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Analysis of the variation in the stiffness modulus through four-point bending tests

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ABSTRACT: Pavement layers are characterized by basic material properties, among which the stiffness modulus and the Poisson ratio assume a preponderant importance in linear elastic analysis. The stiffness modulus is usually assessed through samples extracted from a pavement or prepared in laboratory. The number of specimens used to calculate the stiffness modulus of an asphalt mixture plays an important role in the precision of pavement design. Thus, this paper presents a study to evaluate the number of tests to assess the stiffness modulus of asphalt mixtures through the four-point bending technique. The results obtained from five different asphalt mixtures were used to evaluate the stiffness dispersion to define the number of tests. A separate study conducted to define the variation of the stiffness modulus allowed to ensure a certain precision in pavement design. This analysis was made for several pavement structures in which the asphalt layer thickness and the subgrade stiffness varied among the samples.

1 INTRODUCTION

The stiffness of asphalt-aggregate mixes is of paramount importance for determining the performance of a pavement and it is essential for the analysis of pavement response to traffic loading (Tayebali et al., 1994). The stiffness modulus of an asphalt material also assumes an important role in pavement design as the pavement layers are characterized, in linear elastic analysis, by the stiffness modulus and the poisson ratio. The stiffness modulus is assessed in samples extracted from the pavement or prepared in laboratory. The stiffness modulus can also be evaluated through in situ tests from asphalt mixtures spread and compacted in the road.

In laboratory, stiffness is assessed using mainly dynamic tests, which are also applied to evaluate the fatigue resistance. The evaluation of the stiffness usually precedes the fatigue evaluation and it is performed for a small number of loading cycles. This type of test only takes a few minutes and the time spent in the equipment does not compromise the fatigue tests.

Due to the nature of asphalt mixtures, heterogeneous mixes composed by aggregates and particles of various dimensions and shapes, it is necessary to take some specimens to appropriately represent the behavior of the material. This fact is also considered in stiffness tests. Stiffness is defined from the average of the measured values. The standard deviation is also used in the stiffness modulus to provide an indication of the variation presented by the material.

Although many fatigue and permanent deformation tests can be used to measure stiffness under conditions similar to those experienced by paving mixes in service, the most used tests include the axial resilient stiffness, diametral resilient stiffness, flexural dynamic stiffness and shear dynamic stiffness.

The number of test samples used to evaluate the stiffness modulus of an asphalt mixture depends on the variability presented during the test. The European standard EN 12697-26, 2004 defines, for four-point bending tests, that from each slab six specimens shall be prepared. Four specimens shall be tested and two shall be held in reserve.

Although the time needed to perform four tests is very short, it is important to investigate whether it is sufficient to obtain a suitable precision for pavement design.

Thus, this paper presents a study to evaluate the number of tests to assess the stiffness modulus of asphalt mixtures through the four-point bending device. The results obtained from five different asphalt mixtures are used to evaluate the stiffness dispersion to define the number of tests. A separate study is conducted to define the variation of the stiffness modulus allowed to ensure a certain precision in the pavement design. This analysis was made for several pavement structures in which the asphalt layer thickness and the subgrade stiffness were different from one another.

2 STIFFNESS MODULUS

The stress-strain relationship under a continuous sinusoidal loading is defined by its complex modulus (E*). This is a complex number that relates stress to strain for linear visco-elastic materials subjected to continuously applied sinusoidal loading in the frequency domain. For any given time, t, and angular load frequency, ω, the complex modulus is defined as the ratio of the amplitude of the sinusoidal stress ($\sigma=\sigma_0\sin(\omega t)$) by the amplitude of the sinusoidal strain ($\varepsilon=\varepsilon_0\sin(\omega t-\varphi)$). For a pure elastic material (ø = 0) it can be observed that the complex modulus (E*) is equal to the absolute value (stiffness modulus).

The complex modulus (E*) can be mathematically expressed as:

$$\left|E^*\right| = \frac{\sigma}{\varepsilon} = \frac{\sigma.e^{i\omega t}}{\varepsilon.e^{(i\omega t-\phi)}} = \frac{\sigma_0.\sin(\omega.t)}{\varepsilon_0.\sin(\omega.t-\varphi)} \tag{1}$$

The complex modulus has a real and an imaginary part that define the elastic and viscous behaviour of the linear viscoelastic material. The absolute value of the complex modulus is called dynamic modulus, i.e. $|E^*| = \sigma_0/\varepsilon_0$. Stiffness data of asphalt mixtures, as obtained from the E* test, provide important information about the linear viscoelastic behaviour of that particular mix over a wide range of temperature and loading frequencies. The complex modulus relationship relating the mixture modulus to temperature and time rate of loading has been an integral part of several mechanistic-empirical design procedures used throughout the world.

The testing equipment used in this study was a CS7800 Axial Testing System and a four-point bending beam device, which had free translation and rotation at the reaction points and at load points.

A servo electric-hydraulic controlled testing system equipped with an automatic data measuring system applied the sinusoidal input strain waveform. Loading data were measured through the load cell and flexural deflections were recorded through a single linear differential variable transducer (LVDT) attached to the centre of the specimen. During the test, load and flexural deformation data were captured electronically every 0.002 s. Actual loading of the specimen was transmitted by the bending beam device, to which the beam specimen was firmly clamped.

The frequency sweep test measured the stiffness (dynamic modulus) and the phase angle of a mixture when subjected to different loading frequencies. Stiffness tests of this study were executed at a strain level of 100 microstrains, at a frequency of 10 Hz and at a test temperature of 20 ºC. To minimize the damage of the beam, only 100 cycles were applied. Prior to testing, the specimens were placed in the environmental chamber for 2 hours at the test temperature.

3 ASPHALT MIXTURES

The development of this study was based on the stiffness modulus results from 5 different asphalt mixtures tested in laboratory using a four point bending beam device. It includes 2 dense graded asphalt mixtures, an asphalt rubber hot mixture, a high stiffness asphalt mixture and a recycled asphalt mixture, as presented in Table 1.

Table 1. Mixtures description

Mixture	Description
1	0/25 dense graded asphalt concrete
2	Open graded asphalt rubber mixture
3	0/19 dense graded asphalt concrete
4	High stiffness asphalt mixture
5	Recycled asphalt mixture

The stiffness moduli of the mixtures used in this study are presented in Table 2, as well as the average and standard deviation for each mixture. The measured values of the stiffness modulus (average values) vary from 2315 to 8789 MPa and the standard deviation varies from 181 to 519 MPa. It seems that mixture 4, with a standard deviation of 181 MPa, presents a relatively low standard deviation, while mixture 5, with a standard deviation of 519 MPa, presents a relatively high standard deviation. The physical properties of the tested specimens (binder and void content) do not present anything atypical to justify the high and low standard deviation obtained.

The standard deviation around 300 MPa was the most frequent value obtained in stiffness modulus tests. However, the standard deviation of 343 for mixture 2 (asphalt rubber mixture) represents about 15% of the average value.

Table 2. Stiffness modulus (MPa) of mixtures used in this study

Specimen	Mixture				
	1	2	3	4	5
1	8214	2467	5728	8779	7696
2	7919	2024	5863	8736	7901
3	8022	2710	5341	9056	8723
4	8416	2424	6063	8842	8850
5	8633	1782	6190	8496	7759
6	8257	2481	5382	8824	8559
Average	8244	2315	5761	8789	8248
Standard deviation	260	343	348	181	519

4 INFLUENCE OF STIFFNESS DISPERSION IN PAVEMENT LIFE

A statistic analysis was made using the stiffness values for all the mixtures, for which a stiffness value was calculated by considering a certain number of tests. Once obtained the results from 6 specimens, combinations of those values were considered as: combinations of 1 to 6 specimen results. The combination of 6 specimens corresponds to the average value of all the tests, as presented in Table 2, being considered as the correct value for the analysis archived in this study.

For each combination of the stiffness values, the average value of the specimens tested was used to predict the pavement life of the structure represented in Figure 2 by using the Shell models (Shell, 1978) indicated in Equation 2 in relation to fatigue. Equation 3 shows a prediction of the life of the pavement in relation to the permanent deformation of the subgrade.

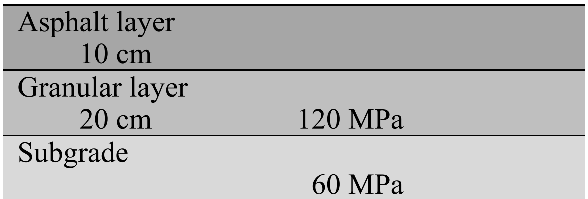

Figure 1. Schematic representation of the pavement used in the statistical analysis

$$N = \left(\frac{\varepsilon_t}{(0.856V_b + 1.08)S_{mix}^{-0.36}} \right)^{-5} \tag{2}$$

$$N = \left(\frac{\varepsilon_c}{0.018} \right)^{-4} \tag{3}$$

Figure 2 presents the results of the pavement life for the combination of 1 specimen, which corresponds to the results of the 6 specimens tested in the stiffness tests, and for the combination of 2 specimens. The horizontal line represents the pavement life considering the average stiffness of all the tested specimens, considered as the exact value in this work. The same representation is depicted in Figures 3 and 4, respectively for the combination of 3, 4 and 5 specimens in the determination of asphalt mixture stiffness to be used in the determination of the pavement life.

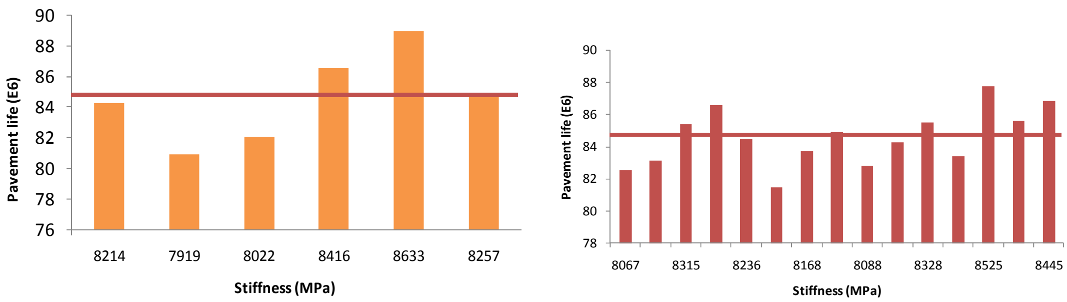

Figure 2. Pavement life for the combination of 1 specimen (left) and for 2 specimens (right)

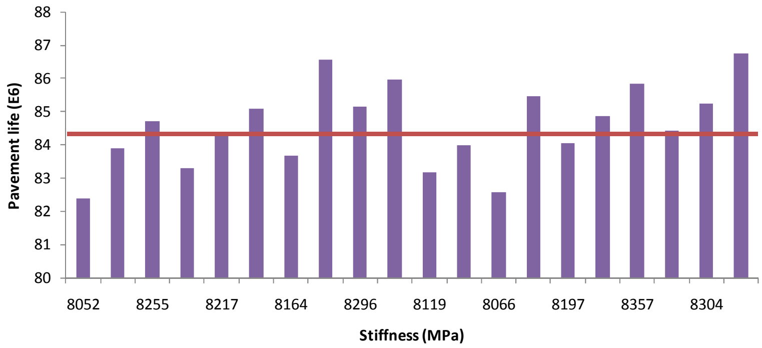

Figure 3. Pavement life for the combination of 3 specimens

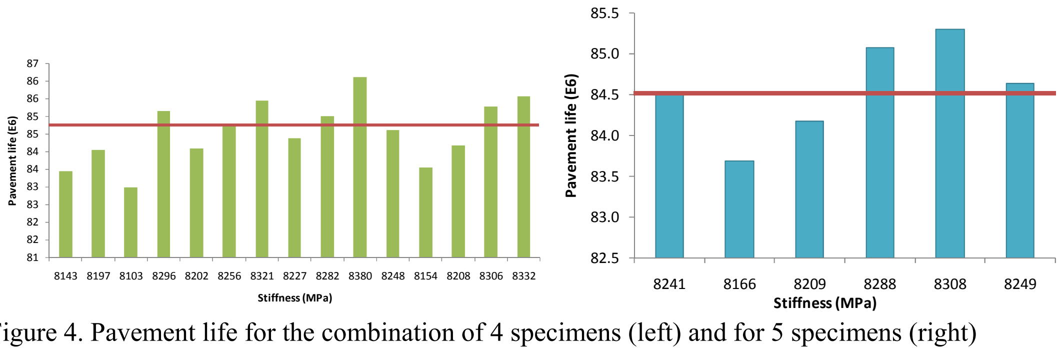

Figure 4. Pavement life for the combination of 4 specimens (left) and for 5 specimens (right)

The analysis of these figures allows concluding that the pavement life, calculated for the various combinations of the tested specimens, is very close to the exact value given by the average of all the tested specimens. This means that for any number of tested specimens the influence in the pavement life is very small. This conclusion, valid for mixture 1 (260 MPa of stiffness standard deviation) and for the studied pavement, indicates that the number of test specimens used to evaluate the stiffness modulus do not have a significant influence on the pavement life.

The results of the pavement life for each combination of specimens were also expressed in terms of the error in the pavement life considering the stiffness given by all the tested specimens. The results for mixture 1 are presented in Figures 5, 6 and 7, in which it can be observed that the error in the pavement life is always inferior to 5%. As the number of specimens is increased in the combination analysis the error decreases, reaching a value lesser than 1% for the combination of 5 specimens.

For practical applications an error of 5% is sufficient due to the uncertainty of the data used to design a pavement. Thus, stiffness tests can be performed with only 1 or 2 specimens.

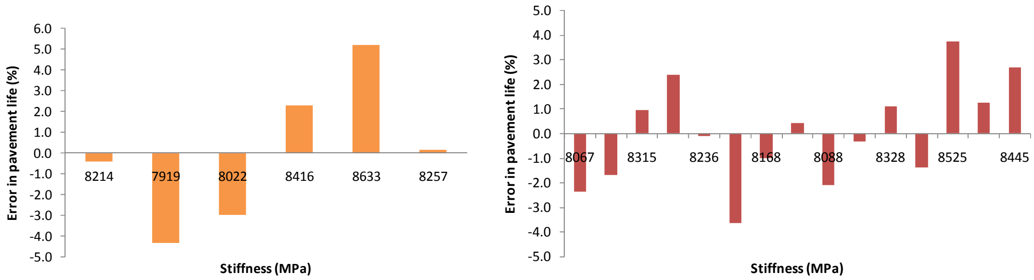

Figure 5. Error in pavement life for the combination of 1 specimen (left) and for 2 specimens (right)

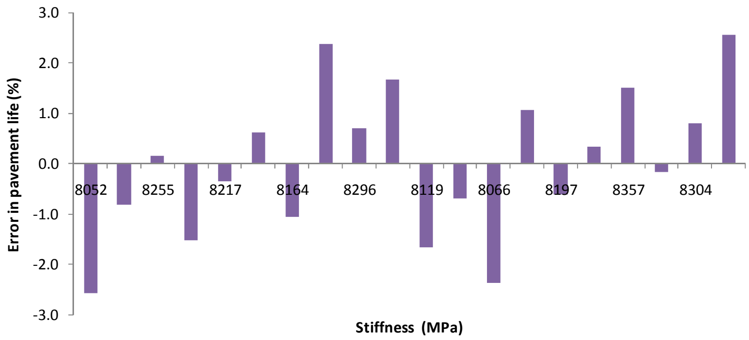

Figure 6. Error in pavement life for the combination of 3 specimens

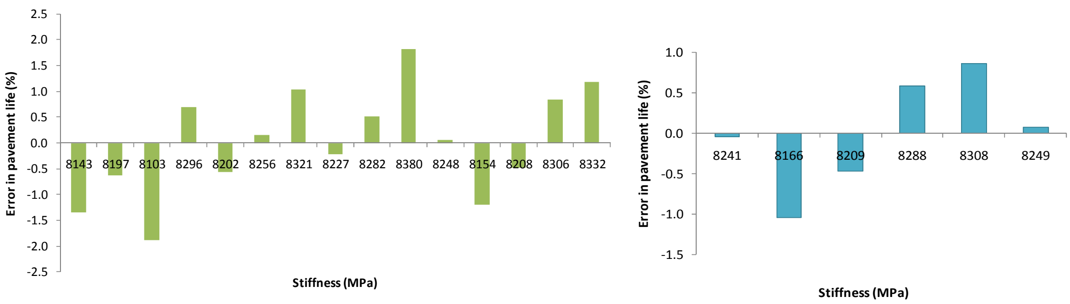

Figure 7. Error in pavement life for the combination of 4 specimens (left) and for 5 specimens (right)

For the other studied mixtures, the error in pavement life for the combination of 2 and 3 specimens is presented in Figures 8 and 9, respectively.

The combination of 2 and 3 specimens gives a stiffness modulus which leads, in most of the calculations, to an error in the pavement life, if compared to the exact value, that for most of the tested mixtures is inferior to 5%. However, for mixture 2, the standard of which is 343 MPa for an average value of 2315 MPa, the error can reach more than 20%. For the other mixtures, the use of 2 or 3 specimens is enough to get an excellent approximation for stiffness, as shown by the reduced error in pavement life.

For mixture 2, with a large dispersion in the stiffness results, the use of 5 specimens leads to error of about 8% in the pavement life, if compared to the value obtained with the average of 6 specimens.

In conclusion, for the studied pavement, the use of 2 specimens in the stiffness test creates errors in the pavement life inferior to 6%, whereas by using 3 specimens it is inferior to 5%. Thus, the use of 3 specimens is suitable for the characterization of the stiffness modulus of a mixture. However, for mixtures with low stiffness modulus, testing more than 3 specimens is recommendable.

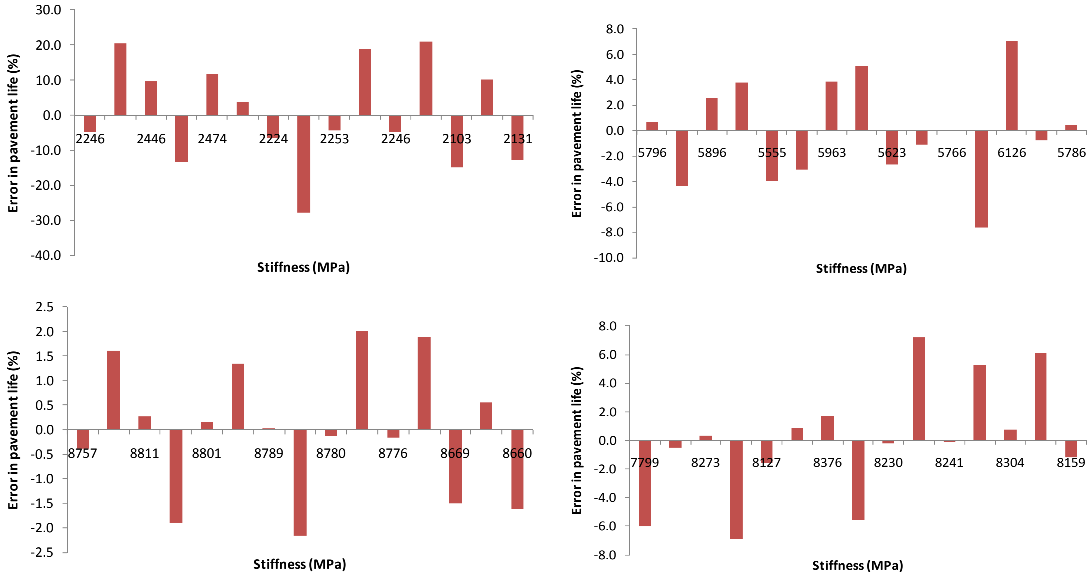

Figure 8. Error in pavement life for the combination of 2 specimens (mix2: top left; mix3: top right; mix4: bottom left; mix5: bottom right)

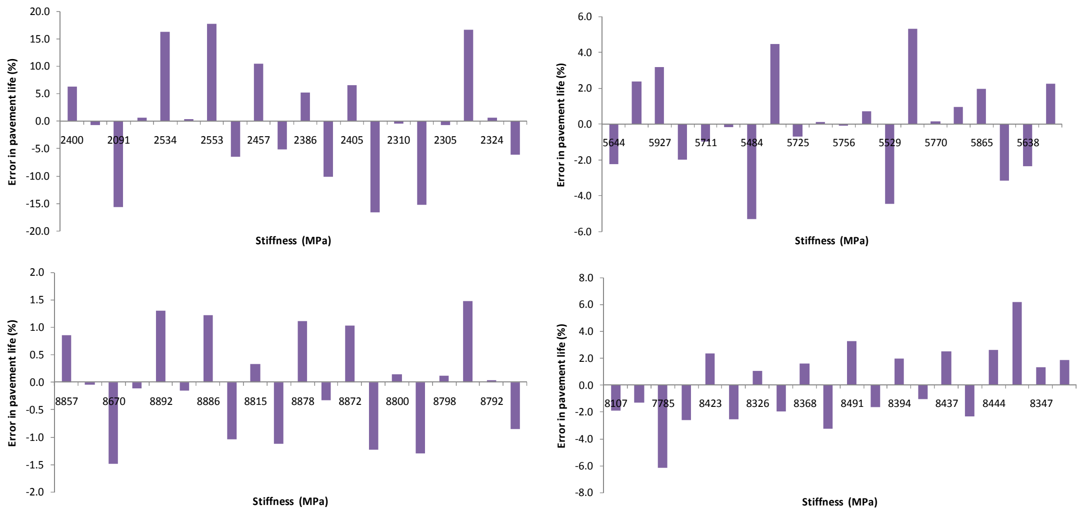

Figure 9. Error in pavement life for the combination of 3 specimens (mix2: top left; mix3: top right; mix4: bottom left; mix5: bottom right)

5 ALLOWED ERROR IN STIFFNESS DETERMINATION

The second part of this work consists in the determination of the stiffness modulus variation what produces a certain error in pavement life. A series of pavements composed by two layers (an asphalt layer and a granular layer) resting on a subgrade layer was studied. The asphalt layer has XX cm thickness and a YY MPa stiffness modulus. The subgrade has a ZZ MPa stiffness modulus. The base layer which is 20 cm thick has a stiffness modulus of 2xZZ MPa. This pavement is represented in Figure 10 and the abbreviation is PAV-XX-YY-ZZ.

Asphalt layer XX cm	YY MPa
Granular layer 20 cm	2xZZ MPa
Subgrade	ZZ MPa

Figure 10. Schematic representation of a pavement PAV-XX-YY-ZZ

The combinations used in this work include three asphalt layer thicknesses (XX), 10, 20 and 30 cm; eight asphalt layer stiffnesses (YY), from 3000 up to 10000 MPa; and three subgrade stiffnesses (ZZ), 60, 100 and 150 MPa.

The strain level at the bottom of the asphalt layer was calculated by using the Bisar software for a standard axle of 80 kN. The typical results follow a exponential variation with the stiffness of the asphalt layer, as it can be observed in Figure 11 for pavement PAV-10-YY-60, i.e. for a pavement with 10 cm of asphalt layer and a subgrade of 60 MPa. The error of the exponential model is inferior to 3%, what allows its use to obtain the tensile strain for any stiffness of asphalt layer.

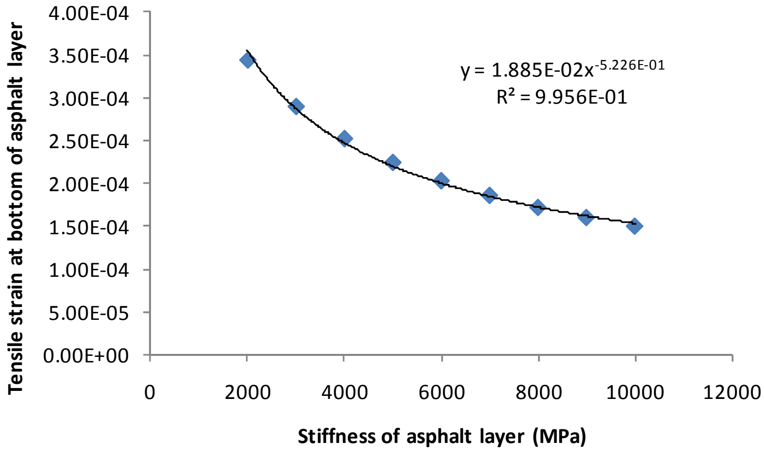

Figure 11. Typical evolution of tensile strain at the bottom of the asphalt layer

The tensile strain at the bottom of the asphalt layer was calculated for all the pavements considered in this work, corresponding to 3 different thicknesses for the asphalt layer, 9 different stiffnesses for the asphalt layer and 3 stiffnesses for the subgrade. The results are presented in Figure 12 in which it is possible to observe the tensile strain exponential variation of the tensile strain with the stiffness of asphalt layer.

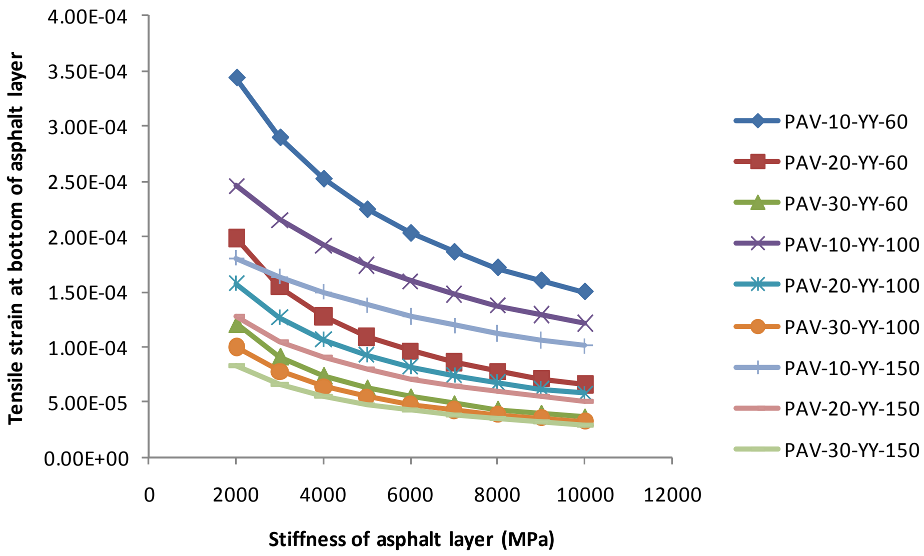

Figure 12. Tensile strain at bottom of asphalt layer of all studied pavements

The objective of this part of the work was to determine the variation for the stiffness modulus of the asphalt layer to obtain an error in the pavement life inferior to 3-5%. These calculations were made by using the Shell model (Equation 2) to define the pavement life due to the fatigue of the asphalt layer.

The application of this model allowed to obtain polynomial laws for the pavement life in relation to the tensile strain for the studied pavements as function of the stiffness of the pavement as illustrated in Figure 13, for pavement PAV-30-YY-60. The pavement life for the other pavements is presented in Figure 14.

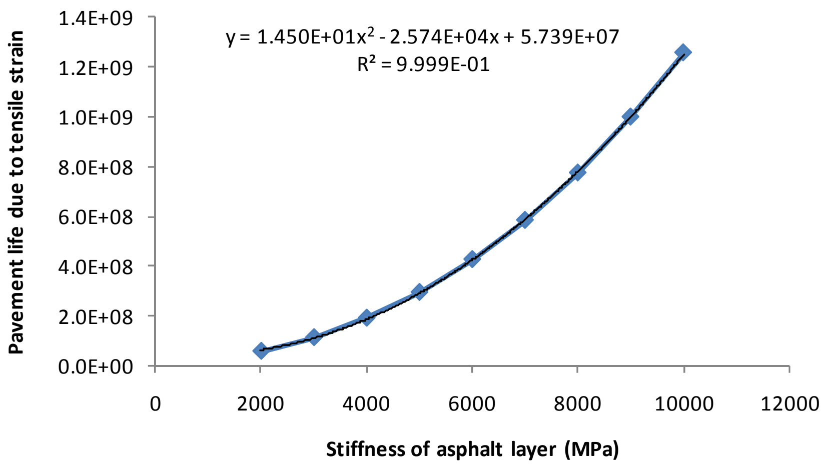

Figure 13. Pavement life as function of the stiffness of the asphalt layer

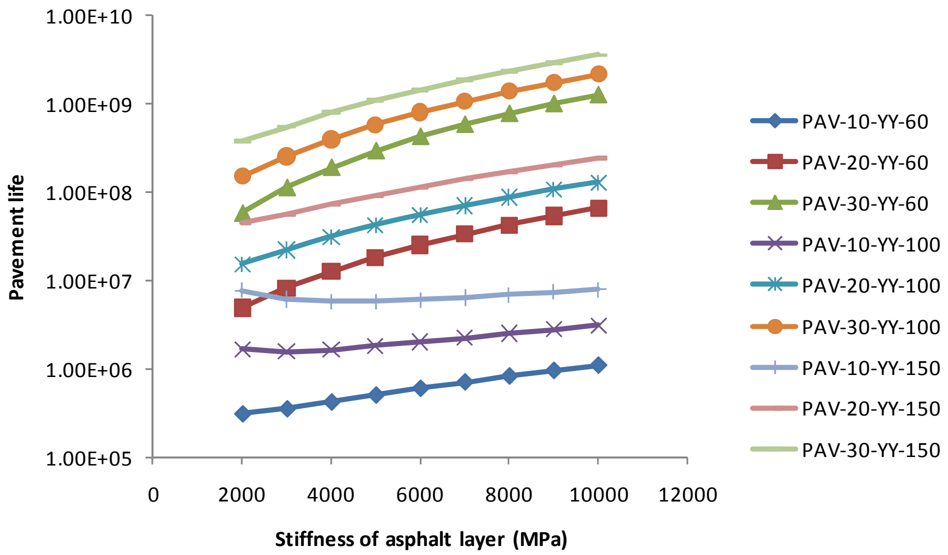

Figure 14. Pavement life as function of stiffness of the asphalt layer for all pavements

For each studied pavement, the variation of the stiffness layer allowed to obtain a certain error in the pavement life, which was calculated by using the following approach:

- For each stiffness of the asphalt layer, the pavement life was calculated by using the models expressed in Figure 14;
- The pavement life calculated in the previous step was increased and decreased in 3% to define the limits of the pavement life for this value of error (3%);
- For each limit, the stiffness of the asphalt layer was calculated by using the same model expressed in Figure 14;
- These limits of the stiffness are the variation in the stiffness of the asphalt layer to obtain a certain error in the pavement life.

By using that approach, stiffness followed the trend presented in Figure 15, for pavement PAV-20-YY-60, where the variation of stiffness is presented for 3% and 5% error in the pavement life.

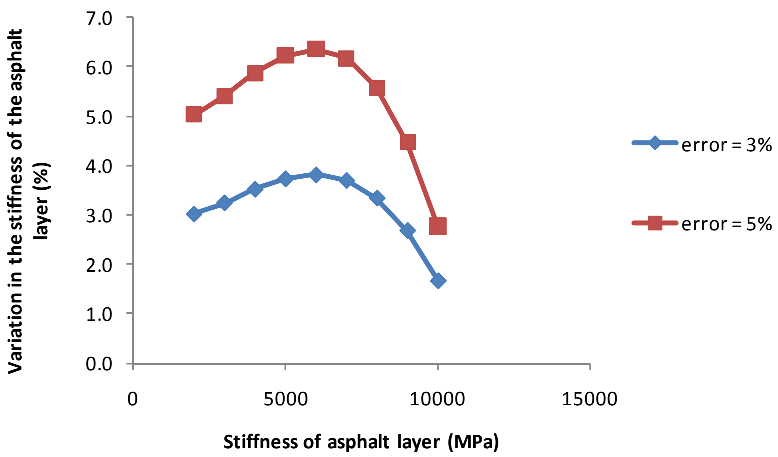

Figure 15. Variation in the stiffness of the asphalt layer to get an error in pavement life

The analysis of this figure allows concluding that the variation in percentage of the stiffness should be about the same one allowed for the pavement life, i.e. if the allowed variation in the pavement life is 5%, the variation in the stiffness of the asphalt layer should be also about 5%. This conclusion is valid for the pavements with 20 cm of asphalt layer and 60 MPa of subgrade stiffness considered in this study.

6 CONCLUSIONS

This work presented an approach to analyze the variation of the stiffness modulus obtained in four-point bending tests. The analysis intended to define the number of test specimens to be used in stiffness modulus tests in order to obtain a precision on pavement life suitable for pavement design.

The analysis of the 5 mixtures considered in this work, i.e. dense-graded conventional mixtures, asphalt rubber mixtures and recycled mixtures and a typical pavement, to define the pavement life, allowed concluding that the use of 2 or 3 specimens in stiffness tests is suitable for pavement design. This conclusion is valid for tests with small dispersion in the stiffness results. For tests with a large dispersion in the stiffness results, a higher number of specimens are needed. 5 specimens can produce an error in the predicted pavement life higher than 8%.

The work presented also defined the variation allowed in terms of stiffness to limit the error in the pavement life. From the results obtained, the variation in percentage in the stiffness should be as much similar as that allowed in the pavement life.

7 REFERENCES

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