture's linear viscoelastic behavior at any temperature and load frequency, that is to say, the complex modulus of the material;

4°) Finally, with the Cole-Cole plot, the parameters of the Huet & Sayegh mathematical and rheological model (E_∞ ; E_0 ; τ ; k ; h ; δ ; A_0 ; A_1 ; A_2) were obtained and calibrated. This step was carried out with the assistance of the software Viscoanalyse (IFSTTAR).

2.2.2 Determination of the Fatigue Models

At this point, the fatigue resistance of the prismatic specimens was evaluated through the Four Point Bending Apparatus. One set of the specimens was tested under sinusoidal loading, whereas the rest of the samples was tested under haversine loading. All fatigue tests were carried out under controlled deformation, at a temperature of 20 °C and a load application frequency of 10 Hz. The failure criterion was the same for both specimen groups: the reduction of the initial complex modulus (defined in the hundredth cycle of the test) to half.

After the experimental part, fatigue models for each one of the loading waveforms (haversine and sinusoidal) were developed. In this paper, the phenomenological approach (Wöhler curve), presented by Equation 6, was chosen to obtain the fatigue curves. In this method, the fatigue equation is determined through the relation between the amplitude of the tensile

deformation applied to the beam and the cycle number, in which half of the initial complex modulus is obtained.

$$N_f = k_1(\varepsilon_t)^{-k_2} \quad (6)$$

where N_f = number of loading cycles to failure; ε_t = specific tensile deformation (microdeformation); k_1 and k_2 = experimental constants.

2.2.3 Numerical Simulation

The purpose of the last step of the study is to estimate the life service of the asphalt mixture layer on a pavement structure, according to the fatigue models obtained under the different waveforms. For that goal, a numerical simulation of a hypothetical pavement structure was conducted in the software ViscoRoute (IFSTTAR). In this numerical simulation, the asphalt layer temperature and its viscoelastic linear behavior (Huet & Sayegh model), as well as the load dynamic of a single double-wheeled axle of 8.2 tons were considered.

The configuration of the hypothetical pavement structure and the characteristics of the applied load were the inputs for the software. The considered structure parameters are presented in Table 3, as follows: asphalt surface course with a thickness of 6 cm at 20 °C, 14 cm thick base layer, subbase with a thickness of 60 cm; and subgrade with infinite thickness. It must highlight that the asphalt surface temperature was set at of 20 °C in the numerical simulation because the fatigue laboratory tests were also conducted at 20 °C.

The dynamic loading characteristics considered in the simulation were: a single double-wheeled axle of 8.2 tons (*United States Army Corps of Engineers - USACE*) at 20 m/s (72 km/h), with a distance of 32 cm between the two wheels, a load per wheel of 2050 kgf, a circular contact area between the tire and pavement of 366 cm² (10.8 cm radius), and a contact pressure of 5.6 kgf/cm². According to Chabot et al. (2010), the laboratory test frequency of 10 Hz corresponds to a speed of approximately 20 m/s (72 km/h), and that is why this speed was selected for the numerical simulation. The configuration of the pavement structure and its load are presented in Figure 3.

As an output, the maximum specific tensile deformation at the bottom of the asphalt surface was calculated by the software on point P (-16,0), as shown in Figure 3. This point was selected because, according to the numerical simulation, it presented the highest deformation under loading. The analyzed points were P (-16,0) and P (16,0), right under the wheels, and P (0,0) at the axle center.

With the highest deformation value and with the fatigue models obtained through the laboratory tests, it was possible to estimate the number of loadings from the single double-wheeled axle (8.2 tons) required to make the asphalt surface reach fatigue failure and to analyze the influence of each waveform (haversine and sinusoidal) used to develop the models on this estimative.

3 RESULTS AND DISCUSSION

3.1 Characterization of the Asphalt Mixture Rheological Behavior

The complex modulus tests were carried out according to the guidelines of EN 12697-26 (EN 2012b), at different temperatures and load frequencies. The loading in this procedure is applied sinusoidally. Table 4 presents the average results achieved for two specimens.

Based on the data presented in Table 4, it was possible to calculate the viscoelastic parameters of the Huet & Sayegh model, which are: $E_{\infty} = 21345.2$ MPa, $E_0 = 42.3043$ MPa, $\tau = 0.01701$, $k = 0.21359$, $h = 0.53921$, $\delta = 2.04866$, $A_0 = 0.0743558$, $A_1 = -0.376794$, and $A_2 = 0.0016876$. These parameters can describe the viscoelastic linear behavior of the asphalt mixture at any temperature and loading frequency with the assistance of Equations 2 to 5.

3.2 Determination of the Fatigue Models

In this stage, the fatigue tests were carried through the Four Point Bending Machine. Twelve specimens were tested under sinusoidal loading and the other twelve under haversine loading. Table 5 shows the laboratory results. For each specimen, it presents the established initial microdeformation and the number of cycles that made the specimen to rupture, that is, the moment when the initial stiffness of the sample is reduced to half.

The fatigue models, according to the loading waveforms, were determined through the phenomenological approach, using the data presented in Table 5. The sinusoidal fatigue model resulted in a curve, whose equation is $N_f = 5.33 \times 10^{22} \varepsilon^{-7.20}$. The haversine fatigue model is given by $N_f = 3.61 \times 10^{24} \varepsilon^{-7.20}$. The two fatigue curves are shown in Figure 4.

Analyzing Figure 4, it is possible to see that the tests with sinusoidal loading resulted in a model whose experimental data presented low dispersion and a very strong correlation coefficient (Karl Pearson classification) ($R^2 = 0.927$). On the other side, the tests carried out with the haversine loading resulted in more disperse experimental data and in a moderate correlation coefficient ($R^2 = 0.779$). Another important factor that should be noticed in the models' comparison is the existence of a "translation" factor between both curves on the horizontal axis once the curve slopes are practically the same.

It can be noticed that for the same deformation level (x - value), the fatigue life determined with sinusoidal loading corresponds to a "Y" value, while the fatigue life determined by the haversine loading test has a value greater than "Y." It means that tests carried out with haversine or sinusoidal loading, even when conducted under the same temperature and frequency conditions, and with the same rupture criterion, will present different values of fatigue resistance. This fact is validated by the evaluation of the microdeformation for 1,000,000 cycles (ϵ_6). In the haversine model, ϵ_6 is equal to 377 $\mu\text{m/m}$, while the ϵ_6 registered for the sinusoidal curve is of 210 $\mu\text{m/m}$.

Briefly, it means that the mechanistic design of the pavement will be influenced by the loading waveforms applied on laboratory tests. In this case, layers that were designed based on fatigue models carried out with sinusoidal loading should be significantly thicker than the ones designed based on haversine loading test results. The fatigue life gap between the models is characterized by the "translation" factor on the horizontal axis. This transverse factor was determined by an interactive method, and the resulting value is 1.8. Which means

that, in tests carried out with haversine loading, the fatigue resistance measured is equivalent to those measured in sinusoidal loading tests, but with an initial microdeformation 1.8 times lower than in the first case. Applying the translation factor obtained by the fatigue law for haversine tests, that is, dividing all microdeformations by the factor 1.8, would change the model equation to $N_f = 5.45 \times 10^{22} \varepsilon^{-7.20}_t$, closer to the sinusoidal curve (Figure 5).

In general, the results of the tests carried out with haversine loading are similar to the ones obtained in sinusoidal loading tests, with around half of the initial amplitude (transverse translation factor of 1.8). That means that there is a strong correlation factor among the tests. As previously explained, during the sinusoidal loading tests, the beam is bended in both directions vis-à-vis its neutral axis, which remains in the same position during the laboratory test, between the extreme positions, although the specimen is bended in only one direction in the haversine loading tests vis-à-vis its neutral axis. In this context, the resulting difference between the fatigue models can be explained by the viscous behavior of the asphalt mixture. The haversine waveform remains only during the initial cycles of the test. In the following cycles, the beam is permanently deformed, which displaces the neutral axis at the same direction of the applied loading. Since the deformation signal does not change during the test, it tends to bring the beam back to its initial neutral position. Due to the displacement of the neutral axis, the loading format is gradually changed into sinusoidal, with an amplitude close to half of the established initial amplitude. Due to this permanent specimen deformation, the loading cannot keep the haversine form during the entire test, quickly turning into a sinusoidal wave with half of its initial amplitude. Another evidence of this phenomenon can be observed at the end of haversine tests, after the removal of the load, when the samples remain slightly curved due to the permanent deformation.

Figure 6 shows the loading response over time of a beam under haversine loading in the Four Point Bending Apparatus, with an initial amplitude of 650 $\mu\text{m/m}$. It can be noticed that, early in the 50th cycle, the upward force is already similar to the downward force and that it remains like this during the entire test, as indicated by the loading answer for the 100th and 5,000th cycles. That is the second indicative that a haversine test with an amplitude of 650 $\mu\text{m/m}$ is, in fact, a sinusoidal test under controlled deformation of about 361 $\mu\text{m/m}$ ($650 \div$ “translation” factor), once the beam suffers a permanent deformation early in the beginning of the test, which causes the displacement of its neutral axis and, consequently, the load starts to swing over this new position.

However, it should be highlighted that the permanent deformation suffered by the specimens is directly linked to the asphalt mixture’s viscoelastic properties, which can be especially expressive at intermediate temperatures (20 °C) (see Table 4). Thus, the effect observed in this study, should be reevaluated if the fatigue tests occur at lower temperatures, under which the asphalt mixture’s behavior would be mainly governed by the material’s elastic component. In perfectly elastic materials, the permanent deformation of the first cycles of the test would not happen, and, therefore, the displacement of the specimen’s neutral axis would not take place, allowing the perfect application of the haversine loading.

In this sense, it is possible to conclude that, for haversine loading tests under intermediate temperatures, the initial amplitude established in laboratory does not correspond to the real deformation applied to the beam during the test. The real deformation is almost half of the initial defined amplitude. Thus, in order to obtain consistent results using tests with haversine

loading waves, the corresponding fatigue model should be built with half of the initial deformation amplitude, that is, the “translation” factor should be applied to the deformation, which, in this case, is of 1.8.

3.3 Numerical Simulation

This simulation’s purpose was to estimate the fatigue life of the asphalt surface layer (at 20 °C) on the pavement structure vis-à-vis the fatigue failure in terms of the numbers of the crossings of a single double-wheeled axle of 8.2 tons at 20 m/s (72 km/h), according to both fatigue models developed (haversine and sinusoidal). For the numerical simulation, the software ViscoRoute was employed, which calculated the maximum specific tensile deformation in the lower fiber of the asphalt surface’s load application point P (-16,0) (Figure 3). The software output deformation was used as the input for the fatigue models. Figure 7 illustrates the response obtained by ViscoRoute, in which the horizontal axis represents the distance of the acting axis vis-à-vis the evaluated point and the vertical axis shows the tensile or compression microdeformation generated on said point.

It can be noticed that there is a sign alternation (compression/traction) in Figure 7, related to the deformations of the evaluated point, P (-16,0). The asphalt layer starts to be deformed when the acting axis is at one meter of distant from the analysis point: initially it is compressed, followed by a traction peak (230.85 $\mu\text{m/m}$), returning to the compressed phase, and finally ceasing the deformation as the load is taken away. As seen in Figure 7, the maximum tensile specific deformation (230.85 $\mu\text{m/m}$) occurred when the acting axle was positioned right over the evaluated point.

The maximum tensile microdeformation was used as the input for both fatigue laws, resulting in the number of crossing cycles of the single double-wheeled axle of 8.2 tons necessary to cause a fatigue rupture on the asphalt surface (20 °C). Table 6 presents the results for the haversine, sinusoidal, and translated haversine model.

Table 6 shows clearly the difference between the estimates, according to the different waveforms. In terms of the number of loading cycles of the 8.2 tons standard axle, the haversine model wrongly predicts that the asphalt mixture will resist to a fatigue rupture of approximately 67 times longer than the result provided by the sinusoidal model, a very significant variation. Nonetheless, with the correction of the haversine model with the translation factor determined on this study, the estimate becomes almost the same. To reassure the difference between the models, a traffic projection of 1.16×10^7 repetitions of the 8.2 tons axle for a ten-year projection was hypothetically considered. As seen in Figure 8, the asphalt mix would be well dimensioned, according to the haversine model. It would additionally have enough capacity to resist a greater traffic volume during its service life. On the other side, considering the sinusoidal model, the asphalt surface layer would be underestimated for the estimated traffic and the fatigue failure would occur long before the end of the projection.

From another perspective, the minimum thickness of the asphalt surface layer necessary to support the estimated traffic (1.16×10^7) was also calculated. When evaluated for the sinusoidal model, the minimum thickness obtained was of 7 cm (Figure 9), indicating that the existent layer of the evaluated structure, with a thickness of 6 cm, is underestimated and

would not resist until the end of the projection. On the other hand, according to the haversine model (Figure 9), the minimum thickness necessary would be only of 4 cm, pointing out that the existent structure is able to resist the traffic load and would not present fatigue damage during the service life of the roadway.

The results presented on Figure 9 confirm a great divergence in the asphalt surface design based on the different loading waveforms employed on the Four Point fatigue resistance test. Through the numerical simulation, a 3-cm difference was obtained between the asphalt layer's thickness calculated with the sinusoidal loading and the one calculated with the haversine loading. Considering this last model, the asphalt surface would have a thickness 43% smaller than the one calculated with the sinusoidal loading. This significant thickness reduction would result on a pavement that would resist only to the few initial years of the project.

4 CONCLUSIONS

The following conclusions were listed, considering the presented results:

- Depending on the loading waveform employed, the fatigue resistance results present a significant difference. Tests carried out on the Four Point Bending Machine with haversine loading present values of fatigue resistance much higher than the ones carried out with the sinusoidal wave loading. The use of the non-adjusted haversine model on an asphalt surface layer's fatigue failure prediction resulted in a service life 67 times greater than the one calculated with the sinusoidal model. In practice, layers designed based on

this non-adjusted haversine model present a thickness considerably thinner than the ones designed with sinusoidal wave tests;

- While testing viscoelastic materials, the Four Point Bending Apparatus is not able to continuously reproduce a haversine loading wave. Shortly, at the beginning of the test, the wave pulse finally takes a sinusoidal form, with half of the initial amplitude established. Conducting fatigue tests with haversine loading for viscoelastic materials requires the adjustment of the initial microdeformation considered to build the fatigue curves. In order to obtain reliable curves, this parameter must agree with the actual deformation applied during the test;
- It should be highlighted that, the temperature of the test affects the magnitude of this correction factor. For tests performed at low temperatures, the behavior of the material is mainly governed by the elastic parcel, the permanent deformation effect is reduced, and, consequently, the correction is smaller or null;
- The use of sinusoidal loading is recommended to carry out fatigue resistance tests on the Four Point Bending Apparatus because, in this kind of test, due to the total alternation of the beam, the permanent deformation does not occur and, consequently, there is no displacement of the neutral axis.

SUGGESTIONS FOR FURTHER RESEARCH

This paper comprises a study about fatigue tests at intermediate temperatures (20 °C), and it should be stressed that the “translation” factor obtained is applied only for this temperature band. Since the asphalt mixture’s behavior is highly affected by the temperature of where it

is applied, the investigation of the translation factor under other test temperatures can be explored.

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Table 1 - Results of aggregate characterization.

Aggregate properties	Results	Specification limits
Flat and elongated particles (ASTM 2010a)	8%	10% max.
Sand equivalent (AASHTO 2008)	65.2%	50% min.
Los Angeles abrasion (ASTM 2014a)	26.9%	35-45% max.
Bulk specific gravity of the coarse aggregate (ASTM 2015a)	2.796 g/cm ³	-
Apparent specific gravity of the coarse aggregate (ASTM 2015a)	2.767 g/cm ³	-
Absorption of coarse aggregate (ASTM 2015a)	0.38%	-

Note: Specification limits correspond to Superpave criteria.

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Table 2 - Physical properties of the modified bitumen.

Modified binder properties	Results
Penetration (ASTM 2013)	37 mm/10
Softening point (ASTM 2014b)	55 °C
Apparent viscosity at 175 °C (spindle 3 and 20 RPM) (ASTM 2015b)	3.57 Pa.s
Elastic recuperation (ABNT 2016)	51.5%
Penetration index [Pfeiffer and Van Doormaal]	-0.7

Table 3 - Characteristics of the pavement structure used in the numerical simulation.

Layers	Rheological behavior	Thickness (cm)	Modulus (E) (MPa)	Poisson (v)
Asphalt surface (20 °C)	Viscoelastic linear	6	*	0.30
Base	Elastic linear	14	333	0.35
Subbase	Elastic linear	60	132	0.35
Subgrade	Elastic linear	Infinite	124	0.45

* The asphalt mixture modulus is calculated by the software ViscoRoute 2.0 according to the parameters of the Huet & Sayegh rheological model, considering the asphalt surface layer temperature and the loading speed.

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Table 4 - Results of the asphalt mixture rheological behavior.								
f (Hz)	0.1	0.2	0.5	1	2	5	10	20
T (°C)	30							
E* (MPa)	193	250	346	518	701	944	1229	1624
δ (°)	35.4	38.0	40.9	42.2	42.4	41.7	41.6	43.9
E ₁ (MPa)	157.3	197.0	261.5	383.7	517.6	704.8	919.0	1170.1
E ₂ (MPa)	111.8	153.9	226.5	347.9	472.6	627.9	815.9	1126.0
T (°C)	25							
E* (MPa)	457	565	756	997	1328	1882	2337	2891
δ (°)	37.4	38.7	39.7	39.5	38.8	36.4	34.9	34.4
E ₁ (MPa)	363.0	440.9	581.6	769.3	1034.9	1514.8	1916.6	2385.4
E ₂ (MPa)	277.5	353.2	482.9	634.1	832.1	1116.8	1337.1	1633.3
T (°C)	20							
E* (MPa)	749	968	1329	1648	2131	2981	3612	4360
δ (°)	36.8	37.2	36.6	35.6	33.9	31.0	29.0	27.5
E ₁ (MPa)	599.7	771.0	1066.9	1339.9	1768.7	2555.2	3159.1	3867.3

E ₂ (MPa)	448.6	585.2	792.3	959.3	1188.5	1535.3	1751.1	2013.2
T (°C)	15							
E* (MPa)	1263	1634	2308	2853	3456	4594	5413	6330
δ (°)	34.3	33.5	31.8	30.0	27.9	24.9	22.8	21.2
E ₁ (MPa)	1043.3	1362.5	1961.5	2470.7	3054.2	4166.9	4990.0	5901.6
E ₂ (MPa)	711.7	901.8	1216.2	1426.5	1617.1	1934.2	2097.6	2289.0
T (°C)	10							
E* (MPa)	2394	2942	3909	4632	5453	6281	7297	8262
δ (°)	29.4	27.8	25.3	23.3	21.3	20.0	17.9	15.5
E ₁ (MPa)	2085.6	2602.4	3534.0	4254.2	5080.5	5902.2	6943.7	7961.5
E ₂ (MPa)	1175.2	1372.1	1670.5	1832.1	1980.8	2148.2	2242.7	2207.9
T (°C)	5							
E* (MPa)	3887	4600	5774	6706	7598	9012	10130	11043
δ (°)	25.0	23.1	20.4	18.2	16.4	14.2	12.5	10.4
E ₁ (MPa)	3522.8	4231.1	5411.8	6370.5	7288.8	8736.6	9889.8	10861.5
E ₂ (MPa)	1642.7	1804.7	2012.6	2094.5	2145.2	2210.7	2192.5	1993.4
T (°C)	0							
E* (MPa)	6337	7238	8534	9650	10618	11974	13057	14073
δ (°)	18.4	16.5	14.5	12.6	11.3	9.7	8.4	6.4
E ₁ (MPa)	6013.0	6939.9	8262.1	9417.6	10412.1	11802.8	12916.9	13985.3
E ₂ (MPa)	2000.2	2055.7	2136.7	2105.0	2080.5	2017.4	1907.4	1568.7

Table 5 - Laboratory fatigue tests results (20 °C and 10 Hz).

Specimens	Strain level (x 10 ⁻⁶)	Number of cycles	
		Sinusoidal waveform	Haversine waveform
1	365	17,634	-
2	346	17,365	-
3	281	145,133	-
4	416	12,074	-
5	231	440,302	-
6	311	128,509	-
7	235	587,950	-
8	261	148,228	-
9	280	79,013	-
10	260	146,097	-

11	344	23,456	-
12	208	1,787,890	-
13	450	-	208,120
14	650	-	15,970
15	550	-	165,950
16	450	-	234,420
17	650	-	44,430
18	650	-	5,590
19	416	-	1,529,000
20	650	-	5,940
21	560	-	36,120
22	550	-	224,520
23	300	-	1,758,370
24	450	-	480,460

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Table 6 - Performance of the asphalt mixture, regarding fatigue failure.

Loading waveform	Fatigue models	$\epsilon_t = 230.85 \mu\text{m/m}$
Sinusoidal	$N_f = 5.33 \times 10^{22} \epsilon_t^{-7.20}$	$N_{8.2 \text{ tons}} = 5.14 \times 10^5$
Haversine	$N_f = 3.61 \times 10^{24} \epsilon_t^{-7.20}$	$N_{8.2 \text{ tons}} = 3.48 \times 10^7$
Translated haversine (correction factor 1.8)	$N_f = 5.45 \times 10^{22} \epsilon_t^{-7.20}$	$N_{8.2 \text{ tons}} = 5.25 \times 10^5$

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Figure Captions:

Figure 1 - Granulometric composition of aggregate mixture.

861 Figure 2 - Production of specimens: (a) compaction, (b) compacted slab, (c) slab sawing, and
862 (d) prismatic specimens.

863 Figure 3 - Representation of the pavement structure and the loading axle used in the
864 simulation (dimensions in cm).

865 Figure 4 - Fatigue curves.

866 Figure 5 - Representation of the haversine model after the application of the translation factor.

867 Figure 6 - Response of a beam under haversine loading.

868 Figure 7 - Variation in the microdeformation of the asphalt surface's lower fiber.

869 Figure 8 - Service life of the asphalt surface calculated through the models *versus*
870 hypothetical estimated traffic.

871 Figure 9 - Fatigue life according to the asphalt surface's thickness: sinusoidal model and
872 haversine model.

Figure 1 - Granulometric composition of aggregate mixture.

90x93mm (300 x 300 DPI)

Figure 2 - Production of specimens: (a) compaction, (b) compacted slab, (c) slab sawing, and (d) prismatic specimens.

89x63mm (300 x 300 DPI)

Figure 3 - Representation of the pavement structure and the loading axle used in the simulation (dimensions in cm).

90x121mm (300 x 300 DPI)

Figure 4 - Fatigue curves.

90x70mm (300 x 300 DPI)

Figure 5 - Representation of the haversine model after the application of the translation factor.

89x69mm (300 x 300 DPI)

Figure 6 - Response of a beam under haversine loading.

90x69mm (300 x 300 DPI)

Figure 7 - Variation in the microdeformation of the asphalt surface's lower fiber.

89x82mm (300 x 300 DPI)

Figure 8 - Service life of the asphalt surface calculated through the models versus hypothetical estimated traffic.

90x71mm (300 x 300 DPI)

Figure 9 - Fatigue life according to the asphalt surface's thickness: sinusoidal model and haversine model.

89x81mm (300 x 300 DPI)