THE INDIRECT TENSILE TEST CONFIGURATION IN THE DETERMINATION OF THE COMPLEX MODULUS OF ASPHALT MIXTURES

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ABSTRACT

The indirect tensile test using repeated load pulses with rest periods has been extensively used for the determination of the stiffness of asphalt mixtures. The main advantage of the indirect tensile test configuration is that can accommodate cylindrical samples compacted in the laboratory or specimens taken by coring from in service pavements. However, in linear elastic or viscoelastic multi-layer calculations, as in pavement design procedures based on mechanistic principles, is the absolute value of the complex modulus |E| used as input value for the asphalt layers. This paper presents the determination of the absolute value of the complex modulus |E*| and the phase angle using the indirect tensile mode with sinusoidal loads. The viscoelastic solution for the indirect tensile test with sinusoidal loads is presented and, to verify it, tests at different temperatures and frequencies were conducted on asphalt mixtures commonly used in Argentina. The obtained |E*| and phase angle results were compared with those obtained from tests using axial compression at the same frequencies and temperatures. Very well agreement was found between both sets of tests. Also, the |E*| mastercurves and shift factors derived from the two methods are in good agreement. It could be concluded that the indirect tensile test with sinusoidal loads may be used as a standard test and analysis protocol to obtain fundamental rheological properties of asphalt mixtures, particularly in forensic analysis with specimens obtained by coring.*

Keywords: Asphalt mixtures, complex modulus, phase angle, indirect tensile test

1. INTRODUCTION

Sustainability has become a key word in our lives. Sustainability is the potential for long-term maintenance of well being and it has environmental, economic, and social dimensions. In road engineering, sustainability is a concept related to more reliable pavement design procedures based on mechanistic principles, longer pavement design lives, more efficient pavement conservation strategies, lower mixing and compaction temperatures for asphalt materials and lower energy consumptions during the overall construction process. Also, the construction of roads is one of the most material demanding industries in the world with great economic as well as environmental impacts. In order to reduce these impacts, significant efforts are seen in terms of recycling and reuse of pavement materials and incorporating waste products-such as old tires, factory rejected roofing shingles, slag aggregates from steel production, sand from metal casting foundries and waste glass- in pavement materials.

For the modern flexible pavements design methods based on mechanistic principles, the mechanical properties of the different materials forming the road layers are used as inputs for the calculations of deflections, stresses and strains into the pavement structure. Particularly for the asphalt mixtures, the absolute value of the complex modulus is the main input material property required to compute stress and strains and to verify the performance characteristics (e.g., fatigue and rutting resistance) for asphalt mixtures. The absolute value of the complex modulus is referred to as the dynamic modulus |E*|.

The dynamic modulus |E*| relates stress to strain for linear viscoelastic materials subjected to continuously applied sinusoidal loading in the frequency domain and it is calculated by dividing the peak to peak stress by the peak to peak axial strain. It could be determined in laboratory by different procedures but in all cases, they require sophisticated equipment and well-trained personnel.

When conventional well known materials are used, the dynamic modulus of the asphalt mixtures could be estimated from other mechanical properties like the Marshall Quotient (stability to flow ratio) or using different predictive models developed by different researchers and based on the volumetric properties of the mixture, the aggregate gradations and the bitumen characteristics. Previous works [1, 2] have reviewed different estimation procedures considering their advantages and disadvantages in terms of necessary inputs and ease of use and it concluded that, when testing results are not available, reliable first order dynamic modulus estimates for asphalt mixtures typically used in Argentina can be obtained using any of the predictive procedures considered.

However, in the frame of sustainability and economy of natural resources, a problem arises when non conventional asphalt mixtures are used with the incorporation of different percentages of recycled materials or other waste by-products. In these cases, the use of such predictive models is at least, questionable and the dynamic modulus must be experimentally determined at different temperatures and loading frequencies in order to describe the dependent stiffness characteristics of the asphalt materials.

The Indirect Tensile Test (ITT) with repeated loading pulses has been extensively used for the determination of the stiffness properties of asphalt mixtures as it is described in [3] but, in those conditions, the ITT is not able to produce a full viscoelastic characterization of the material over a wide range of temperatures and loading frequencies as it is required in pavement design procedures based on mechanistic principles. The main advantage of the ITT over other tests configurations is that the required samples can be prepared at the laboratory using conventional procedures or taken from in service pavements by coring. As an example, the test protocol developed in the United States of America under a NCHRP Project [4] calls for the use of axial compression testing with sinusoidal loading using 100 mm diameter and 150 mm tall asphalt concrete specimens. As a typical asphalt layer thickness is less than few centimetres, the required specimens cannot be directly cored from the surface of the pavement and thus, this experimental configuration seems not to be adequate for forensic studies of existing pavements.

However, if the dynamic modulus |E*| is a true material property describing this full viscoelastic characterization of the asphalt mixtures, it could be determined using any experimental procedure considering the adequate theoretical basis and calculations. There are two major differences between the axial compression and ITT tests: - the state of stress (a uniaxial stress state in compression testing and a biaxial state of stress for the ITT testing configuration) and - the relationship between compaction direction and the direction in which the stress-strain analysis is performed. These differences raise questions about the equivalency of both experimental procedures in determining the same dynamic modulus results.

This paper validates the determination of the dynamic modulus |E*| using the indirect tensile mode with sinusoidal loads at different temperatures and frequencies conducted on asphalt mixtures commonly used in Argentina. The |E*| results obtained with the ITT procedure were compared with those obtained from tests using uniaxial compression at the same frequencies and temperatures. Very well agreement was found between both sets of tests showing that the indirect tensile test with sinusoidal loads may be used as a standard test to obtain fundamental rheological properties of asphalt mixtures.

In this study two asphalt mixtures containing non conventional aggregates were considered. The scantiness of availability of good quality aggregates in the Litoral region of Argentina has always been a serious drawback for the construction of roads. The high cost of transportation from the scanty production centres, with distances over 350 km must be taken into account. This serious technical-economical drawback has determined the need to use local aggregates tough they may not comply with the conventional standards of quality. In this paper two different calcareous soil-sand-asphalt mixes were considered. These mixtures are a kind of asphalt mixtures prepared and laid hot formulated with approximately equal weights of two local materials: a fine graded siliceous sand and a local boring-pits of soil A-4 of the third horizon characterized by having undergone a not altogether developed process of calcification which determines the presence of hard and porous calcareous nodules. The origin and development of the use of this material has been empirical and hence the determination of its fundamental engineering properties (the dynamic modulus and the phase angle) could allow its analysis when pavement design procedures based on mechanistic principles are used.

2. DYNAMIC MODULUS CALCULATIONS

2.1 Uniaxial compression with sinusoidal loads

When a tall cylindrical sample of asphalt mixture is subjected to an axial sinusoidal load in a steady state, a uniaxial compressive state of stress σ develops into the sample in the form of:

$$\sigma = \sigma_0 \cdot \sin(\omega \cdot t) \tag{1}$$

with:

σ : instantaneous sinusoidal applied stress
σ_0 : applied stress amplitude (peak to peak)
ω : angular frequency
t : time

The material response to this sinusoidal applied stress is an axial strain shifted along the time as:

$$\varepsilon = \varepsilon_0 \cdot \sin(\omega \cdot t - \phi) \tag{2}$$

where:

ε : instantaneous sinusoidal strain
ε_0 : strain amplitude (peak to peak)
ϕ : phase angle

Thus, the dynamic modulus |E*| is calculated as:

$$|E^*| = \sigma_0 / \varepsilon_0 \tag{3}$$

2.2 Indirect tensile test with sinusoidal loads

When a cylindrical sample is subjected to compressible loads distributed along two opposite generators as in the ITT mode, a biaxial state of stress develops into the specimen. Assuming the plane stress state, the stresses along the horizontal diameter of the ITT specimen are:

$$\sigma_x(x) = \frac{2\,P_0}{\pi\,h\,a}\left[f(x) - g(x)\right] \tag{4}$$

$$\sigma_y(x) = \frac{2\,P_0}{\pi\,h\,a}\left[f(x) + g(x)\right] \tag{5}$$

where:

P_0 : applied load
h : thickness of specimen
a : loading strip width
f(x), g(x) : mathematical functions depending on the specimen and loading strip sizes

According to the elastic-viscoelastic correspondence principle applied to the ITT mode with sinusoidal loads in a steady state, the strains along the horizontal diameter result:

$$\varepsilon_x(x) = \frac{1}{|E^*|} \cdot \left(\sigma_x(x) - \mu \cdot \sigma_y(x)\right) \tag{6}$$

with:

$|E^*|$: dynamic modulus

μ : Poisson's ratio

The development of the viscoelastic solution for the determination of the dynamic modulus with the indirect tensile test configuration has been presented in a previous paper [5] following the same procedure as it was presented by other authors [6, 7, 8]. Instead of presenting the details involved in this derivation, only the final expression for the dynamic modulus is presented as:

$$|E^*| = \frac{P_0}{\Delta h_0 \,.\, h}\left(K_1 + \mu \,.\, K_2\right) \tag{7}$$

where

P_0 : amplitude of the applied sinusoidal load

Δh_0 : amplitude of the resulting horizontal deformation

K_1, K_2 : coefficients depending on the specimen diameter and gauge length

3. PROCEDURES AND MATERIALS

3.1 Testing procedures

In this paper, uniaxial compression and biaxial indirect tensile tests with sinusoidal loads (haversine) were performed using a servo-pneumatic machine, developed at the Road Laboratory of the University of Rosario, using a 5000 N load cell, which is capable of applying load over a range of frequencies ranging from 0.01 Hz to 5 Hz. A proportional valve controlled by the computer is used to generate the sinusoidal loadings at the required frequency. The test frame is enclosed into a temperature chamber. The temperature control system is able to achieve the required testing temperatures ranging from 0 °C to 50 °C. The data acquisition system was also developed at the Road Laboratory of the University of Rosario and is capable of measuring and recording data from three channels simultaneously: two for displacements and one for the load cell.

3.2 Asphalt mixtures

Six different asphalt mixtures were considered in this study identified as A, B, J, K, H and I. A brief description of each one is presented in Table 1.

Table 1: Asphalt mixtures considered

Id.	Description	Asphalt content by weight (%)	Bitumen type	Air Voids (%)	Maximum aggregate size (mm)
A	Dense asphalt concrete with basaltic aggregates	4.7	Conventional AC30	4.9	19.0
B	Dense asphalt concrete with basaltic aggregates	5.1	Conventional AC30	4.1	19.0
H	Non conventional asphalt mixture with calcareous soil and natural sand	9.0	Conventional AC70-100	3.2	37.5
I	Non conventional asphalt mixture with calcareous soil and natural sand	9.3	Conventional AC70-100	3.1	25.0
J	Dense asphalt concrete with granitic aggregates	4.5	Polymer modified PmB-III	4.2	19.0
K	Dense asphalt concrete with granitic aggregates	4.8	Polymer modified PmB-III	3.9	19.0

It should be noted that the mixtures H and I are two different non conventional asphalt mixtures formulated with a local calcareous soil (named "Tosca" in Argentina), natural sand and asphalt bitumen [9, 10]. Due to the geographical and geological characteristic of the Litoral region of Argentina where the absence of good quality rock aggregates requires carrying this kind of materials from distances sometimes over 350 kilometres, this sub normal aggregate is used as a substitute in asphalt base layers in order to reduce costs preserving the natural resources. The resulting asphalt mixtures have remarkable rheological properties as are shown later herein.

In order to obtain tall samples with a homogeneous distribution of air voids along the height of the specimens, the samples used in this study were cored from existing pavements where the asphalt layer thickness was thicker enough to obtain a relationship height/diameter equal to 1.5. These specimens with 100 mm diameter were first used for the determination of the dynamic modulus in uniaxial compression. At the end of these tests, each sample was cut in order to obtain two sub samples with 50 mm height approximately from the upper and the lower half of the original specimen. Then, each sub sample was subjected to the determination of the dynamic modulus using the indirect tensile test configuration. Figure 1(a) shows some samples used for the |E*| measurements in uniaxial compression while Figure 1(b) shows the resulting sub samples used for the |E*| determinations using the indirect tensile test with sinusoidal loads.

3.3 Tests in uniaxial compression

The measurements of the dynamic modulus in uniaxial compression were carried out following a procedure similar as it is described in the AASHTO TP-62 Standard [11]. Two samples of each asphalt mixtures were tested and the obtained results were averaged. The samples were instrumented with 2 LVDT´s attached on the central part onto two diametrically opposed generators using a gage length equal to 70 mm. Figure 2(a) and (b) show the used testing equipment and a detail of the instrumented sample.


(a)

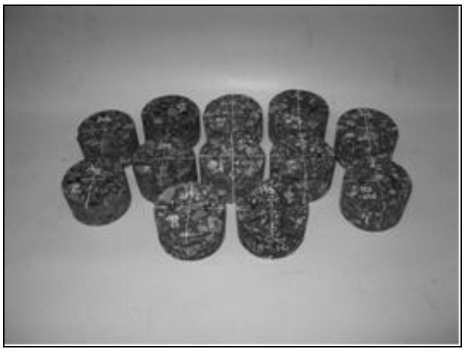
(b)

Figure 1: Samples and sub samples used for the tests

The |E*| measurements in uniaxial compression were determined for 7 frequencies (5, 4, 2, 1, 0.5, 0.25 and 0.10 Hz) and 4 temperatures (10, 20, 30 and 40 °C) in order to have a full viscoelastic characterization of the asphalt mixtures. At each temperature, the lowest load compatible with the capability of the data acquisition system was used in order to avoid the induced damage in the samples and in all cases, the resulting strains were maintained under 80 micro-strains.


(a)


(b)

Figure 2: Testing configuration in uniaxial compression

3.4 Tests in indirect tensile mode

The dynamic modulus measurements in the indirect tensile test with sinusoidal loads were performed at the same frequencies and temperatures used for the tests in uniaxial compression. In order to increase the simplicity of the test, only horizontal deformations were measured. From previous studies [12], the Poisson's ratio was adopted as a function of the test temperature in the form:

$$\mu = a + b\,T \qquad (8)$$

where:

μ : Poisson's ratio

T : testing temperature (ºC)

a, b : regression constants (a = 0.223, b = 0.005)

The horizontal deformations were measured using LVDT´s mounted on each of the specimen faces using a 50 mm gauge length. For the adopted gauge length and for specimens with 100 mm diameter, the coefficients K1 and K2 result: K1 = 0.236 and K2 = 0.777. Figure 3(a) and (b) show the used testing equipment and a detail of the instrumented sample. In these tests, the four sub samples were tested and the obtained results were averaged.

3.5 Viscoelastic characterization of asphalt mixtures

Since the behaviour of viscoelastic materials is dependent on temperature and frequency, the dynamic modulus is determined at multiple frequencies and temperatures. A single, continuous curve could be developed using the frequency-temperature superposition principle. This principle states that rheologically simple materials, such as the asphalt mixtures, can be shifted in the frequency domain to produce a single, smooth and continuous curve to a reference temperature TR.

(a) **(b)**

Figure 3: Testing configuration in indirect tensile mode

To develop this curve, the dynamic modulus vs. frequency values at various temperatures are horizontally shifted along the frequency axis in a logarithmic scale to form a single curve at a reference temperature TR. The equation for the shifted frequency in a logarithmic scale, known as the reduced frequency fR, is:

$$fR = aT \cdot f \tag{9}$$

where:
fR : Reduced frequency
f : Testing frequency
aT : Shift factor

The shift factors referenced to the temperature TR were modelled according to a polynomial equation in the form:

$$\log(aT) = C_1 \cdot T^2 + C_2 \cdot T + C_3 \tag{10}$$

with:
T : Testing temperature
C_1, C_2, C_3: Polynomial coefficients

In this paper, the dynamic modulus |E*| master curves were modelled according to a sigmoidal function in the form of:

$$\log(|E^*|) = \alpha + \frac{\beta}{1 + e^{[\gamma + \delta \cdot \log(fR)]}} \tag{10}$$

with:
α, β, γ, δ : Constants

The constants of the sigmoidal model were obtained simultaneously with the polynomial coefficients of the shift factors by minimising the sum of the square of the errors of the experimental and model values using the Solver function in the Excel spreadsheet.

4. OBTAINED RESULTS

Figure 4 shows a comparison of the average dynamic modulus results obtained with the uniaxial compression and indirect tensile tests at all the testing frequencies and temperatures for the six asphalt mixtures considered in this study (in arithmetic space on the left and in logarithmic space on the right). Also on this figure, the line of equality and other two lines corresponding to percentages differences (the difference between the measured values in uniaxial compression and in indirect tensile divided by the measured dynamic modulus in uniaxial compression) equal to ± 25% are included.

In general, the percentage differences in absolute values were lower than 25 % and they are within the same orders of magnitude than others obtained from predictions of the dynamic modulus using predictive equations and models well accepted by the pavement community [13, 14, 15, 16]. These errors were considered very acceptable since it was observed that replicate samples tested in the laboratory might exhibit a difference in the order of 20 to 30 %. Also, the data points are distributed on both sides of the line of equality without a perceptible bias between results obtained with the two experimental procedures.

Figures 5 shows the dynamic master curves constructed from the average results obtained with both the uniaxial compression and the indirect tensile tests with sinusoidal loads for the six mixtures considered in this study at a reference temperature TR equal to 20 °C.

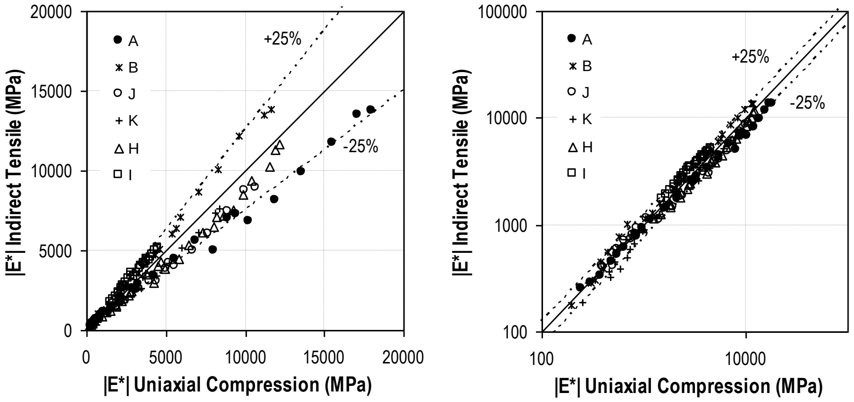

Figure 4: Comparison of |E*| results in uniaxial compression and indirect tensile tests (in arithmetic space on the left and in logarithmic space on the right)

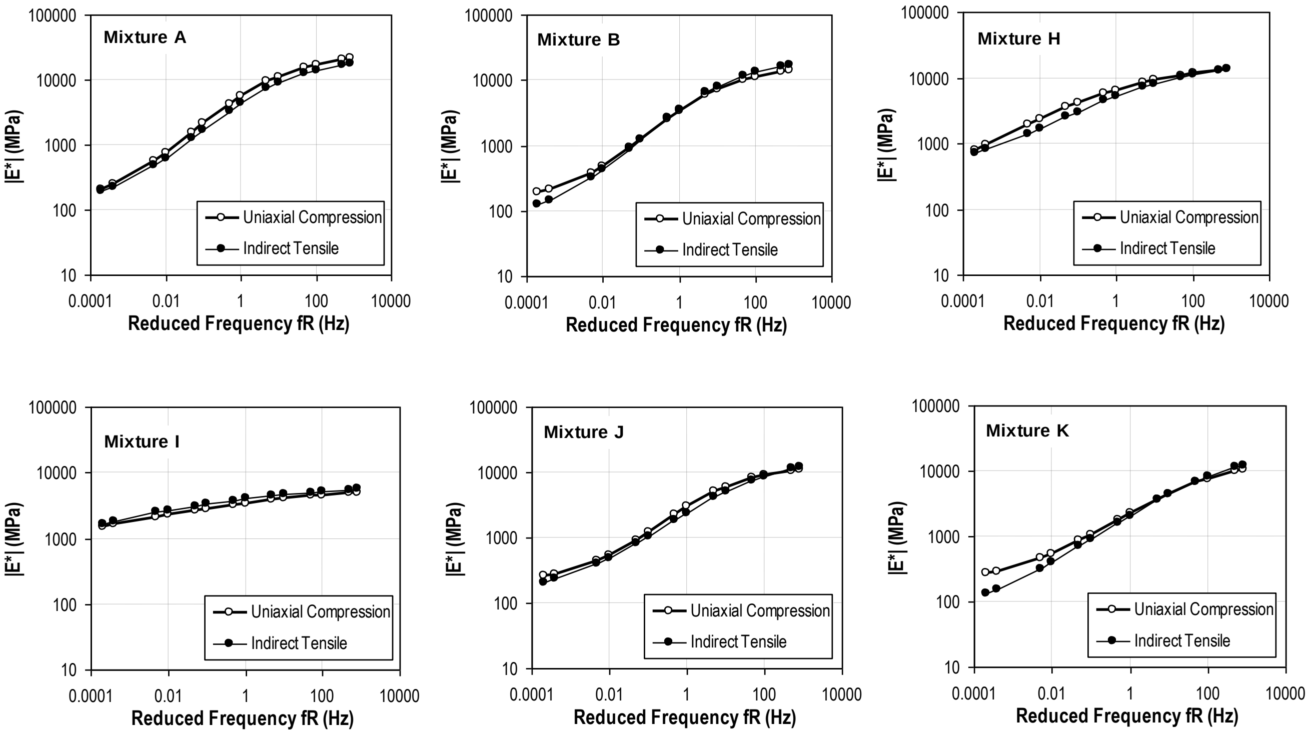

Figure 5: Dynamic modulus master curves for the tested asphalt mixtures

The dynamic modulus master curves developed from both testing procedures are in very good agreement. The greatest differences were observed for the asphalt mixture K at low frequencies with differences ranging from 25 to 35 %. As it was pointed out before, the asphalt mixtures H and I show a different behaviour than the other mixes with lower |E*| values at high frequencies (or low temperatures according to the frequency-temperature superposition principle) and higher |E*| values at low frequencies (or high temperatures). For the conventional asphalt mixtures, the |E*| values vary approximately 100 times from high to low frequencies while for the non conventional asphalt mixtures made with calcareous soil this variation is only 10 times.

During the dynamic modulus tests, the phase angle ϕ between stress and strain was also measured. Figure 6 shows the variation of the phase angle ϕ as a function of the dynamic modulus |E*| measured with the uniaxial compression and the indirect tensile tests for the six asphalt mixtures considered. Well agreement was also found for the phase angle results obtained with both experimental procedures. It is also remarkable the different behaviour of the non conventional asphalt mixtures H and I with lower phase angle values and hence, a more “elastic” behaviour than the other mixtures.

Figure 7 shows a comparison between phase angles measured in uniaxial compression and indirect tensile. Also on this figure, the line of equality and the two lines corresponding to percentages differences equal to ± 25% are included. In general, the percentage differences are smaller than 25% but there is a noticeable bias with greater phase angles measured in indirect tensile than in uniaxial compression.

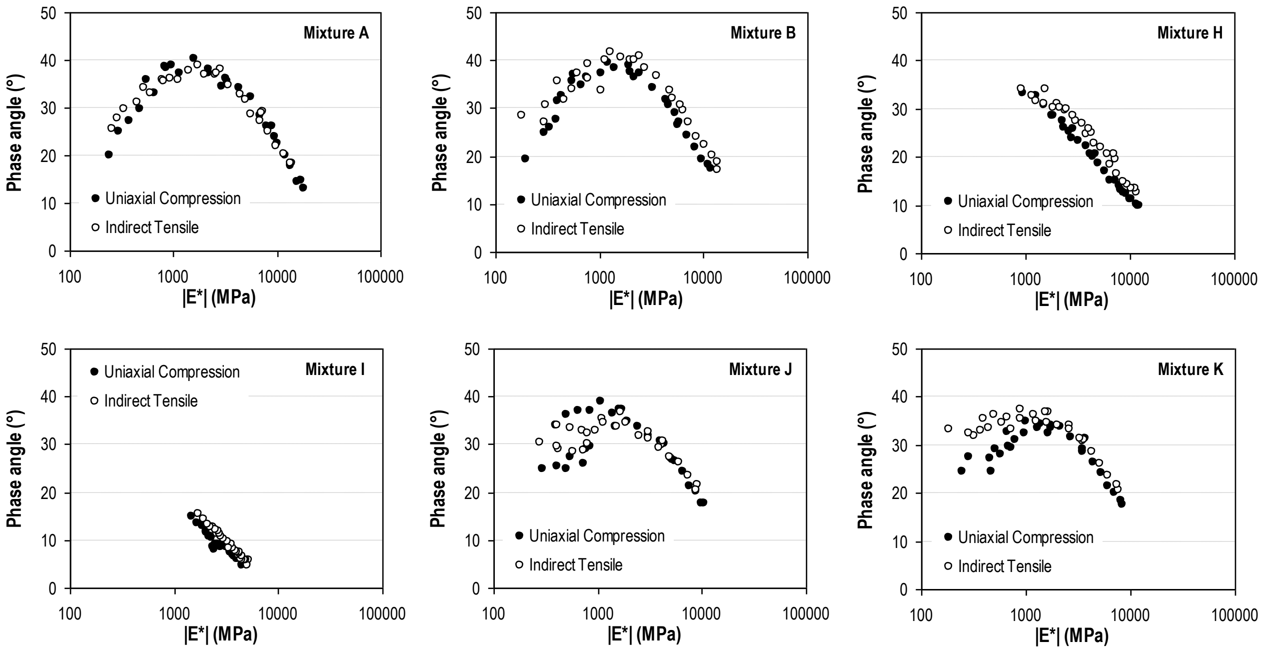

Figure 6: Phase angle variations for the tested asphalt mixtures

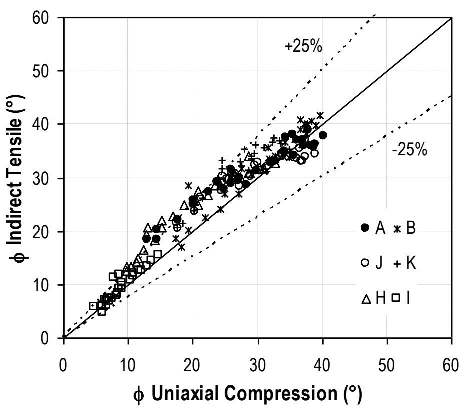

Figure 7: Comparison of phase angle results in uniaxial compression and indirect tensile tests

The obtained results for the mixtures H and I made with calcareous soil, sand and asphalt show that the behaviour of these mixtures could be considered very promising when used as base layers against the two major distress types in asphalt pavements: fatigue cracking and rutting. At low temperatures, these mixtures are softer and more “elastic” with smaller phase angles than the conventional mixes and hence, better adapted to resist fatigue damage. At high temperatures, these mixtures are stiffer and also more “elastic” with smaller phase angles compared to the conventional mixtures and then, more resistant to the development of permanent deformations.

Figure 8 shows a comparison of the shift factors aT at the testing temperatures used in the uniaxial compression and the indirect tensile tests (10, 20, 30 and 40 ºC) referred to the temperature of 20 ºC and obtained in the construction of the sigmoidal master curves. Also in this case, there is a very good agreement between shift factors obtained with the two experimental procedures used in this study.

To evaluate the performance of these comparisons, the quality of the comparisons between measured values in uniaxial compression and indirect tensile mode was assessed using goodness-of-fit statistics according to subjective criteria proposed by Witczak et al. [17], and shown in Table 2. The statistics include correlation coefficient, R2 and Se/Sy (standard error of estimate values/standard deviation of measured values).

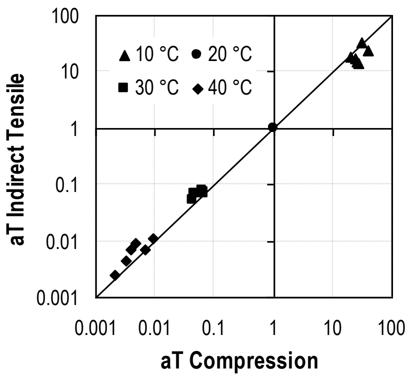

Figure 8: Comparison of shift factors

Table 2: Criteria for Goodness-of-Fit Statistical Parameters

Criteria	**R^2**	**Se/Sy**
Excellent	≥ 0.90	≤ 0.35
Good	0.70 – 0.89	0.36 – 0.55
Fair	0.40 – 0.69	0.56 – 0.75
Poor	0.20 – 0.39	0.76 – 0.89
Very Poor	≤ 0.19	≥ 0.90

Table 3 presents the evaluation of the quality of the comparisons according to these criteria. The goodness-of-fit statistics show that the comparisons between values obtained in uniaxial compression and indirect tensile are excellent for the dynamic modulus, phase angles and shift factors.

Table 3: Goodness-of-Fit Statistics for the Predictive Procedures

Space	**R^2**	**Se/Sy**	**Evaluation**
Dynamic Modulus |E*|	0.91	0.26	Excellent / Excellent
Phase Angle ϕ	0.90	0.32	Excellent / Excellent
Shift Factor aT	0.90	0.26	Excellent / Excellent

5. CONCLUSIONS

This paper presents a comparison of the dynamic modulus |E*| of six different asphalt mixtures obtained in uniaxial compression and indirect tensile mode at different testing frequencies and temperatures. Excellent agreement was found in these comparisons for the dynamic modulus, the phase angles and the resulting shift factors. This analysis has shown that the dynamic modulus |E*| is a true material property describing the full viscoelastic characterization of the asphalt mixtures and it could be determined using any experimental procedure considering the adequate theoretical basis and calculations. Based on the obtained results it could be concluded that the indirect tensile test with sinusoidal loads (haversine) is able to produce reliable dynamic modulus values to be used in the modern flexible pavements design methods based on mechanistic principles.

Two of the tested mixtures (the non conventional asphalt mixtures formulated with local calcareous soils, natural sand and asphalt bitumen) H and I show a different rheological behaviour with lower |E*| values at high frequencies (or low temperatures according to the frequency-temperature superposition principle), higher |E*| values at low frequencies (or high temperatures) and lower phase angle values indicating a more “elastic” behaviour than the other mixtures. The behaviour of these mixtures could be considered very promising when used as base courses against the two major distress types in asphalt pavements: fatigue cracking and rutting. At low temperatures, these mixtures are softer and more “elastic” with smaller phase angles than the conventional mixes and hence, better adapted to resist fatigue damage. At high temperatures, these mixtures are stiffer and also more “elastic” with smaller phase angles compared to the conventional mixtures and then, more resistant to the development of permanent deformations.

In the frame of economy of natural resources, longer pavement lives and more reliable pavement design procedures, the indirect tensile test (ITT) with sinusoidal loads could be able to characterize the full viscoelastic behaviour of asphalt mixtures. This conclusion is based on the obtained results and the quality of the comparisons with the mixtures considered in this study. However, the applicability to other mixtures like open porous asphalt, SMA, mixtures containing RAP or other waste by-products should be verified.

Hence, the implementation of such test could promote the use of those non conventional materials and provide a tool that could allow the industry and road agencies to recognize the impacts of different sustainable construction techniques, materials and methods.

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