ENGLISH VERSION..

Los efectos de la forma de la onda de carga en la estimación de la vida a la fatiga de la capa asfáltica en la estructura del pavimento

The influence of the wave loads in the estimation of life to the fatigue of asphalt layer in pavement structure

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Fecha de Recepción: 10/07/2018
Fecha de Aceptación: 02/01/2019
PAG 136-145

Abstract

The phenomenon of fatigue can be considered as one of the main causes of the asphalt surface course failure. The Four Point Bending Apparatus is the widespread equipment used to determine the fatigue resistance of asphalt mixtures. Worldwide there are several standard procedures that rule this test. The main difference between them remains in the waveform, in which the load is applied, and in the failure criteria. This paper reports the influence from the waveform, haversine or sinusoidal, on the fatigue resistance of an asphalt mixture. In addition, through numerical simulation, it was evaluated the influence of the models obtained in the design of the thickness of the asphalt layer required for the structure of a pavement. The conclusion is that the use of haversine waves in fatigue tests results in a fatigue life of the asphalt surface layer almost 67 times bigger than the ones found on sinusoidal tests.

Keywords: *Flexible pavements; asphalt mixture; waveforms; fatigue failure; numerical simulation*

Resumen

El fenómeno de fatiga como unos de los principales mecanismos de deterioro de las capas asfálticas. El ensayo de fatiga a flexión por cuatro puntos de apoyo es uno de los procedimientos más utilizados para determinar la resistencia a la fatiga de las mezclas asfálticas. Existen, a nivel internacional, diversas normas que estandarizan este tipo de ensayo, las cuales se diferencian básicamente por la forma de la onda de carga aplicada y por el criterio de rotura utilizado. Este artículo tiene como objetivo presentar los resultados de la influencia del tipo de onda de carga utilizada, haversine o sinusoidal, en la resistencia a la fatiga de una mezcla asfáltica, como también, la influencia de los modelos de fatiga obtenidos en la previsión de la rotura por fatiga de la capa asfáltica en una estructura de un pavimento flexible. Al final, se concluyó que la vida útil de la capa asfáltica estimada utilizando los modelos obtenidos en el ensayo con ondas con forma haversine fue 67 veces mayor que cuando estimada con los modelos de los ensayos realizados con carga sinusoidal.

Palabras clave: Pavimentos flexibles, mezclas asfálticas, onda de carga, rotura por fatiga, simulación numérica

1. Introduction

Currently, there are different devices for estimating the fatigue characteristics of asphalt mixtures, among them, the four-point bending fatigue testing machine, which is one of the most used worldwide. In Europe, the test standardization is regulated by the standard (EN12697-242004), in Australia by (AG-PT/T233 2006) of the Austroads Guide, and in the USA by the standards (ASTM D7460 2010) and (AASHTO T321 2014). The standards' differences are mainly related to the waveform loading and the failure criterion. The European procedure and the AASHTO US standard (American Association of State Highway and Transportation Officials) indicate the use of sinusoidal loading waveform. The Australian and ASTM US standard recommend the haversine loading waveforms.

Thus, several studies addressing the fatigue strength of asphalt layers have used the haversine loading waveform (Hernández et al., 2013) (Cooper et al., 2017) (Goli et al., 2017) (Mamlouk et al., 2012), while others have used the sinusoidal loading waveform (Varma et al., 2016) (Rasouli et al., 2018) (Melo and Trichês, 2017) (Melo et al., 2018), thereby indicating that researchers do not agree on which is the best waveform for this test. Therefore, we must be careful when comparing fatigue models obtained by standardized procedures using different loading waveforms, because there can be a great disparity of results, mainly when loads are applied for estimating fatigue cracking of asphalt layers in a pavement structure.

This paper reports the results of a comparative study on the influence of haversine and sinusoidal waveforms on fatigue strength models of an asphalt mixture, and their consequences and impact on the estimated bending fatigue of the asphalt layer in flexible pavement structure.

2. Materials

For the purpose of this study, an asphalt mixture with the following materials was produced: mineral aggregates (Gneiss metamorphic rock), hydrated lime (CH-2, dolomitic

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type) and asphalt rubber binder (with 20% addition of tire crumb rubber). The grading curve used for the asphalt mix design fits into band IV-B of the Asphalt Institute. This curve is composed of 39% coarse aggregates (passing sieve ¾" (ASTM) and retained in sieve N◦ 4 (ASTM)), 53% fine aggregates (passing sieve N◦ 4 (ASTM) and retained in sieve N◦ 200 (ASTM)) and 7.2% mineral filler (passing sieve N◦ 200).

The asphalt mix design was prepared to withstand heavy-traffic conditions, according to the Marshall method. The procedures adopted for the design followed the recommendations of standards (ASTM D6926 2016) and (ASTM D6927 2015). Once the design stage was concluded, the asphalt mixture showed the following volumetric characteristics: optimal binder content percent, 6.1%; air volume (Va), 4.20%; voids filled with asphalt (VFA), 77.2%; stability of 11444 N; flow of 13.4 (0.25 mm); voids in mineral aggregate (VMA), 14.1%; and filler/asphalt ratio of 1.18.

After completing the mix design in the laboratory, plates for cutting out prismatic specimens were manufactured. The plates were compacted in the IFSTTAR compaction table (French Institute of Science and Technology for Transport, Development and Networks). The hardened asphalt mix plates were cut with a circular saw, thereby cutting out five prismatic specimens from each plate; the specimens had the following dimensions: 5.08 x 6.35 x 38.1 cm (± 0.1 mm). The plate compaction and specimen cutting procedures are shown in (Figure 1).

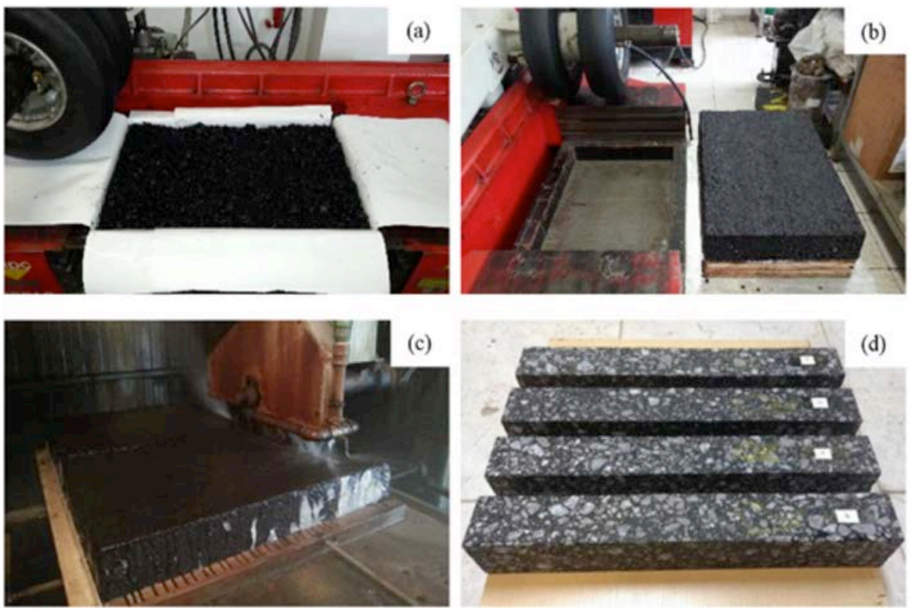

Figure 1. *Plate compaction and specimen cutting procedures: a) compaction, b) compacted plate, c) plate cutting and d) cut prismatic specimens*

In total, 30 specimens were cut out. However, following a triage process based on the dimensions and air volume (Va), 26 specimens were selected; two were used for the complex modulus test and the other 24 were used for the fatigue test. The specimens for the fatigue test were divided into two groups of 12 specimens each, one group for the haversine wave tests and the other for the sinusoidal wave test.

3.Method

3.1Characterization of the Linear Viscoelastic Behavior and Determination of Asphalt Mix Fatigue Models

First, the rheological parameters of the asphalt mixture were established, whose behavior is characterized in the field of the linear viscoelasticity. The rheological parameters ($E\infty$; E_0; τ; k; h; δ; A_0; A_1; A_2) established in this phase correspond to the mathematical and rheological Huet-Sayegh model (H&S) (Huet, 1963), which are mathematically represented by (Equation 1) and calculated alternatively by (Equation 2), (Equation 3) and (Equation 4). The H&S model was used in the numerical simulation stage of the pavement structure, which was required for estimating the service life of the asphalt layer.

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

$$E^*\left(i\omega\tau(\theta)\right) = \sqrt{E_1\left(i\omega\tau(\theta)\right)^2 + E_2\left(i\omega\tau(\theta)\right)^2} \tag{2}$$

$$E_1\left(i\omega\tau(\theta)\right) = E_o + \frac{\frac{1+\delta\left(i\omega\tau(\theta)\right)^{-k}\cos\left(k\frac{\pi}{2}\right)+\left(i\omega\tau(\theta)\right)^{-h}\cos\left(h\frac{\pi}{2}\right)}{E_\infty - E_o}}{\left(\frac{1+\delta\left(i\omega\tau(\theta)\right)^{-k}\cos\left(k\frac{\pi}{2}\right)+\left(i\omega\tau(\theta)\right)^{-h}\cos\left(h\frac{\pi}{2}\right)}{E_\infty - E_o}\right)^2 + \left(\frac{\delta\left(i\omega\tau(\theta)\right)^{-k}\sin\left(k\frac{\pi}{2}\right)+\left(i\omega\tau(\theta)\right)^{-h}\sin\left(h\frac{\pi}{2}\right)}{E_\infty - E_o}\right)^2} \tag{3}$$

$$\boldsymbol{E_2\left(i\omega\tau(\theta)\right)} = \frac{\dfrac{\delta\left(i\omega\tau(\theta)\right)^{-k} sin\left(k\frac{\pi}{2}\right)+\left(i\omega\tau(\theta)\right)^{-h} sin\left(h\frac{\pi}{2}\right)}{E_\infty - E_0}}{\left(\dfrac{1+\delta\left(i\omega\tau(\theta)\right)^{-k} cos\left(k\frac{\pi}{2}\right)+\left(i\omega\tau(\theta)\right)^{-h} cos\left(h\frac{\pi}{2}\right)}{E_\infty - E_0}\right)^2 + \left(\dfrac{\delta\left(i\omega\tau(\theta)\right)^{-k} sin\left(k\frac{\pi}{2}\right)+\left(i\omega\tau(\theta)\right)^{-h} sin\left(h\frac{\pi}{2}\right)}{E_\infty - E_0}\right)^2} \quad (4)$$

Where: E = complex modulus; E_1 = real parameter; E_2 = imaginary parameter; E∞ = infinite complex modulus; E_0 = static modulus; i = complex number; □ = dashpot relaxation time, $\tau(\theta) = e^{(A_0+A_1\theta+A_2\theta^2)}$; θ = temperature; ω = angular frequency; f = frequency; k, h = parameters of parabolic elements; δ = dimensionless constant; A_0, A_1 e A_2 = scalar parameters.*

The rheological parameters were determined based on the complex modulus data of the asphalt mixture, at different frequencies (0.1; 0.2; 0.5; 1; 2; 5; 10; and 20 Hz) and temperatures (0; 5; 10; 15; 20; 25; and 30°C) (EN 12697-26, 2004b) with the help of the IFSTTAR Viscoanalyse software.

Once the H&S parameters were decided, the prismatic specimens were tested to estimate the four-point flexural strength. A group of specimens was tested with sinusoidal loading waveforms and the other one with harversine waveforms. All tests were performed at controlled strain, 20°C and 10 Hz frequency. The cracking criterion was the same for both groups, stiffness reduction at 50% of the initial value.

After completing the fatigue tests for all specimens, the models for each tested loading waveform (haversine and sinusoidal) were established. This research used the phenomenological approach (Wöhler curve) to obtain the material's fatigue laws.

3.2 Numerical Simulation

The objective of the final stage was to estimate the service life of the asphalt layer in the pavement structure, based on fatigue models defined for different types of wave loading (haversine and sinusoidal). The numerical simulation of the pavement structure was carried out with the software ViscoRoute 2.0, developed by IFFSTAR. The simulation considered the following parameters: the temperature of the asphalt layer and its linear viscoelastic behavior (Huet-Sayegh mathematical and rheological model), and the dynamics of the load effects from a two-wheel simple axle of 8.2 tons.

The characteristics of the pavement structure and the load applied were used as input data to feed the program. (Table 1) shows the characteristics of the simulated pavement structure, which is composed of the following layers: 6 cm thick surface asphalt layer and temperature of 20°C; 14 cm thick base layer; 60 cm thick subbase; and foundation soil with infinite thickness. The reason for setting the asphalt layer temperature at 20°C in the numerical simulation is to provide a similar temperature than that used in laboratory fatigue tests, which was 20°C.

Table 1. *Pavement structure used in the numerical simulation*

Layers	***Rheological Behavior***	***Thickness (cm)***	***Modulus (MPa)***	***Poisson (ν)***
Asphalt layer (20 °C)	*Lineal Viscoelastic*	*6*	***	*0.30*
Base	*Lineal elastic*	*14*	*333*	*0.35*
Subbase	*Lineal elastic*	*60*	*132*	*0.35*
Foundation soil	*Lineal elastic*	*Infinite*	*124*	*0.45*

**Modulus determined by software ViscoRoute 2.0 according to parameters of the Huet-Sayegh rheological model, based on the temperature of the asphalt layer and the speed of the loads*

In relation to the dynamic loads applied to the structure, a two-wheel simple axle of 8.2 tons was considered (United States Army Corps of Engineers - USACE), travelling at a speed of 72 km/h; the wheels of each pair were separated by a distance of 32 cm, the load per wheel was 2.05 tons, the contact area between the wheel and the pavement surface was circular with 366 cm^2 and the contact pressure was 5.6 kgf/cm^2. The numerical simulation defined a 72 km/h speed, in order to match the test frequency used in the laboratory fatigue test, which was 10 Hz, corresponding to approximately 20 m/s (72 km/h) (Chabot et al. 2010). The pavement structure and the load scheme are shown in (Figure 2).

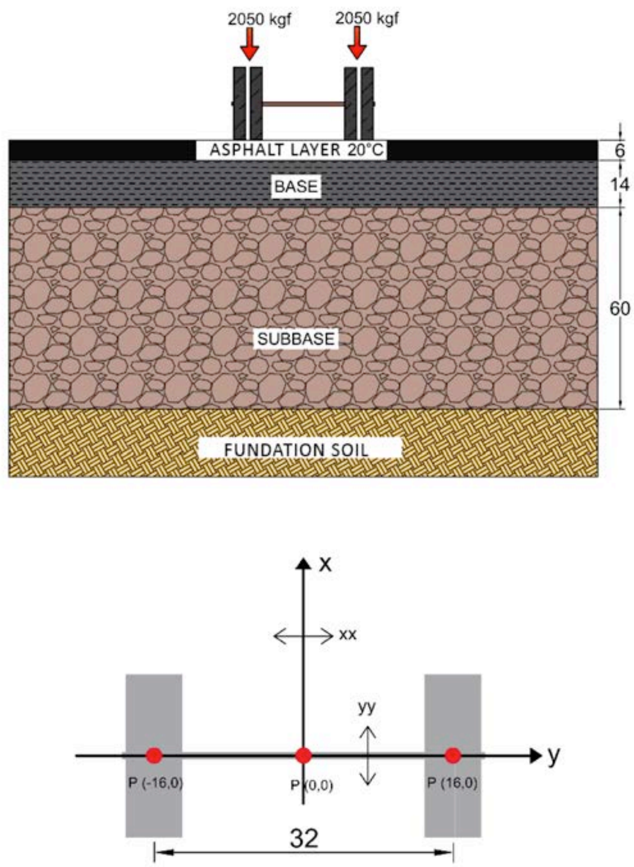

Figure 2. *Representation of the axle acting on the pavement structure (dimensions in cm)*

As output data of the program, the maximum value of the tensile microstrain in the lower face of the asphalt layer was obtained in point P (-16, 0) (Figure 2). The microstrain value allowed obtaining the number of load repetitions with the 8.2-ton axle, which caused the fatigue cracking in the asphalt layer, based on the fatigue models established in the laboratory (with haversine and sinusoidal waveforms).

These results allowed measuring the influence of the type of wave load used in the laboratory fatigue tests on the service life estimation of asphalt layers in pavement structures.

4. Results and Discussion

4.1Characterization of the Linear Viscoelastic Behavior and Determination of Asphalt Mix Fatigue Models

In order to characterize the linear viscoelastic behavior of the asphalt layer, a complex modulus test was carried out at different temperatures and load frequencies, with controlled deformation (50 µm/m). The data allowed to determine the viscoelastic parameters of the Huet-Sayegh model: $E\infty = 21345.2$ *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 linear viscoelastic behavior of the asphalt layer at any temperature and frequency, through (Equation 1), (Equation 2), (Equation 3) and (Equation 4).*

The four-point bending fatigue tests were carried out in this stage. Twelve specimens were tested with the haversine waveform, while the other twelve specimens were tested with the sinusoidal waveform. The results are shown in (Table 2), which indicates the cycle number where each specimen reached 50% of the initial stiffness (cracking criterion) and the initial microstrain defined for the test.

Table 2. *Fatigue test results*

Specimen	Tensile strain	Total number of cycles	
	(x 10^{-6})	Sinusoidal waveform	Haversine waveform
1	365	17634	-
2	346	17365	-
3	281	145133	-
4	416	12074	-
5	231	440302	-
6	311	128509	-
7	235	587950	-
8	261	148228	-
9	280	79013	-
10	260	146097	-
11	344	23456	-
12	208	1787890	-
13	450	-	208120
14	650	-	15970
15	550	-	165950
16	450	-	234420
17	650	-	44430
18	650	-	5590
19	416	-	1529000
20	650	-	5940
21	560	-	36120
22	550	-	224520
23	300	-	1758370
24	450	-	480460

The results of (Table 2) allowed generating fatigue models according to the phenomenological analysis, for each of the two specimen groups, in accordance with the loading waveform. The models are shown in (Table 3) and (Figure 3).

***Table 3**. Resulting fatigue models*

Waveform	*Fatigue model*	R^2
Sinusoidal waveform	$N_f = 5.33\ x\ 10^{22}\ \varepsilon_t^{-7.20}$	*0.927*
Haversine waveform	$N_f = 3.61\ x\ 10^{24}\ \varepsilon_t^{-7.20}$	*0.779*

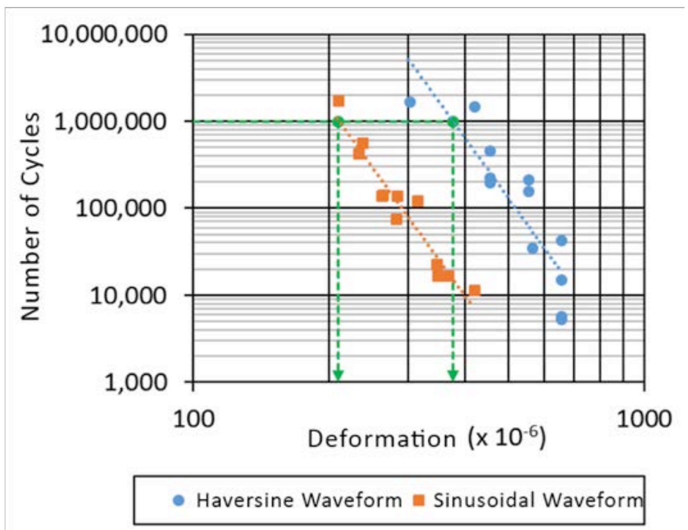

***Figure 3.** Fatigue curves based on the waveform used in the test*

The analysis of the models (Figure 3) and (Table 3), allows verifying that there is a "translation" factor between them, in the axis of abscissas, because the curve slopes are almost identical. We observed that, for a similar strain level (value in X), the fatigue life measured with sinusoidal waves is a "Y" value, and the fatigue life measured in the test with haversine waves is quite higher than the "Y" value. This means that the tests carried out with sinusoidal or haversine waves, under the same conditions of temperature, frequency and cracking criteria, produce different fatigue strength. For example, for 1,000,000 cycles, the microstrain (ε_6) in the haversine model is equal to 377 μm/m, while in the sinusoidal model it is 210 μm/m. In other words, the mechanistic pavement design will be influenced by the type of loading waveform applied in the laboratory test. Consequently, the mechanistic design of asphalt layers considering fatigue models with sinusoidal waves, will produce thicker layers than those whose design use fatigue models obtained with haversine waves. The magnitude of this difference is characterized by the "translation" factor of the models in the axis of abscissas; the estimated value was 1.8. This means that, in tests performed with haversine waves, the estimated fatigue strength will be equivalent to that determined for tests with sinusoidal waves with an initial microstrain 1.8 times smaller. When applying the "translation" factor in the haversine model (dividing all microstrains by 1.8), the model becomes $N_f = 5.45\ x\ 10^{22}\ \varepsilon_t^{-7.20}$, that is, the model is equal to the sinusoidal model. The (Figure 4) shows the effect of applying the "translation" factor in the haversine model.

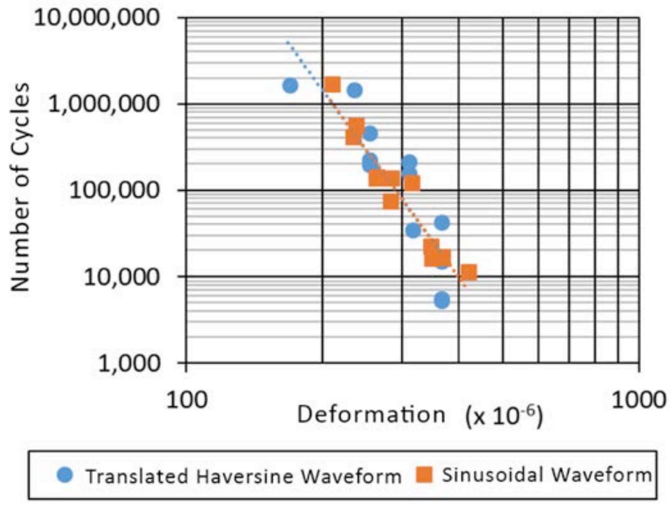

Figure 4. *Application of the "translation" factor in the fatigue model with haversine wave*

Thus, the tests carried out with haversine waves produced similar results as those obtained with sinusoidal waves, with approximately 50% of the established initial range ("translation" factor of 1.8). This means that there is a strong correlation between the test results. As explained earlier, in the test with sinusoidal waves, the specimen deforms in both directions in relation to the centerline, and its neutral position, which is located in the mid distance between the extreme positions; it does not change during the test. In the test with haversine waves the specimen is bent in only one direction in relation to its centerline. Therefore, the difference obtained between the models can be explained by the viscous behavior of the asphalt mixture. The haversine waveform is kept only during the initial cycles of the test; in the remaining cycles, the specimen suffers a permanent strain and its neutral position is quickly displaced in the same direction of the strain. As the strain signal is not altered and tends to attract the specimen to the initial neutral position, due to the displacement of the centerline, the pulse ends up transforming into a sinusoidal one, with a range similar to 50% of the initially established range. Consequently, the load loses the haversine waveform during the test. A further indication of this phenomenon can be observed at the end of the test, when the load is withdrawn, since the specimens tested with haversine loading waveform remain slightly bent, due to the permanent strain they have suffered.

The (Figure 5) shows the response of a specimen subjected to the haversine loading pulse for 650 µm/m. You can observe that, in the 50th cycle, the ascending force is proportional to the descending force. This proportionality is kept during the entire test, as demonstrated by the response to the 100th and 5,000 load cycles. This is a further indication that the haversine test with 650 µm/m is actually a sinusoidal test with controlled deformation of approximately 361 650 µm/m (650 ÷ "translation" factor), because when the specimen suffers a permanent strain at the beginning of the test, it displaces its centerline, and the harmonious loading starts oscillating around this new position.

Nevertheless, it should be highlighted that the specimen's permanent strain is directly related to the viscoelastic characteristics of the tested material, and these characteristics are significantly manifested at intermediate temperatures (20°C). Thus, the effect observed in this research should be better evaluated if the fatigue test is carried out at lower temperatures, where the behavior of the asphalt mix would be ruled mainly by the elastic component of the material. In case of working with perfectly elastic materials, the permanent strain would not occur at the beginning of the test and, consequently, the centerline would not be displaced, thereby allowing the perfect application of a haversine loading pulse.

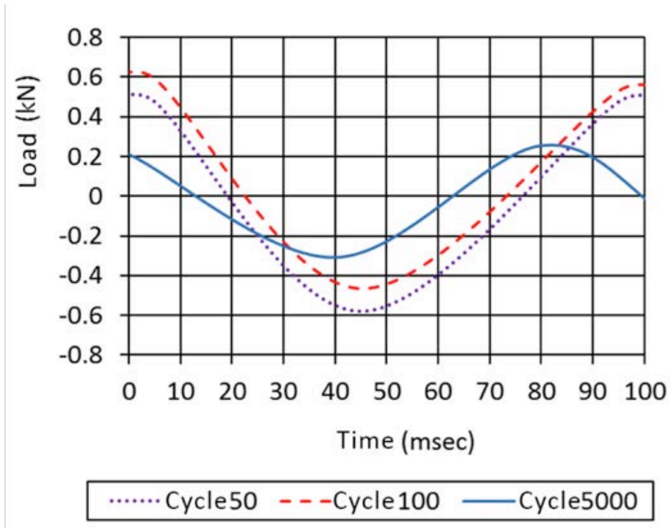

Figure 5. *Specimen response to a haversine loading pulse*

Therefore, it can be concluded that, in haversine waveform testing, the range of the initial strain in the program is not the real strain applied to the specimen during the test. The actual strain is approximately 50% of the initial strain range. Thus, in order to get consistent values throughout the tests with haversine waveforms, you have to build the fatigue model with approximately 50% of the initial strain range for the test, that is, to apply a "translation" factor of 1.8 in this case.

4.2 Numerical Simulation

The numerical simulation allowed verifying that the highest tensile microstrain is 230.85 μm/m, when the acting axle is exactly over the analysis point. Once the highest value is defined, it is used to feed the fatigue models and determines how many times the 8.2- ton axle has to pass to cause fatigue cracking on the asphalt layer (20°). The (Table 4) shows the results obtained when using models with haversine wave, sinusoidal wave and displaced haversine wave.

Table 4. *Asphalt layer fatigue performance*

Loading waveform	***Fatigue model***	***ε_t = 230.85 μm/m***
Sinusoidal waveform	$N_f = 5.33\ x\ 10^{22}\ \varepsilon_t^{-7.20}$	$N_{8.2\ ton} = 5.14\ x\ 10^5$
Haversine waveform	$N_f = 3.61\ x\ 10^{24}\ \varepsilon_t^{-7.20}$	$N_{8.2\ ton} = 3.48\ x\ 10^7$
Translated Haversine waveform (corrected by the factor of 1.8)	$N_f = 5.45\ x\ 10^{22}\ \varepsilon_t^{-7.20}$	$N_{8.2\ ton} = 5.25\ x\ 10^5$

The (Table 4) shows the difference in the estimated fatigue cracking value of the layer when the haversine or sinusoidal models are used. Based on the number of load repetitions of the 8.2-ton axle, the haversine model estimates, erroneously, that the asphalt mixture will withstand fatigue approximately 67 times more than when the service life is calculated with the sinusoidal model; this difference is highly significant. However, when the fatigue model is corrected by the "translation" factor found in this research, the predictions are equaled. In order to further emphasize the difference between the models, according to (Figure 6), and hypothetically considering that the pavement thickness is designed for 10 years, the traffic prediction is 1.16 x 10 repetitions of 8.2-ton axles, thereby concluding that the thickness of the asphalt layer was well designed according to the haversine model. What is more, this layer will have the capacity to withstand a greater traffic volume during its service life. On the other hand, according to the sinusoidal model, the asphalt layer is underestimated for the expected loads and fatigue cracking could occur sooner than planned by the pavement design.

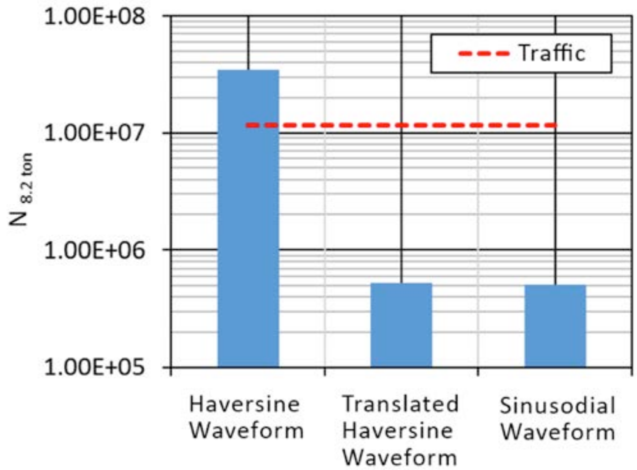

Figure 6. *Asphalt layer service life predicted by fatigue models versus hypothetical traffic expectation*

When evaluating the results based on the asphalt layer's minimum thickness for the predicted traffic volume (1.16 x 10), the layer needs at least seven centimeters if a sinusoidal model is used for the analysis (Figure 7); the existing thickness, of six centimeters, seems underestimated. Moreover, according to (Figure 7), when the haversine model is used, a four-centimeter asphalt layer is enough to withstand the expected traffic, indicating that the existing thickness (6 cm) is overestimated. This structure will not run the risk of suffering fatigue failure during the service life designed for the project (10 years).

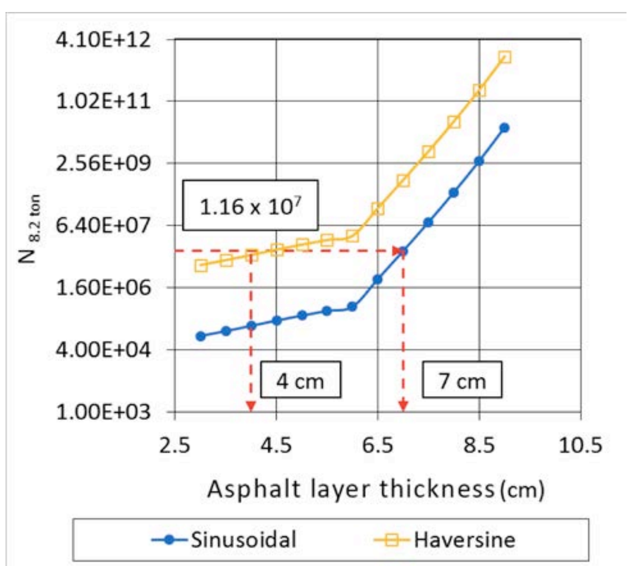

Figure 7. *Fatigue life based on the layer thickness*

The analysis shown in (Figure 7) confirms the great difference in the asphalt layer design based on the loading waveform used in the laboratory fatigue strength test. The numerical simulation stands out for a significant 3 cm difference in the thickness between the layer designed with the sinusoidal model and the one designed with the haversine model. In the latter, the pavement's asphalt layer has a thickness 43% below that of the sinusoidal model. This significant thickness reduction will produce a pavement structure that will barely last the first years of those estimated for the project.

5. conclusions

The results described above allowed concluding the following:

Fatigue strength results show significant differences based on the type of loading wave. The tests carried out with the haversine wave showed a much higher fatigue strength than those with the sinusoidal wave.

There is a "translation" factor between the fatigue models obtained with the sinusoidal wave and the haversine wave, which was 1.8 for the case studied herein.

The four-point bending fatigue test is not able to continually reproduce a haversine waveform signal for viscoelastic materials.

Fatigue tests performed in viscoelastic materials with haversine wave lead to determine erroneous fatigue models that need to be adjusted according to the real strain observed in the test.

The results of the numerical simulation confirmed that the waveform used to define the asphalt layer fatigue strength has a great influence on the service life prediction for the pavement structure's asphalt layer.

Pavements designed based on haversine wave tests have thicknesses quite lower than those estimated according to sinusoidal wave tests, that is, the layer of the latter has an underestimated thickness.

The use of sinusoidal loads is recommended when performing four-point bending fatigue tests.

6. Acknowledgements

The authors wish to thank the Rede Temática do Asfalto/Petrobras for their investment in the Pavement Laboratory of the Federal University of Santa Catarina and to the same University for their support and incentive to academic research.

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