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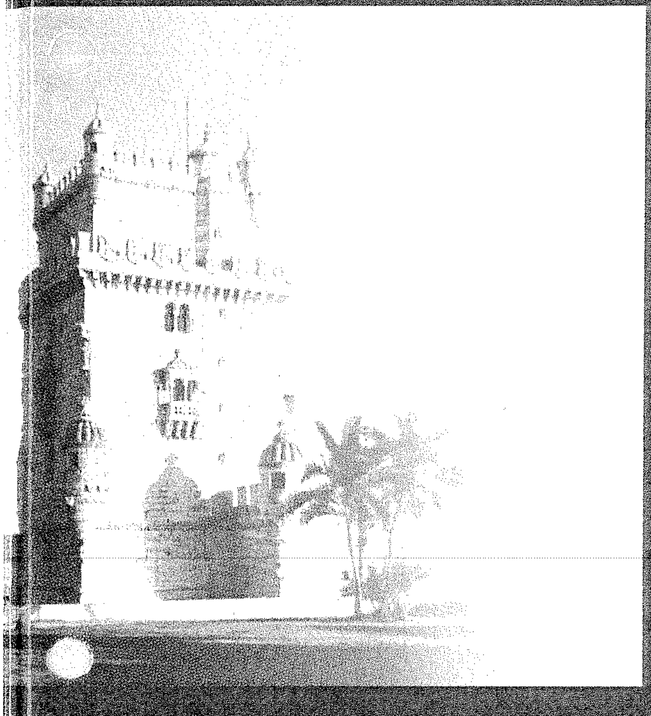

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The Influence of Fine Aggregate on the Bituminous Mixture Mechanical Behaviour

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ABSTRACT: This paper presents the results obtained during the implementation of a new laboratory tests to evaluate the asphalt-aggregate adhesion. Those tests performed on the mixture mastic, are based on tension and shearing properties of the mixture. The calibration and validation of those laboratory tests was made comparing the performance of mastic specimens with the fatigue and permanent deformation of corresponding mixtures. This paper presents the fatigue and permanent deformation results of bituminous mixtures used in wearing and base courses. For each type of mixture, five mixtures were defined, by changing the gradation curve (from more to less fine aggregates). All mixtures were produced and compacted in laboratory. Specimens for tests were obtained by cored and sawed from compacted slabs. For stiffness and fatigue, tests were executed on four point bending beam on controlled strain, whereas for permanent deformation tests were the repetitive simple shear test at constant height.

KEYWORDS: Stiffness modulus, phase angle, fatigue life, permanent deformation

1 INTRODUCTION

A new laboratory tests for the characterization of the coarse aggregate bond to the asphalt mastic is being developed at the University of Minho. Those tests evaluates the tensile and shear properties of the bond region of a bituminous mixture and correlates the results with tensile fatigue cracking and permanent deformation resistance of the whole bituminous mixture.

One of main objectives of that study is to understand in which way the mastic gradation influence the bituminous mixture properties evaluated using the new tension and shear laboratory tests.

Laboratory tests (tension and shear) on mastic specimens with and without course aggregates have been executed at the University of Minho to simulate the adhesion between the binder and the aggregate. For this study, mastic was defined as the material that is bond to course aggregate. A sieve analysis of the material bond to the different course aggregate was performed which allow to define some mastic gradations and binder content for each course aggregate size.

These mastics with different aggregate gradations and binder content were subjected to tension and shear tests to evaluate the adhesion between the bitumen and the aggregate.

Some important conclusions were obtained based only on those tests performed on mastic specimens.

So, to validate those conclusions, standard fatigue and permanent deformation tests were executed on bituminous mixtures with different aggregate gradations, correlated with the one used in the mastic specimens.

2 EXPERIMENT DESIGN

2.1 *Materials*

In this study two types of bituminous mixtures were used. A dense graded bituminous mixture for base courses and a bituminous mixture for wearing courses, following the Portuguese normalization. Based on each aggregate gradation, more four mixtures were defined. Two mixtures where the gradation curve is below and two mixtures where the gradation curve is above the gradation curve defined by the Portuguese normalization. These four gradation curves were defined changing the amount of aggregates in the sieves #20, #40, #80 and #200.

Thus, the gradation curve proposed by the Portuguese normalization for wearing courses was used to produce mix number 1 (more fines) to 5 (less fines), as presented in Table 1, and the gradation curve proposed by the Portuguese normalization for base courses was used to define mixes 6 (more fines) to 10 (less fines), as presented in Table 2. These gradation curves can also be observed in Figure 1 and Figure 2, respectively for wearing and base courses.

Table 1. Aggregate gradations used for wearing courses bituminous mixtures.

Sieve	Diameter (mm)	Percentage of material passing				
		Mix 1	Mix 2	Mix 3	Mix 4	Mix 5
3/4"	19,000	100.0	100.0	100.0	100.0	100.0
1/2"	12,500	84.0	84.0	84.0	84.0	84.0
3/8"	9,500	71.3	71.3	71.3	71.3	71.3
No. 4	4,750	55.4	55.4	55.4	55.4	55.4
No. 10	2,000	36.4	36.4	36.4	36.4	36.4
No. 20	0,850	30.6	29.7	23.7	24.7	22.4
No. 40	0,425	27.0	25.5	15.6	17.2	13.3
No. 80	0,180	15.7	14.0	10.5	9.3	7.1
No. 200	0,075	8.7	6.9	7.4	4.3	3.3
Rest		0.0	0.0	0.0	0.0	0.0

Table 2. Aggregate gradations used for base courses bituminous mixtures.

Sieve	Diameter (mm)	Percentage of material passing				
		Mix 6	Mix 7	Mix 8	Mix 9	Mix 10
1"	25,000	100.0	100.0	100.0	100.0	100.0
3/4"	19,000	96.2	96.2	96.2	96.2	96.2
1/2"	12,500	80.0	80.0	80.0	80.0	80.0
3/8"	9,500	72.5	72.5	72.5	72.5	72.5
No. 4	4,750	59.2	59.2	59.2	59.2	59.2
No. 10	2,000	42.9	42.9	42.9	42.9	42.9
No. 20	0,850	36.3	35.2	30.8	28.4	25.7
No. 40	0,425	32.3	30.4	23.1	19.1	14.5
No. 80	0,180	18.5	16.7	13.7	10.2	7.7
No. 200	0,075	9.8	8.1	7.9	4.6	3.5
Rest		0.0	0.0	0.0	0.0	0.0

For each mixture studied, the optimum binder content was calculated using the formula based on the specific surface of the aggregates developed by Duriez, M. (1950):

$$t_b = \alpha \times k \times \sqrt[5]{\Sigma} \tag{1}$$

where t_b = binder content; Σ = ratio between the bulk density of the aggregates and the; k = function of the binder content of the mixture and Σ = depends on the grading curve of the aggregates. Table 3 presents the binder content for each mixture, given in percentage of aggregate weight.

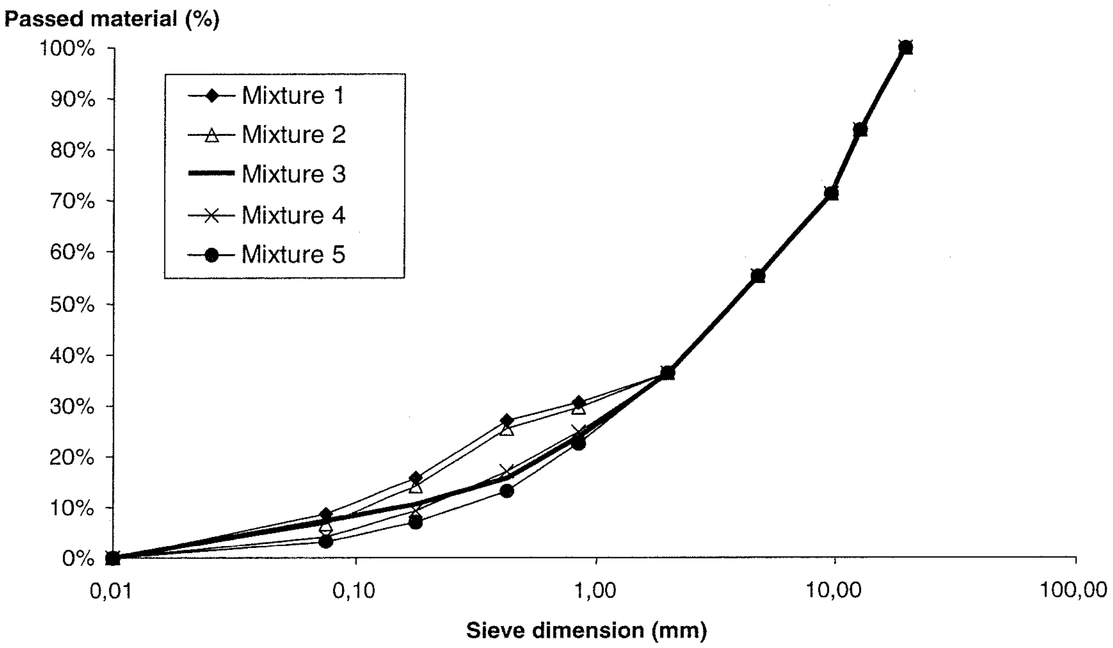

Figure 1. Aggregate gradation curve for wearing course bituminous mixtures.

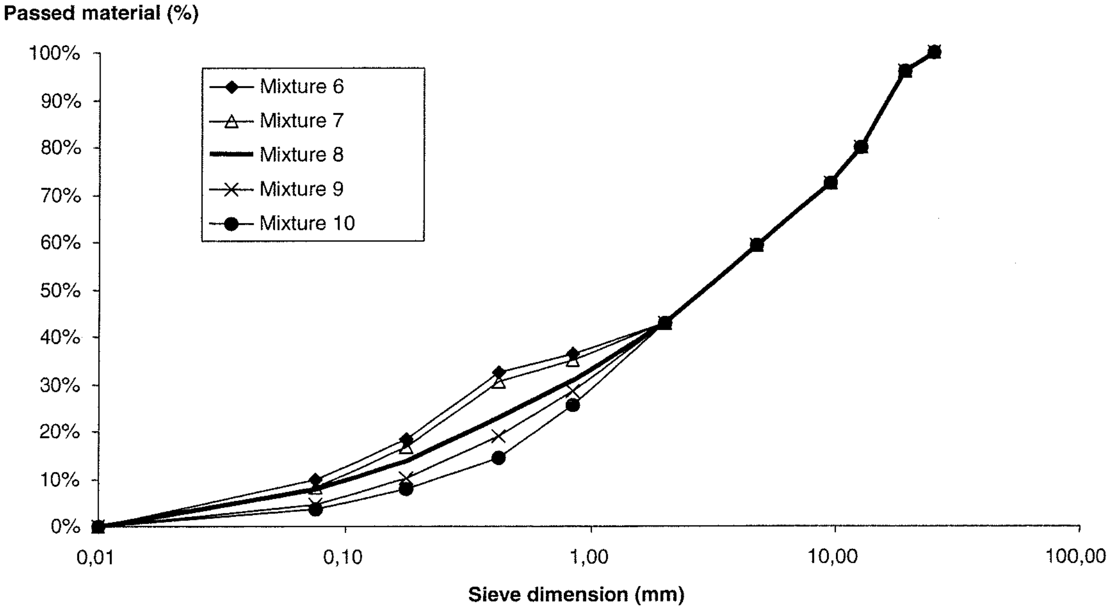

Figure 2. Aggregate gradation curve for base course bituminous mixtures.

Table 3. Binder content (in percentage of aggregate weight) for the mixtures used in this study.

Mix	Binder content (%)	Mix	Binder content (%)
1	6.0	6	6.0
2	5.8	7	5.8
3	5.8	8	5.8
4	5.4	9	5.3
5	5.2	10	5.1

Table 4. Air-void content for the mixtures used in this study.

Mix	Air-void content (%)	Mix	Air-void content (%)
1	1.3	6	4.9
2	2.9	7	7.4
3	1.2	8	4.0
4	5.0	9	6.6
5	7.7	10	10.8

2.2 *Specimen Preparation*

To produce the specimens, the bituminous mixtures were produced and compacted in laboratory. The aggregates were heated at 178°C and for the bitumen (PEN 50/70) the temperature was 150°C. After mixing, the mixtures were placed in an over at 135°C during 4 hours to be subjected to the conditioning recommended by SHRP-A003A (Tayebali et al. 1994). The compaction was made with a lightweight vibratory steel roller in a steel coated wood mold. The amount of mixture that was placed in the mold was always the same to control the air void content but in some mixtures, part of the mixture could not be fitted in the mold.

One day after compaction the slab was extracted from the mold and some days later the slab was sawed and cored to produce beams and cylindrical specimens used in fatigue tests and shear tests. The air-void content was measured in all specimens and the average for each mixture is presented in Table 4.

3 STIFFNESS MODULUS AND PHASE ANGLE

The bituminous mixtures exhibit linear-viscoelastic behavior as such that their response is time of loading and test temperature dependent. This behavior is represented by the following relationship:

$$S_{mix} = \frac{\sigma}{\varepsilon}(t, T) \tag{2}$$

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

The material stiffness measures the ability to spread the traffic loads over an area. This parameter represents an important rule in the design of pavements once the design strain level is a function of the material stiffness.

The stiffness modulus and the phase angle were measured using a frequency sweep test. All the frequency sweep tests of this study were executed at a strain level of 150 micros mm/mm, and at 10, 5, 2, 1, 0.5, 0.2 and 0.1 Hz.

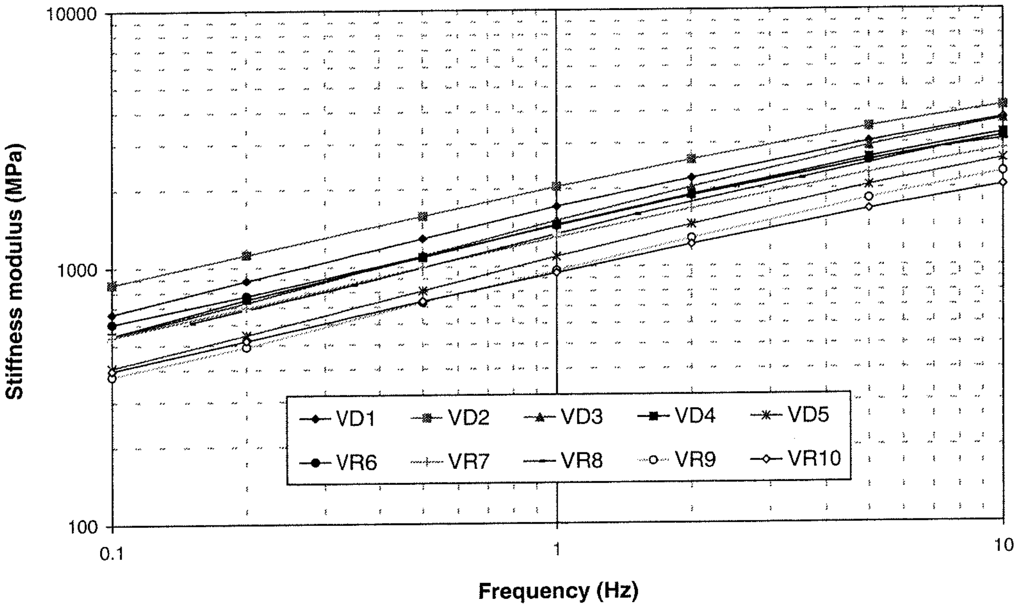

Figure 3. Stiffness modulus plotted against frequency.

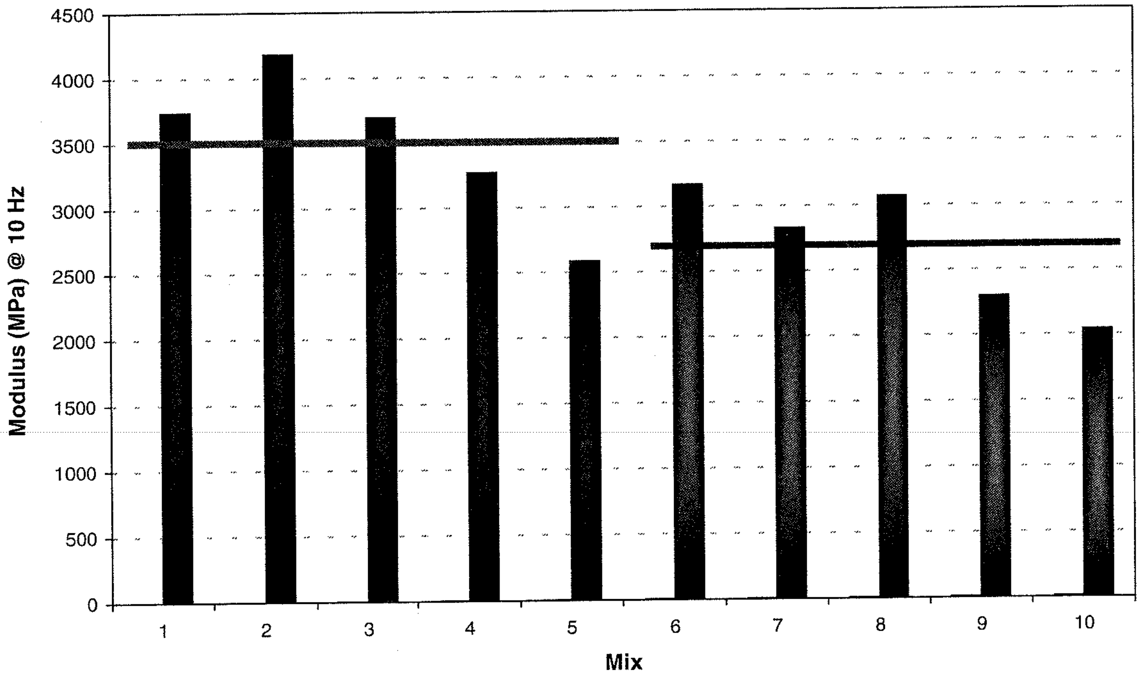

Figure 4. Stiffness modulus at 10 Hz.

Figure 3 presents stiffness modulus of all mixes as a function of applied frequency. As expected this relationship follows a linear trending when the logarithm phase angle is plotted against the logarithm of the stiffness modulus. In Figure 4 the stiffness modulus at 10 Hz is plotted to shows the ranking of studied mixes and it can be concluded that the increase of fines increases the stiffness modulus. The horizontal lines represent the average value for each type of mix.

Figure 5 presents the phase angle of all mixes as a function of applied frequency and in Figure 6 the phase angle at 10 Hz is plotted to shows the ranking of studied mixes and it can be concluded that the increase of fines decreases the phase angle. The horizontal lines represent the average value for each type of mix.

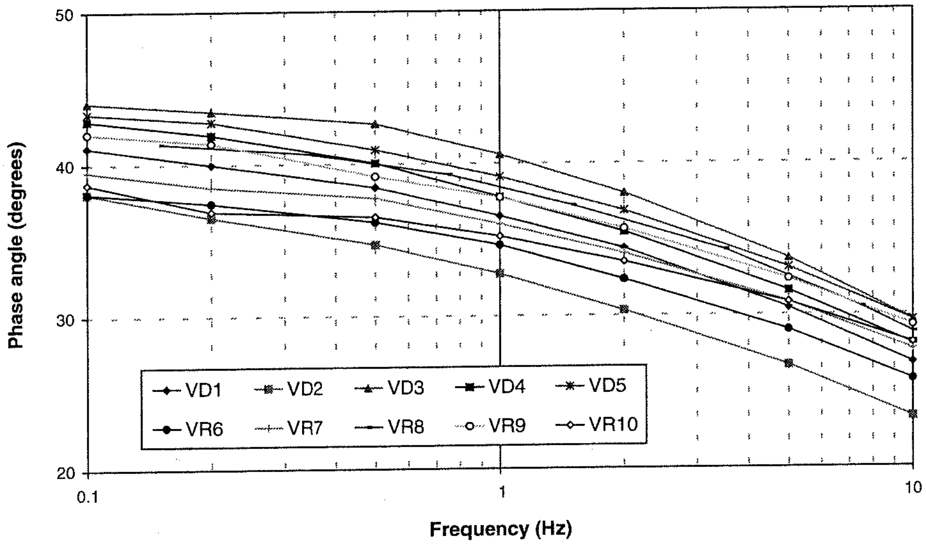

Figure 5. Phase angle plotted against frequency.

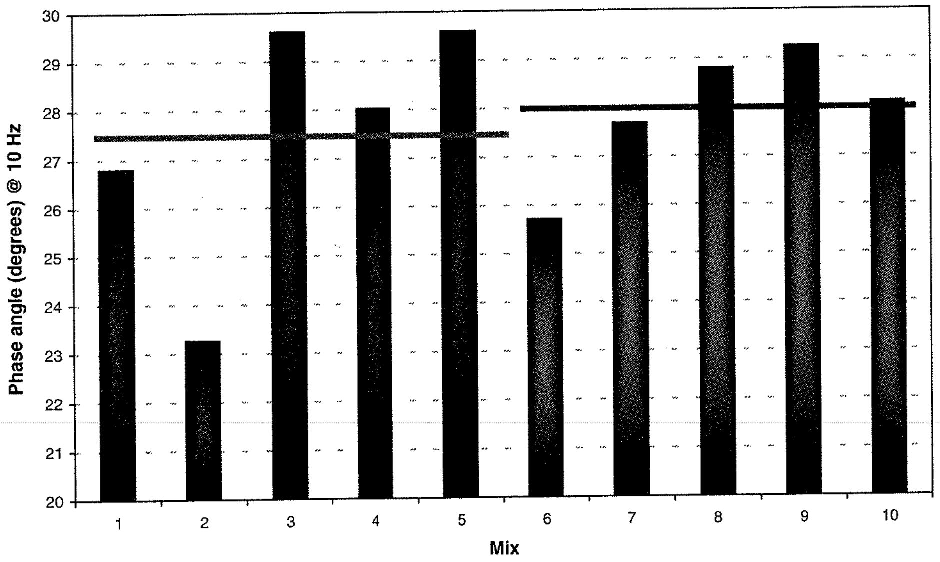

Figure 6. Phase angle at 10 Hz.

4 FATIGUE LIFE

One of the major modes of distress considered in the asphalt concrete pavement design is the fatigue cracking. When an asphalt pavement layer rests on an untreated aggregate base layer, the passage of a wheel load causes the pavement to deflect.

The resistance to fatigue of a bituminous mixture is the ability to withstand repeated bending load without failure. This form of distress manifests itself by the appearance of cracking in the pavement surface. The fatigue of a bituminous mixture has been directly associated with the repeated application of tensile stresses or strains and it is generally accepted that it can be very well evaluated by a four point bending test (Pais, 1999). Fatigue tests are performed imposing strain or stress repetitively until failure occurs. The fatigue life is characterized by the relationship between the strain level and the number of repetitions to reach the mixture failure.

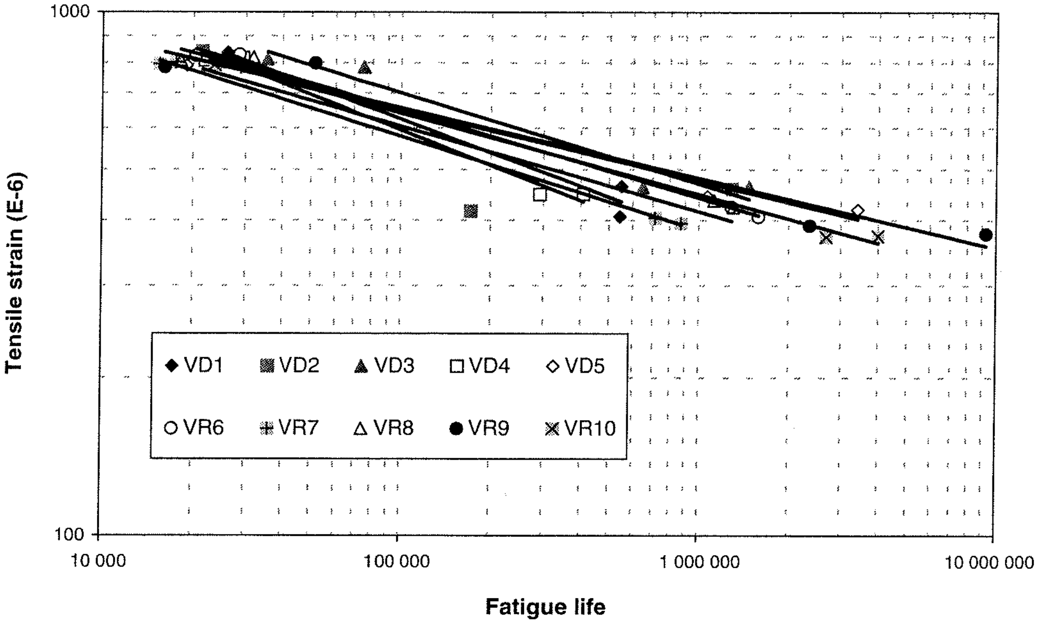

Figure 7. Fatigue curves for all mixes.

The mode of loading influences the mixture performance and controlled stress versus controlled strain is applied as a function of pavement structure (i.e., pavement thickness and stiffness). The repetitively applied loads usually follow a sinusoidal pattern although the traffic pavement response seems to be different.

The fatigue life of bituminous mixtures is influenced by several factors such as test temperature, frequency of applied loads. Aggregate gradation has an important effect on fatigue life as demonstrated by Sousa et al. (1998).

Fatigue cracking occurs gradually with cumulative straining of the pavement. The traditional approach based on a strain criterion has been used. However, the dissipated energy concept more accurately describes fatigue failure in dense graded bituminous mixtures.

A fatigue model has been established using a linear regression between fatigue life logarithm, log Nf, and the initial strain logarithm, log εt, for controlled strain tests. The fatigue model is as follows:

$$N = c\left(\frac{1}{\varepsilon_t}\right)^d \tag{3}$$

where N = the number of repetitions to failure, ε_t = the tensile strain applied, c and d = experimentally determined coefficients.

To evaluate the bituminous mixture fatigue resistance, flexural fatigue tests were conducted according to the AASHTO TP8-94 (Standard Test Method for Determining the Fatigue Life of Compacted Hot Mix Asphalt (HMA) Subjected to Repeated Flexural Bending). They are intended to simulate pavement distress due to traffic loads during its expected design life. Fatigue Life is defined as the number of cycles until a 50% decrease of the initial stiffness of the test beam is achieved. Tests were executed at 20°C and at 10 Hz frequency rate of loading. Four fatigue tests were performed for each mix, two at a strain level of 800×10^{-6} and to at 400×10^{-6}.

The fatigue curves of all tests are presented in Figure 7 where it can be observed the results of all fatigue tests. The ranking of these bituminous mixtures can be found in Figure 8 where the fatigue life at 100×10^{-6} is presented. The analysis of this figure shows that the decrease of fine aggregates increases the fatigue life.

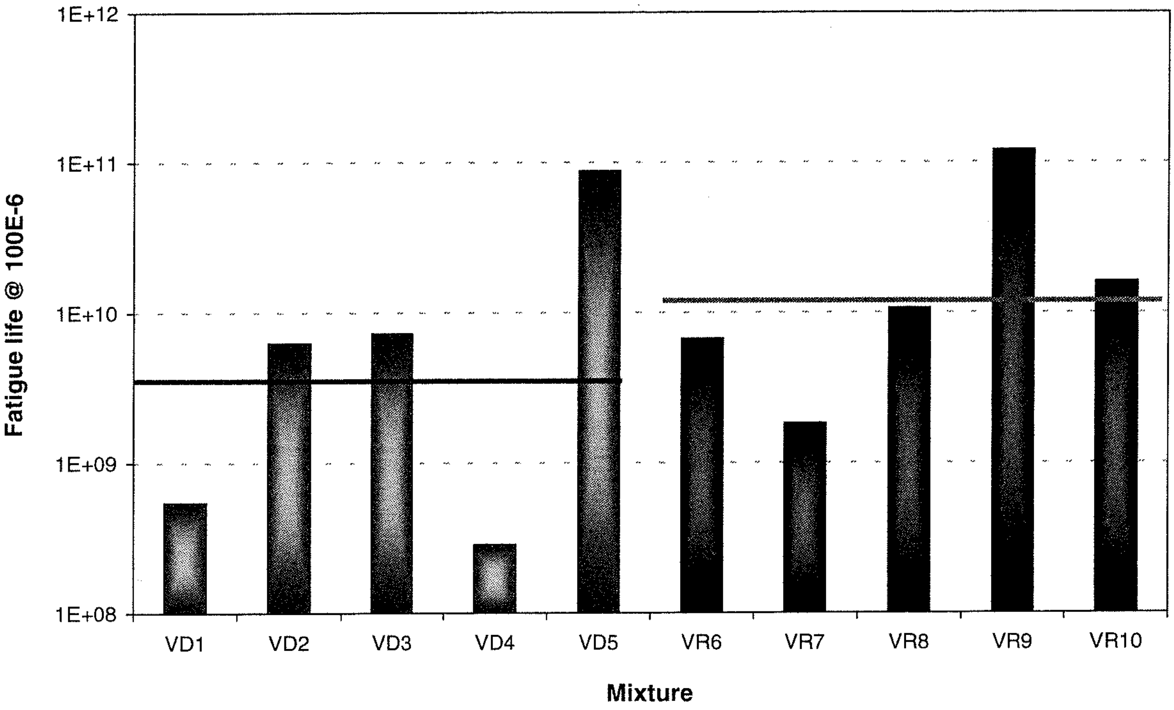

Figure 8. Fatigue life at a strain of 100 × 10^{-6}.

5 PERMANENT DEFORMATION

Permanent deformation in bituminous mixtures is primarily a plastic shear flow phenomenon at constant volume, occurring near the pavement surface, caused by the shear stresses occurring below the edge of the truck tires.

Also, intrinsically linked to this procedure is the assumption that most of the permanent deformation occurs on the hottest days with the heaviest trucks. This assumption stems from observations in the laboratory that bituminous mixtures exhibit strong plastic behavior described by a plasticity function that exhibits kinematics hardening. This hardening seems to be associated with the capability of the mixture to develop better particle-to-particle contact as it develops shear strains, and with the capability of the aggregate skeleton to develop dilatancy forces that in turn are capable of developing stabilizing confining stresses (Sousa, 1994).

This phenomenon appears to be best captured by the RSST-CH executed at the highest 7 day pavement temperature at 5 cm depth. One of the advantages of this test is that it does not cause any change in volume in the specimen during testing. This is particularly important because a mix's resistance to shear deformation should be measured with a test that does not cause any change in volume (densification or dilation) (Sousa, 1994).

The SHRP A-698 permanent deformation methodology to predict the accumulation of rut depth in asphalt concrete mixes was used and adapted, yielding the selection of adequate loading times, eventually to be used in the Repetitive Simple Shear Test at Constant Height for the prediction of rut depth.

RSST-CH testing was undertaken with 0.1 seconds loading times, plus a rest period of 0.6 seconds. For each bituminous mixture, 3 replicates were tested at 50°C. The magnitude of the loading pulse was set at 70 kPa. The test temperature was chosen to be representative of the maximum average seven day temperature at 5 cm depth.

A procedure to estimate the permanent deformation of asphalt concrete pavement based on the RSST-CH test was developed (Sousa et al, 1993). Figure 9 diagrams a nomograph of the procedure. It is composed of four quadrants and it should be followed clockwise starting in Quadrant 1.

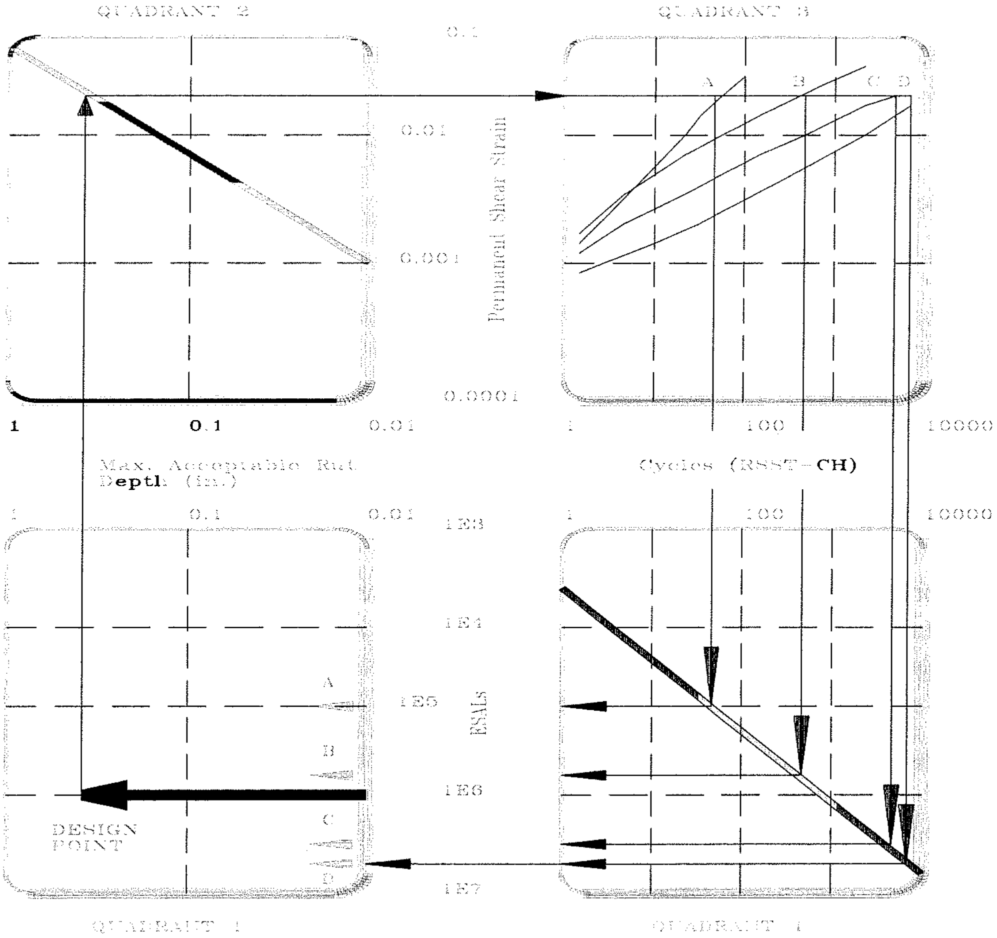

Figure 9. Nomograph procedure to estimate rutting performance.

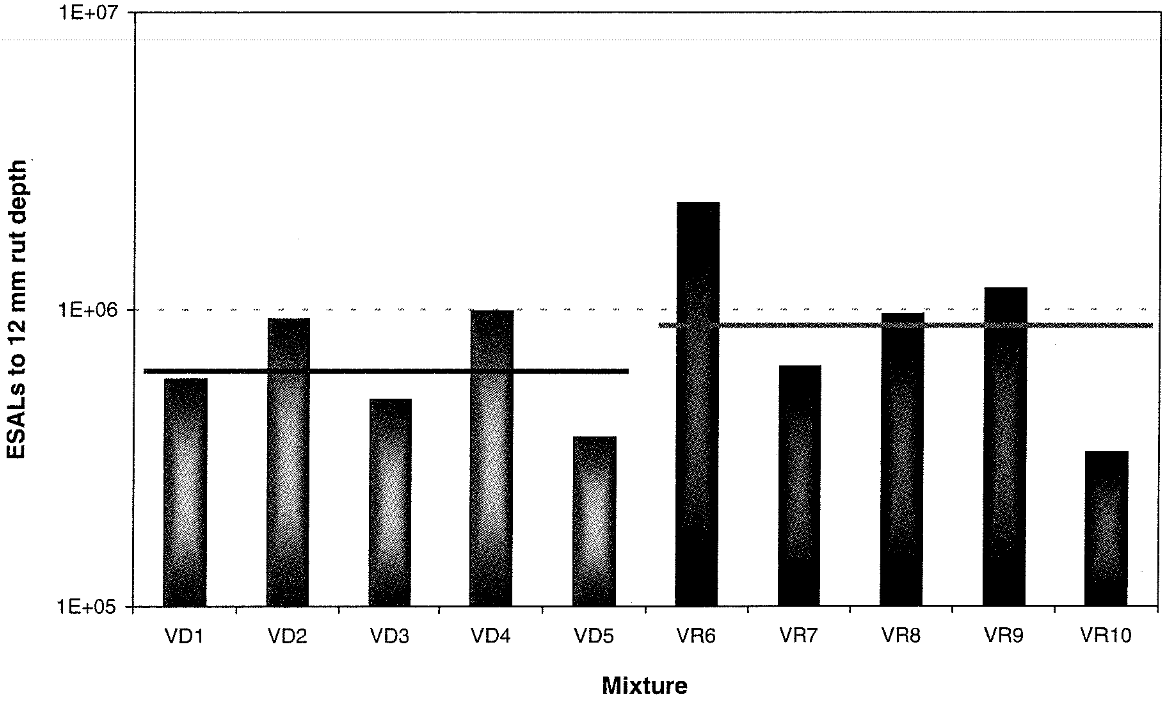

Figure 10. Permanent deformation test results.

The procedure to estimate the permanent deformation starts by defining the rut depth level to be considered. The permanent shear strain, which is used to obtain the number of cycles in the RSST-CH, is calculated as following:

$$\text{Rut depth (mm)} = 279 * \text{Permanent Shear Strain} \tag{4}$$

The number of ESALs is calculated using the following model:

$$\log(\text{\# of cycles}) = -4.36 + 1.24 \log(\text{\# of ESALs}) \tag{5}$$

The permanent deformation results for all bituminous mixtures, expressed in number of ESALs to reach 12.5 mm rut depth, are presented in Figure 10. It can be concluded that, in this case, the permanent deformation was influenced by the air-void content. The increase of the air-void-content increases the permanent deformation.

6 CONCLUSIONS

This paper presented a evaluation of the stiffness, fatigue and permanent deformation performance of bituminous mixtures with different aggregate gradation based on the gradation proposed by the Portuguese normalization for wearing course and base courses.

From this analysis, the following conclusions can be made:

- The increase of fine aggregates increases the stiffness modulus and decreases the phase angle;
- The decrease of fine aggregates increases the fatigue life;
- The permanent deformation is influenced by the air-void content. The increase of the air-void-content increases the permanent deformation.

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