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Shear Tests for Characterization of Bituminous Mixture Stiffness

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Abstract

This paper presents the results of a study where the shear stiffness and the shear phase angle of bituminous mixtures, with two different air-void contents and three different bitumen contents were measured using shear strain controlled tests. The shear tests were carried out at three temperatures, 4, 20 and 40 °C, and 10, 5, 2, 1, 0.5, 0.2 and 0.1 Hz frequencies were used, in agreement with SHRP M-003 specification. The specified strain level of 0.0001 mm/mm was used beside two more strain levels, 0.0002 mm/mm and 0.0005 mm/mm.

With this study a shear behaviour comparison between mixtures with two air void contents, three bitumen contents was carried out at three test temperatures, seven frequencies and three strain levels. Five replicates for the main mixture and two replicates for the other mixtures were used. A total number of 693 shear tests were performed.

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This paper presents the results of a study where the shear stiffness and the shear phase angle of bituminous mixtures, with two different air-void contents and three different bitumen contents were measured using shear strain controlled tests. The shear tests were carried out at three temperatures, 4, 20 and 40 °C, and 10, 5, 2, 1, 0.5, 0.2 and 0.1 Hz frequencies were used, in agreement with SHRP M-003 specification. The specified strain level of 0.0001 mm/mm was used beside two more strain levels, 0.0002 mm/mm and 0.0005 mm/mm.

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1 Introduction

The flexural stiffness of bituminous mixtures is of paramount importance in the determination of pavement performance and for the analysis and design of pavements. This stiffness, in conjugation with the Poisson ratio, is used in the multilayer elastic analysis to determine the critical level of strain to which the mix is subjected under the traffic load and environmental conditions. The flexural loss-stiffness (product of the stiffness and sine of the phase angle between stress and strain) is required to estimate fatigue life of mixes using surrogate fatigue models [1].

Usually, stiffness of bituminous mixtures is measured with flexural tests. Sometimes, diametral tests (indirect tensile) are used to estimate the stiffness. Nevertheless this test the stiffness is a function of the Poisson ratio. Because of the difficulty in accurately measure the vertical and horizontal deformation ratio, the Poisson ratio is not calculated but assumed.

Recently, shear tests have been used to predict stiffness and phase angle between stress and strain. Shear quantities are correlated with the corresponding flexural ones, allowing their application in pavement analysis and design. In state of the application of the shear results in the prediction of fatigue life, shear results are used directly in the evaluation of permanent deformation and in the evaluation of cracking propagation. These last two phenomena are governed by the shear response of the bituminous mixtures.

2 Shear stiffness

The bituminous mixtures exhibit linear-viscoelastic behavior as such that their response is time of loading and test temperature dependent:

$$S_{mix} = \frac{\sigma}{\varepsilon}(t,T) \tag{2.1}$$

where S_{mix} = mixture stiffness; σ = stress level; ε = strain level; t = time of loading; T = test temperature.

To calculate the shear stiffness, horizontal displacement of the specimen and shear load are combined using the following relationships:

$$\tau_{12}(shear\ stress) = \frac{shear\ load}{area} \tag{2.2}$$

$$\varepsilon_{12}(shear\ strain) = \frac{shear\ displacement}{height\ of\ specimen} \tag{2.3}$$

$$G(shear\ stiffness) = \frac{\tau_{12}}{\varepsilon_{12}} \tag{2.4}$$

2.1 Shear stiffness in other utilizations

The shear stiffness is utilized in flexural applications such as in the prediction of fatigue life of bituminous mixtures. The most important relationship between shear and flexural stiffness is as follows:

$$G(shear\ stiffness) = \frac{E(flexural\ stiffness)}{2(1+\upsilon)} \tag{2.5}$$

where υ = Poisson ratio.

There is some evidence to suggest that the values of Poisson's ratio expressed by equation 2.5 may differ from the values for strain ratio defined by measured values of the axial and radial strains obtained during testing. This suggests, of course, non linear response characteristics for the bituminous mixtures.

Within SHRP Program Tayebali et al. [2] proposed the following equations to convert shear quantities in flexural quantities, for tests executed at 10 Hz and 20 °C:

$$E = 8.560(G)^{0.913} \qquad R^2=0.712 \tag{2.6}$$

$$E^{"} = 81.125(G^{"})^{0.725} \qquad R^2=0.512 \tag{2.7}$$

$$\sin\phi_E = 1.040(\sin\phi_G)^{0.817} \qquad R^2=0.813 \tag{2.8}$$

where E = flexural stiffness, in psi; S" = flexural loss stiffness, in psi; G = shear stiffness, in psi; G" = shear loss stiffness, in psi; sin ϕ_E = sine of phase angle in flexural test and sin ϕ_G = sine of phase angle in shear test.

Other important utilization of the shear stiffness is in the fracture mechanics applications. The prediction of crack propagation using finite element analysis requires an appropriate modelization of the vicinity of the crack tip. Special elements have been developed. Among the best performers are the Barsoum elements [3]. For these elements the stress intensity factors are computed using the following relationship where the G (shear stiffness) is used.

$$K_I = \sqrt{\frac{2\pi}{L}}\frac{G}{k+1}\left[4(v_B - v_D) + v_E - v_C\right] \tag{2.9}$$

$$K_{II} = \sqrt{\frac{2\pi}{L}}\frac{G}{k+1}\left[4(u_B - u_D) + u_E - u_C\right] \tag{2.10}$$

Other application of shear results is the prediction of the permanent deformation of bituminous mixtures. Shear parameters are used to compute values utilized in the permanent deformation calculations.

3 Test apparatus

The test apparatus existing in the University of Minho and used in this study was a CS7400-S shear test machine produced by James Cox and Sons and introduced during the SHRP program. A microcomputer system using the ATS software provides feedback closed-loop control to the servo-hydraulic system, test temperature and data acquisition. The testing equipment can perform dynamic axial and shear loading with or without rest periods. Repetitive loading with sinusoidal, triangular, haversine or user defined patterns can be performed. The machine can provide temperature control between -20 °C and 70 °C, with an accuracy of 0.5 °C. The closed-loop control of the servohydraulic system can execute tests at any frequency from 0.01 to 20 Hz. The loading conditions include both the controlled-load and controlled-deformation modes. These capabilities allow the equipment to be used to define frequency response of a material over a wide range of temperatures, frequencies and strains propagation [4].

The machine testing capabilities and accommodation of add-on testing modules permits fatigue and stiffness testing as well as permanent deformation evaluation using axial and shear mode of loading. A reflective cracking device can be linked to study reflective fatigue cracking in flexible pavement overlays simulating the mode I and mode II of crack propagation [5].

To test in shear mode, cylindrical specimens with either 15 cm diameter by 5 cm high or 20 cm diameter by 7.5 cm high can be used. For this study, due the maximum nominal aggregate size (25 mm) the small specimens were used. The test specimens are glued to aluminum caps, top and bottom, using an epoxy resin. This process is made in an independent machine that ensure the parallelism between the two caps. Figure 1 shows the shear machine installed at the University of Minho and Figure 2 shows a schematic representation of the shear device used in this study.

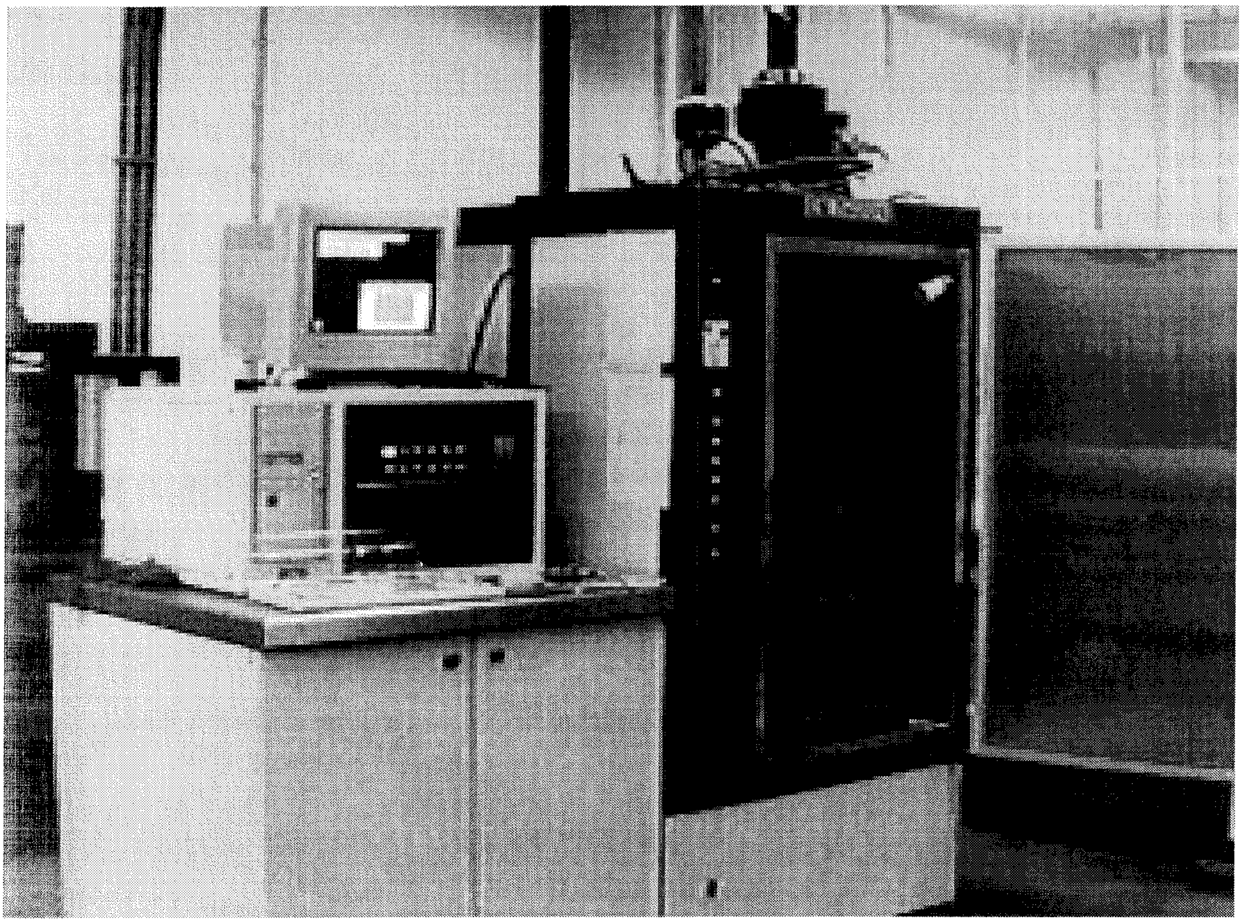

Figure 1. Shear machine installed at the University of Minho

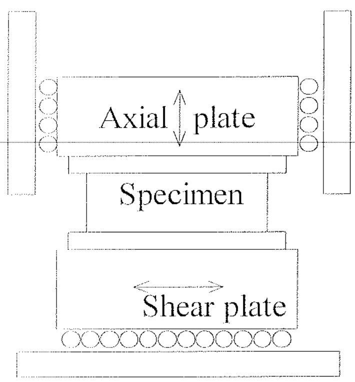

Figure 2. Schematic representation of shear device

4 Testing Program

4.1 Materials

The bituminous mixtures of this study are a dense graded bituminous mixture with a maximum aggregate size of 25 mm manufactured according the Portuguese standards and are used in binder layers. The aggregate was a crushed granit with the grading curve shown in Table 1. Usually these mixtures are placed in the road with 4% air void content and the bitumen content is near 5.5% by weight of aggregates. Furthermore this mixture (main mixture) and three more different mixtures were used in this study. One having 7% air void content and 5.5% bitumen content, and the others have 4.5 and 6.5% bitumen content for 4% air void content. The Table 2 shows the different mixtures used in this study. The bitumen used in all mixtures was a conventional 60/70 penetration grade. In laboratory some slabs with 70 cm long by 50 cm wide by 7.5 cm high were produced to cut the specimens with 150 mm in diameter by 50 mm high. The mixtures were compacted in laboratory using a rolling wheel compactor using the procedures proposed by Pereira et al. [6].

Table 1. Aggregate grading curve

Sieve #	Percentage passing
3/4"	94
1/2"	80.5
#4	52.5
#10	39
#40	21.5
#80	13.5
#200	7.5

Table 2. Mixtures used in this study

Air void content	Bitumen content
4 %	5.5 %
7 %	5.5 %
4 %	4.5 %
4 %	6.5 %

4.2 Testing

The shear tests were conducted in strain control at constant height. The vertical actuator of the machine is controlled by a LVDT to keep constant the height of the specimen when the shear actuator produce shear displacements. The shear actuator applies a sinusoidal displacement to the specimen to produce the desired shear strain. During the test, axial and shear loads and displacements are recorded to calculate the desired engineering parameters.

The tests were carried out in agreement with SHRP M-003 specification [7]. For the four different mixtures the influence of test frequency, temperature and load magnify was studied. Frequency sweep tests were carried out at 10, 5, 2, 1, 0.5, 0.2 and 0.1 Hz for each of the three specified test temperatures (4, 20 and 40 ºC) and two three levels were analised (100E-6, 200E-6 and 500E-6).

Before testing, the specimen is preconditioned by applying a sinusoidal horizontal shear strain of amplitude 100E-6 at a frequency of 10 Hz for 100 cycles. After preconditioning, a series of 7 tests are performed in descending order of frequency and in ascending order of strain level. To minimize damage of the specimen only 100 displacement cycles were applied for the first three frequencies, 55 cycles for the next two frequencies and 10 cycles for the last two frequencies. Prior to testing, the specimen was placed in the oven for two hours to achieve the test temperature.

4.3 Data analysis

For each test the recorded shear load and displacement were used to compute the shear complex modulus and the shear phase angle as function of frequency, temperature and strain level.
For the mixture with 4% air-void content and 5.5% bitumen content, a trace of the influence of frequency, temperature and strain level on shear complex modulus and phase angle is presented in figure 4.1 and figure 4.2, respectively.
The shear complex modulus shows a nearly linear variation in a log-log scale. This not happen only for the 40°C test temperature. At this temperature the increase of frequency increase the variation of the shear complex modulus. The strain level, as shown in figure 4.1, has a no constant behaviour in the shear complex modulus. Only at 4°C test temperature a clearly influence of strain level in the shear complex modulus is observed. With the increase of test temperature the behaviour of the 100E-6 and 200E-6 strain level on the shear complex modulus is almost equal.
The shear phase angle which the trace is shown in figure 4.2 present a behaviour highly dependent of test temperature. For each test temperature, the configuration of the curve shear phase angle versus frequency is completely different. At 4°C test temperature the shear phase angle increase with the strain level and decrease with the frequency. At 20 and 40°C the shear phase angle for the high strain level is lesser than at the other strain levels. It must also be noted that for 40°C test temperature the shear phase angle increase with the frequency.

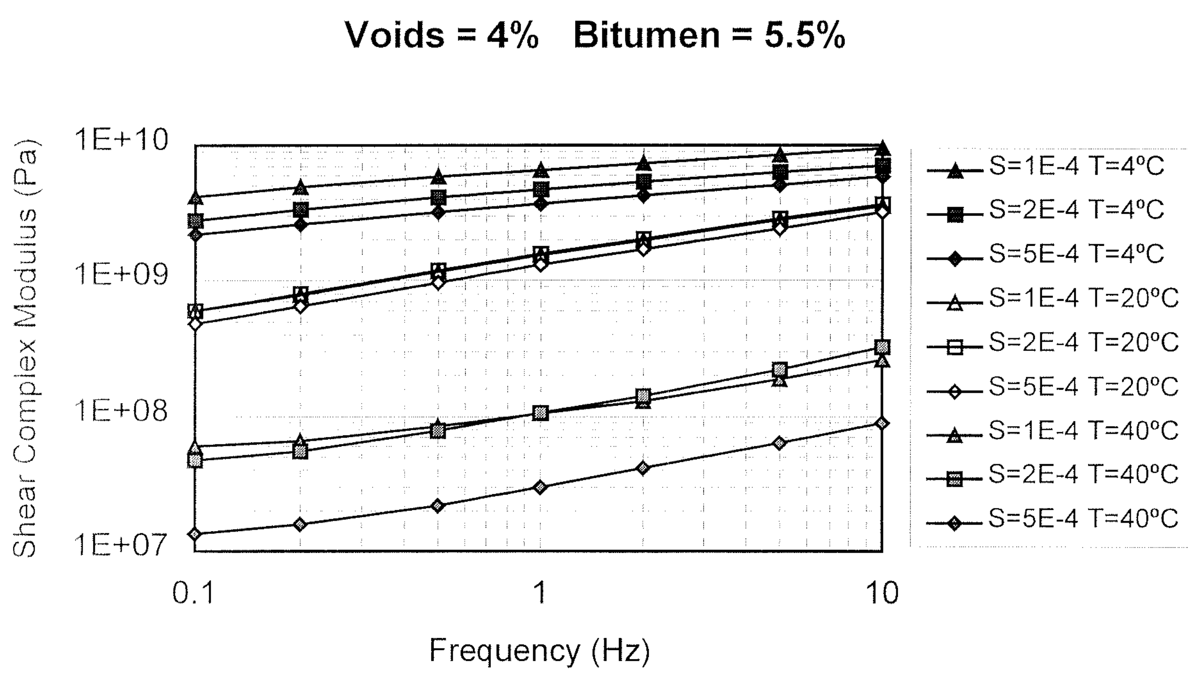

Figure 4.1. Shear complex modulus as function of frequency, temperature and strain level

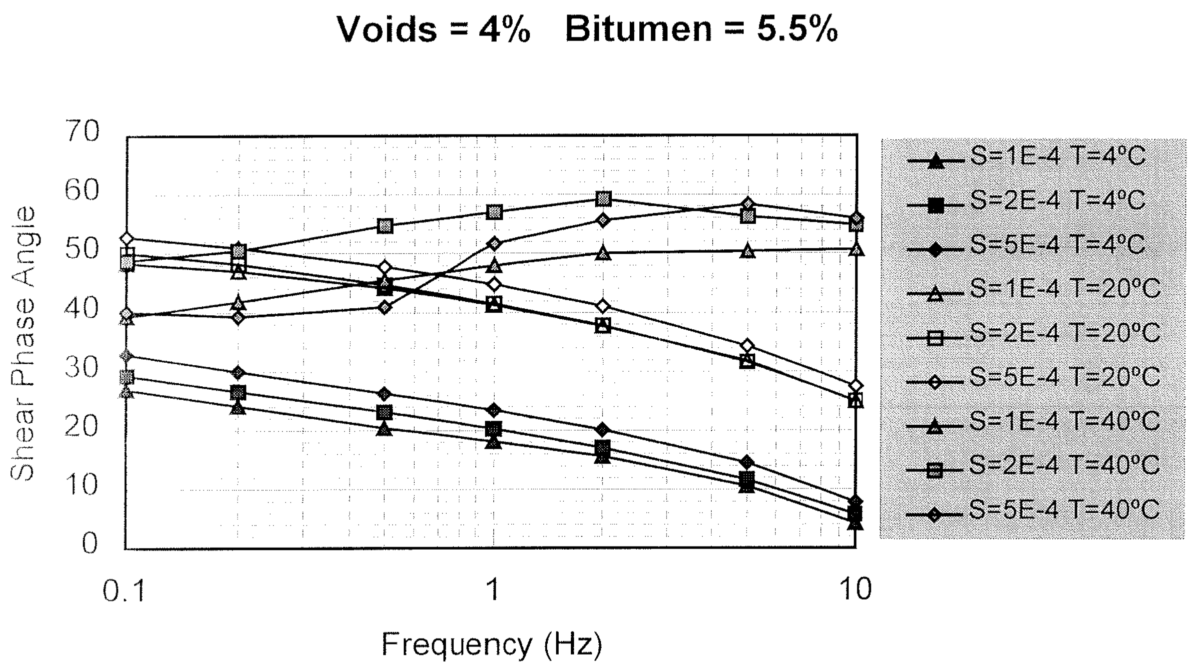

Figure 4.2. Shear phase angle as function of frequency, temperature and strain level

4.4 Influence of void and bitumen contents on shear quantities

The last three mixtures of this study were used to find the influence of the air-void and bitumen content on shear complex modulus and shear phase angle for 10 Hz test frequency.

Figure 4.3 present the influence of the air-void content on shear complex modulus and it must be noted the decrease of the shear complex modulus with the void content. At 40°C test temperature the void content don't have influence on the shear complex modulus.

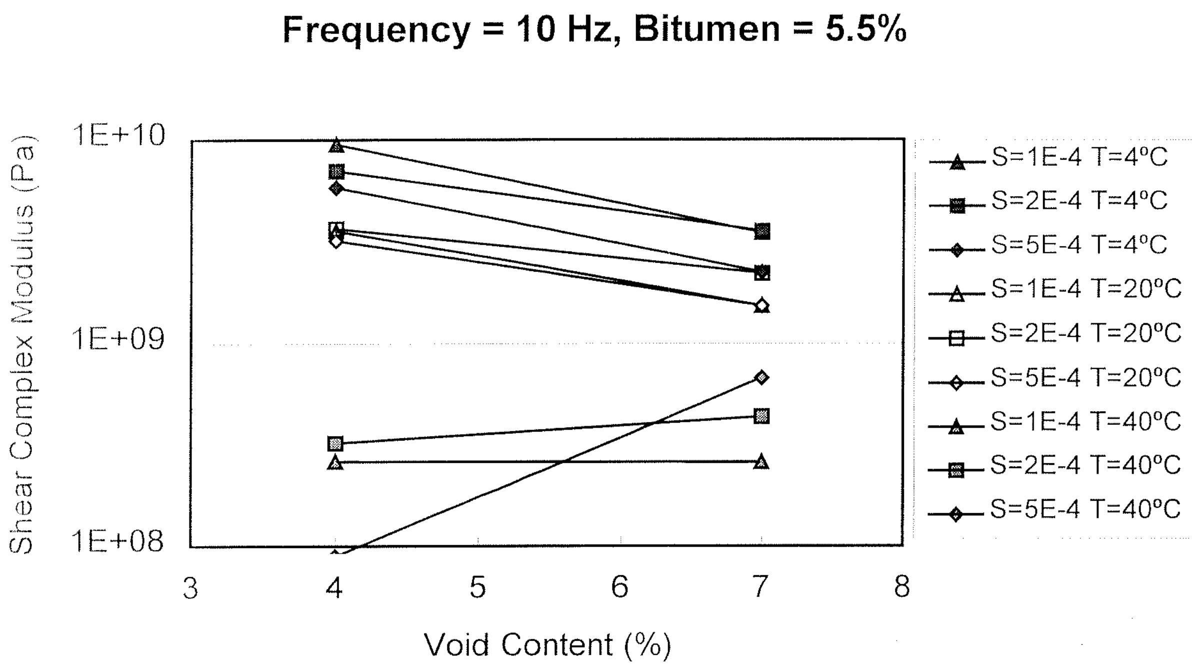

Figure 4.3. Influence of void content on shear complex modulus

Figure 4.4 shows the influence of void content on shear phase angle and it can be concluded the decrease of the visco-elastic behavior with the void content. The shear phase angle for 7% air-void content is lesser than 30% of the phase angle of 4% air-void content. The strain level has no influence on the phase angle at 7% air-void content.

As shown in figure 4.5 the shear complex modulus increase with the bitumen content up to the optimum bitumen content (given by Marshall test) and after decrease with the bitumen content. The influence of the strain level is noted only at high test temperature but the figure shows the little increase of the shear complex modulus with the strain level.

The trace of the influence of bitumen content on the shear phase angle has the same behavior of the shear complex modulus as shown in figure 4.6.

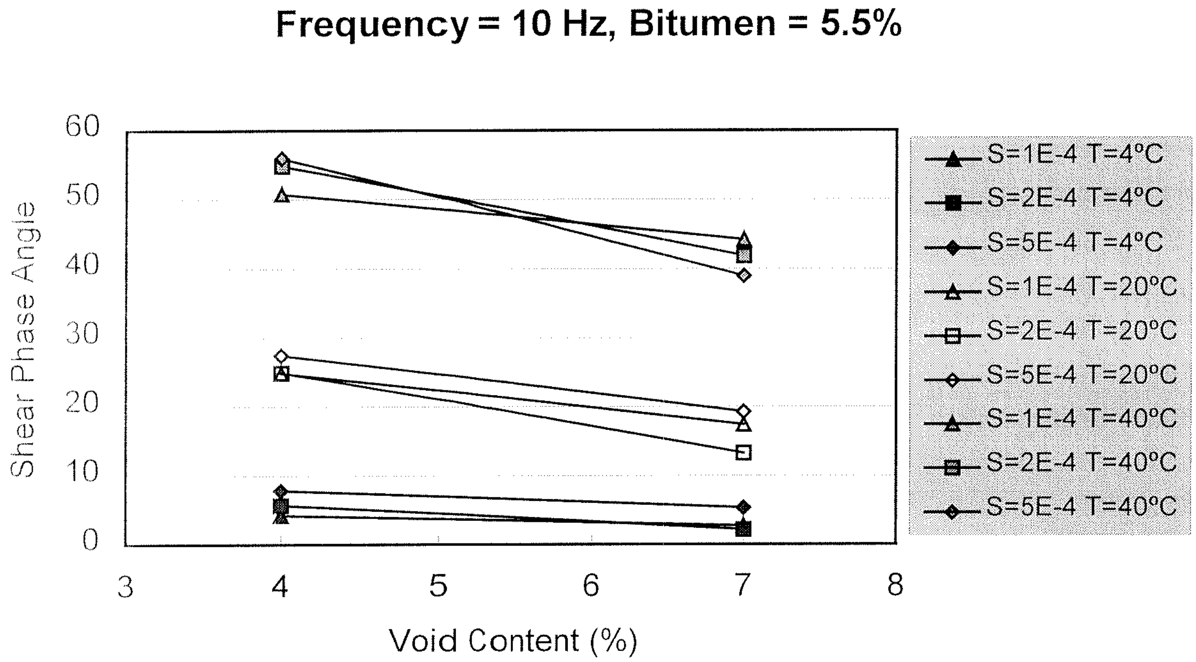

Figure 4.4. Influence of void content on shear phase angle

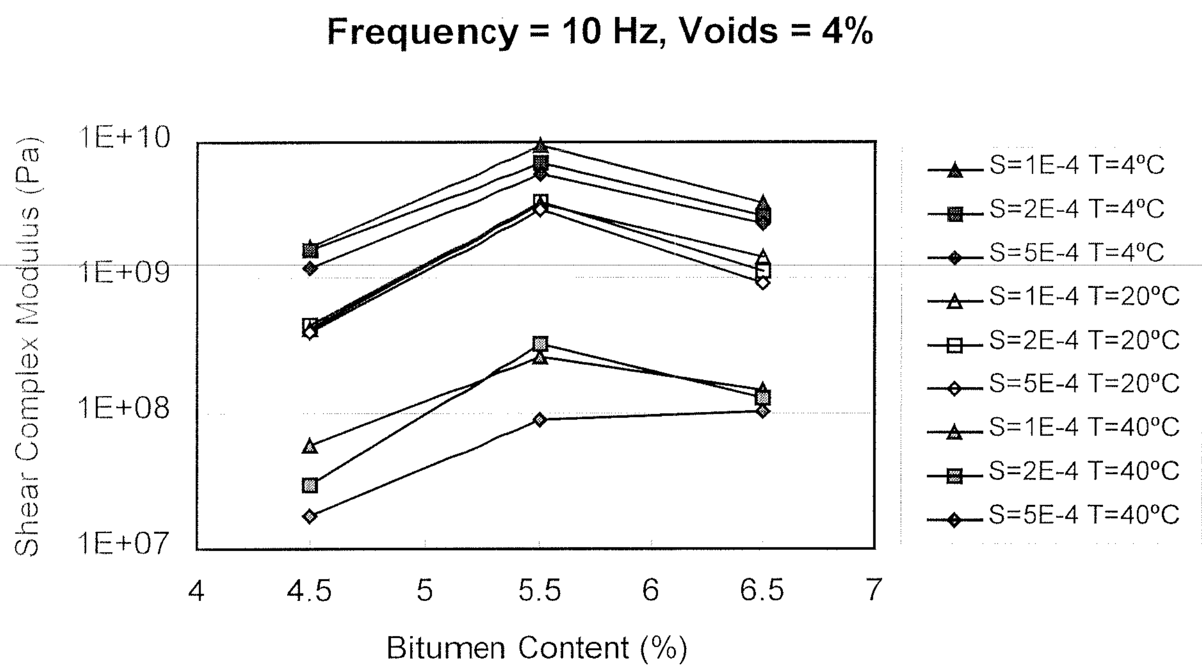

Figure 4.5. Influence of bitumen content on shear complex modulus

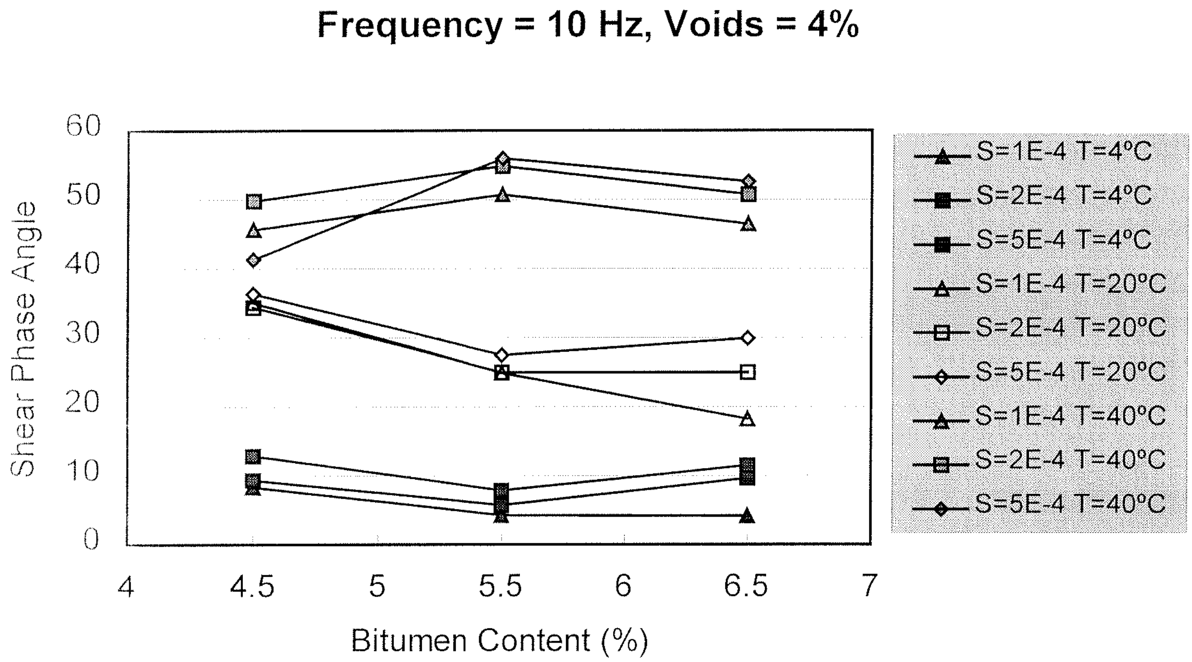

Figure 4.6. Influence of bitumen content on shear phase angle

5 Conclusions

This paper presented the results of shear tests made with four different bituminous mixtures. With these shear tests, the shear complex modulus and the shear phase angle was evaluated and a comparison was made between shear properties and test variables (frequency, temperature and strain level).
It was concluded that the test strain level does not have a great influence on shear properties. Air-void content decrease the shear properties and bitumen content different from the optimum produces the same effect on the shear properties.
The figure 4.5 shows that this laboratory test can be used in the design of bituminous mixtures. Such as other tests for the design of bituminous mixtures, this test can define a optimum bitumen content, but using mechanical variables (shear stiffness and shear phase angle), important in pavement analysis and design.
At this moment, the Road Pavement Laboratory of the University of Minho is conducting other tests with this methodology to evaluate the remain bituminous mixtures mechanical properties. The main goal of this laboratory is to produce a mixture design method for the Portuguese bituminous mixtures and define design criteria for permanent deformation.

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