INFLUENCE OF THE MASTIC BINDER IN THE BITUMINOUS MIXTURES BEHAVIOUR

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ABSTRACT: The flexible road pavements are subjected to the repetitive traffic loading, which, among others factors, originate their natural or premature degradation. The bituminous mixtures behaviour must be evaluated using repetitive loading tests that allow the study of their fundamental properties (i.e. fatigue, permanent deformations, and stiffness modulus) when subjected to the loading conditions which occur in the pavement. The behaviour of the bituminous mixtures is strongly influenced by the mastic properties and thus the objective of this work is to study the influence of the mastic characteristics in the bituminous mixtures behaviour. This behaviour was analysed by the evaluation of the complex modulus and fatigue life using repetitive bending at four points and the permanent deformation evaluated using repetitive simple shear tests at constant height (load control). In this work the mastic was defined as the material (filler, fine aggregate and bitumen) which is bonded to the coarse aggregates in a bituminous mixture.

KEY WORDS: Bituminous mixtures, mastic, complex modulus, fatigue, permanent deformation

1. INTRODUCTION

During the last decades the performance of flexible pavements has been improved as a request for the ever-increasing aggressive traffic , not only due the increase of loads per axel, but also the configuration of axels and wheels.

In order to improve the pavements performance, it is necessary to ensure an adequate behaviour of the bituminous mixtures, which depends essentially on their composition. To study the composition of the bituminous mixtures, the use of mix design methods is required. Nowadays, the mix design methods are based on the use of mechanical tests which simulate the behaviour of the bituminous mixture in the pavement. Thus, it is possible to study the bituminous mixture composition which will optimise the behaviour required in service, among others: 1) Rutting resistance; 2) Fatigue cracking resistance; 3) Low temperature cracking resistance; 4) Adhesion; 5) Wearing resistance.

The behaviour of the bituminous mixtures is greatly influenced by the mastic binder, the material used to bond the coarse aggregates. In this work, and following the studies of the authors, the mastic is defined as the material with dimensions below 2 mm.

The objective of this work is to evaluate the bituminous mixture behaviour for different mastics using performance-related tests to evaluate the: 1) fatigue resistance; 2) rutting resistance; 3) stiffness modulus.

2. BITUMINOUS MIXTURES BEHAVIOUR

2.1 Tests to characterise the bituminous mixtures behaviour

The fundamental and the simulation tests should represent the stress and strain conditions applied to the bituminous mixtures, during the repetitive loading of traffic and under the effect of the climatic agents. Other factors, such as the resting and loading periods and the degree of compaction of the bituminous mixtures, should represent also the existing conditions of the pavement.

However, the conditions *in situ* are continuously changing. Thus, it is difficult to select the correct mode of loading to perform the mechanical tests to evaluate the bituminous mixtures behaviour. The state of stress and strain, applied to the bituminous mixtures, can only be represented through great simplifications. Whiteoak [1] refers that the repeated triaxial test is the one which can closely reproduce this complex tension condition, imposed on the pavement, but it cannot reproduce the reversion effect of the shear stress.

The existing conditions *in situ* are simplified, by considering only the critical conditions, in the performance of the bituminous mixtures and for the pavement. The following characteristics are usually evaluated to characterize the bituminous mixtures and pavement performance:

1) The fatigue cracking caused, essentially, by repetitive horizontal tensile stresses, which result from the pavement bending due to traffic;

2) The permanent deformations, caused by vertical compression, and from a plastic deformation, caused by sheer efforts, which occur in the extremities of the vehicle wheels.

The main performance characteristics required to the bituminous mixtures used in the flexible road pavements are: i) the stiffness modulus; ii) the fatigue cracking resistance; iii) the rutting resistance. The main tests used to evaluate these properties of the bituminous mixtures will be indicated below.

2.2 Stiffness modulus

In order to model and design a pavement, the bituminous mixtures are characterised by their stiffness modulus and Poisson coefficient. When attending to the visco-elastic behaviour of the bituminous mixtures, the knowledge of the phase angle is also important.

The stiffness of a bituminous mixture depends on the temperature and on the loading period, which is related to the speed of the vehicles. Thus, an elastic stiffness can be defined at low temperatures and short loading periods and a viscous stiffness can be defined at high temperatures and long loading periods.

The elastic stiffness, to which correspond the highest stiffness values, is used to characterise the bituminous mixture for design. The viscous stiffness of a bituminous mixture is fundamental to predict the permanent deformation. The elastic stiffness of a bituminous mixture is a function of the elastic stiffness of the bitumen and volumetric composition of the bituminous mixture. The knowledge of the bituminous mixtures stiffness is important in order to determine the pavement resistance and to analyse the pavement answer to the vehicles load.

The coefficient of Poisson is important to the structural analysis of a pavement. The value of the coefficient of Poisson varies between 0.35, for low temperatures, and 0.50, for high temperatures.

The behaviour of a bituminous mixture is visco-elastic and its mechanical properties are dependent on the temperature and loading period. The evaluation of this behaviour is done by the application of a sinusoidal loading, such as:

$$s = s_0 \cdot \sin\left(w \cdot t\right) \tag{1}$$

The answer of the material to the applied load causes a deformation, which follows the Equation 2.

$$e = e_0 \cdot \sin\left(w \cdot t - j\right) \qquad (2)$$

The quotient between the applied stress and the produced strain defines the complex modulus of the bituminous mixture, according to Equation 3:

$$E^* = \frac{s_0}{e_0} \cdot \left(\cos j + i \cdot \sin j\right) = \left|E^*\right| \cdot \left(\cos j + i \cdot \sin j\right) \qquad (3)$$

The complex modulus can also be presented by its value in modulus $|E^*|$ and by its angle of phase f , respectively, according to Equations 4 e 5.

$$\left|E^*\right| = \sqrt{E_1^{\,2} + E_2^{\,2}} \qquad (4)$$

$$j = \arctan\left(\frac{E_2}{E_1}\right) \qquad (5)$$

This is the most frequent form to present the mechanical properties of a bituminous mixture, considering a temperature and a frequency of load application.

The determination of the stiffness modulus is done using repeated tests, usually used also to determine the fatigue characteristics or the permanent deformations of the bituminous mixtures. The complex modulus can be determined, by the following tests:

- Tensile and compression uniaxial tests (with or without confinement) (E*);
- Shear test at constant height (G*);
- Bending test in 2, 3 or 4 points (E*);
- Indirect tensile test (E*).

Tayebali et al. [2] performed bending, axial and indirect tensile tests to evaluate the bituminous mixtures stiffness. They concluded that the stiffness obtained with indirect tensile tests assumes superior values, when compared to the stiffness obtained with flexural and axial tests.

2.3 Fatigue resistance

The failure of a bituminous mixture caused by fatigue consists in the presence of cracking under the action of repeated loads. The maximum value of the stress installed in each load application is inferior to the stress that causes the failure of the bituminous mixture in only one loading cycle. This sort of failure manifests itself, in an advanced state of degradation, by the appearing of “alligator” cracking.

The evaluation of the fatigue life of a bituminous mixture, needed to design pavements, should be done by using mechanical tests, which should reproduce the *in situ* conditions.

The pavements are submitted to a state of repeated stress, caused by the application of the vehicles loads, which produces the bituminous mixtures fatigue. To characterize the fatigue resistance of a bituminous mixture, it is necessary to evaluate that behaviour under a state of stress similar to the one found *in situ*. There are several methods to determine the fatigue resistance, which simulate the conditions *in situ*. These methods involve a variety of test techniques, types of equipments, configuration, type and loading modes, test conditions and analysis procedures.

Concerning the fatigue tests, most existing results were obtained in simple bending tests. In these tests the stresses or stains are applied repeatedly to the specimen until the failure, or until the specimen shows modifications in its characteristics, which make the bituminous mixture inadequate. The results of these tests can be expressed by the Equation 6, proposed by Monismith et al. [3]:

$$N_f = a\left(\frac{1}{e}\right)^b \cdot \left(\frac{1}{E}\right)^c \quad (6)$$

where:
e = applied strain;
a, b, c = statistical coefficients;
N_f = number of load applications that produce the specimen failure;
E = stiffness modulus.

The laboratory fatigue study should consider several test hypotheses, which are referred by Tayebali et al. [2]. These hypotheses usually describe the fatigue behaviour of the bituminous mixtures tested in the laboratory and they are also used in the analytical models of pavement design. The fatigue tests should be done without permanent deformation accumulation. Although this phenomenon occurs in the bituminous mixtures, simultaneously with the fatigue cracking, it should be avoided during the tests because it avoid a correct results analysis.

The most used tests to evaluate the fatigue cracking resistance of the bituminous mixtures are the following ones (Azevedo [4]):

- Simple bending, in one of the following test configurations:
  1) Beams simply supported, loaded in a pulse or sinusoidal mode, with central loading in one or in two points;
  2) Trapezoidal or cylindrical beams in console, loaded in a sinusoidal mode in its free extremity;
- Simple tensile, loaded in a pulse or sinusoidal mode;
- Diametrical compression (indirect tensile), applying pulse compression loads on cylindrical specimens, in a diametrical direction;
- Fracture tests on specimens with an induced crack;
- Real scale tests on experimental parts of real road pavements submitted to controlled traffic.

In order to determine the fatigue life of the bituminous mixtures, several types of equipment, which accomplish different types of simple bending tests, were developed. Among these tests, the most used nowadays and the one which presents more advantages, when compared to other tests, consists of submitting simply supported beams to repeated loads, with central loading in two points. In that type of bending test the loads are applied to the specimen in four points, assuring the existence of a central zone of maximum constant moment without transverse efforts. The failure of the specimen always increases in this area of constant moment and that produces a smaller dispersion of results.

Usually, the criterion used to define the fatigue life of a bituminous mixture is the reduction of its stiffness modulus to half of its initial value. Thus, in the tests with imposed stress, the value of the strain will duplicate, while in the tests with imposed strain (used in the present work), the value of the stress will be reduced to half of its initial value.

2.4 Permanent deformation resistance

The permanent deformations of the bituminous mixtures gradually increase with the repetition of load applications, and they can be manifested by longitudinal depressions in the path wheels due the heavy vehicles, eventually with lateral elevations, especially in the case of high depth rutting.

When put in a pavement, and during the first years of service, a bituminous mixture is submitted to a process of reduction of its porosity (pos-compaction), until the value of 3% is reached. This phenomenon, which happens due to the heavy traffic loading, causes permanent deformations in the pavement and these can be evaluated by using mechanical creep and simple compression tests.

According to Sousa [5], after this initial densification, the permanent deformation of the bituminous mixtures occurs due to shear loads which happen closely to the surface of the pavement, in the area that confines the contact area between the tire and the pavement. These efforts increase without the occurrence of volume variations in the bituminous mixture and they are the main mechanisms of rutting development during the life period of the pavement.

The tests used to characterise the bituminous mixtures behaviour, concerning its resistance to permanent deformations, are the following ones:
- Simple compression tests, with static or repetitive loading;
- Triaxial compression tests, with static or repetitive loading;
- Shear tests, with static or repetitive loading;
- Wheel-tracking tests;
- Real scale tests on experimental parts of real road pavements submitted to controlled traffic.

Among several types of tests, the shear test can reproduce, with certain simplicity, the conditions which are present *in situ* and cause the permanent deformations. This test seems to be adequate to study permanent deformations, since rutting is caused mainly by plastic shear deformations (Sousa et al. [6]).

3. STUDY OF MIXTURES BEHAVIOUR USING REPETITIVE LOADING TESTS

3.1 Studied Bituminous Mixtures

In Table 1, eight bituminous mixtures evaluated in this work and their properties are presented. The composition of these mixtures was obtained through the Portuguese APORBET standards [7] for the bituminous mixtures usually used in the pavement wearing course. The aggregate gradation of these mixtures, above sieve #10, is identical. The only variation presented in the gradation curve is defined in the fines aggregates, defining in this study the mastic gradation.

Table 1. Bituminous mixtures studied in this work and their properties

Type of mixture	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7	Mix 8
Grading curve								
Passed #3/4”	100.0 %	100.0 %	100.0 %	100.0 %	100.0 %	100.0 %	100.0 %	100.0 %
Passed #1/2”	83.7 %	83.7 %	83.7 %	83.7 %	83.7 %	83.7 %	83.7 %	83.7 %
Passed #3/8”	71.2 %	71.2 %	71.2 %	71.2 %	71.2 %	71.2 %	71.2 %	71.2 %
Passed #4	47.8 %	47.8 %	47.8 %	47.8 %	47.8 %	47.8 %	47.8 %	47.8 %
Passed #10	32.5 %	32.5 %	32.5 %	32.5 %	32.5 %	32.5 %	32.5 %	32.5 %
Passed #20	24.0 %	24.0 %	24.0 %	24.0 %	24.0 %	27.0 %	17.0 %	24.0 %
Passed #40	16.9 %	16.9 %	16.9 %	16.9 %	16.9 %	22.4 %	8.5 %	16.9 %
Passed #80	9.4 %	9.4 %	9.4 %	9.4 %	9.4 %	13.3 %	4.9 %	9.4 %
Passed #200	5.3 %	5.3 %	5.3 %	5.3 %	5.3 %	7.6 %	3.0 %	5.3 %
Binder content	Medium 5.2 %	Inferior 4.4 %	Superior 5.9 %	Medium 5.2 %	Medium 5.2 %	Medium 6.5 %	Medium 3.2 %	Medium 5.2 %
Bitumen type	35/50	35/50	35/50	50/70	35/50	35/50	35/50	35/50
Filler type	Limestone	Limestone	Limestone	Limestone	Granite	Limestone	Limestone	Limestone
Initial aging	No	No	No	No	No	No	No	Yes
Study objective	Base composition	Binder content superior	Binder content inferior	Type of bitumen	Type of filler	Fine mastic	Coarse mastic	Aging

The Marshall mix design method was used to obtain the optimum binder content of 5.2%. The base composition, used in mix 1, is the normalised composition with the optimum binder content, by using the reference materials (a 35/50 bitumen and a calcareous filler).

Mix 2 and 3 are variations of mix 1, by using high and low binder contents. Mix 4 uses a 50/70 bitumen and mix 5 used a granite filler, instead of the reference material (limestone). The bituminous mixes 6 and 7 were obtained using a different grading curve of the material passed in the #10 sieve, respectively more fines and less fines. The composition of mix 8 is equal to mix 1, but it was submitted to previous conditioning to simulate the mixture aging during the first years of the pavement using the method recommended by Von Quintus et al. [8], and it involved the heating of the loose bituminous mixture, during a period of 24 hours, in a ventilated oven at a temperature of 135 ºC.

3.2 Repetitive Bending Test in Four Points (stiffness modulus and fatigue life)

The European norm EN 12697-26 [9] was followed to determine the stiffness modulus of a bituminous mixture, using the four points bending test. A sinusoidal loading was applied in strain control, at 100E-6. The bending tests were done at the temperatures of 5, 15 and 25 ºC and at the frequencies of 10, 5, 2, 1, 0.5, 0.2 and 0.1 Hz. In Figure 1, the specimen used in these tests is shown.

Figure 1. Beam specimen used in four points bending test

The variation of the stiffness modulus and the phase angle, function of the frequency, is presented in Figures 2 and 3, for the temperature of 15 ºC. In Table 2 the variation of the stiffness modulus and of the phase angle with the temperature, for the frequency of 10 Hz, is presented.

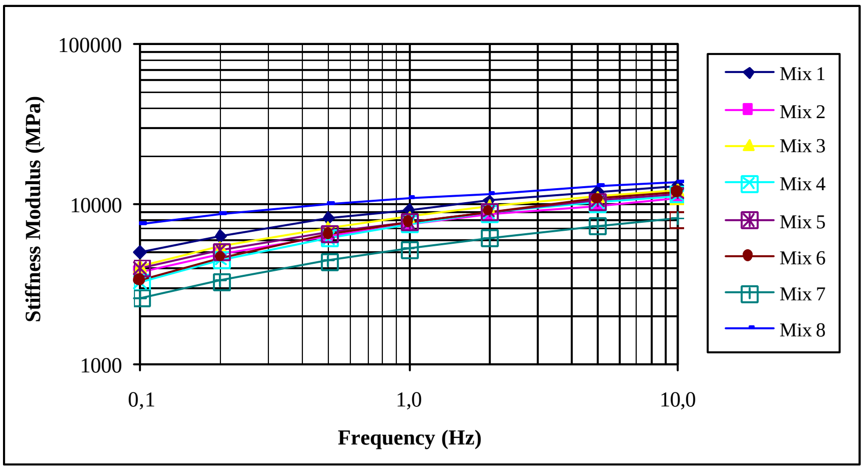

Figure 2. Stiffness modulus obtained in four points bending test at 15 ºC

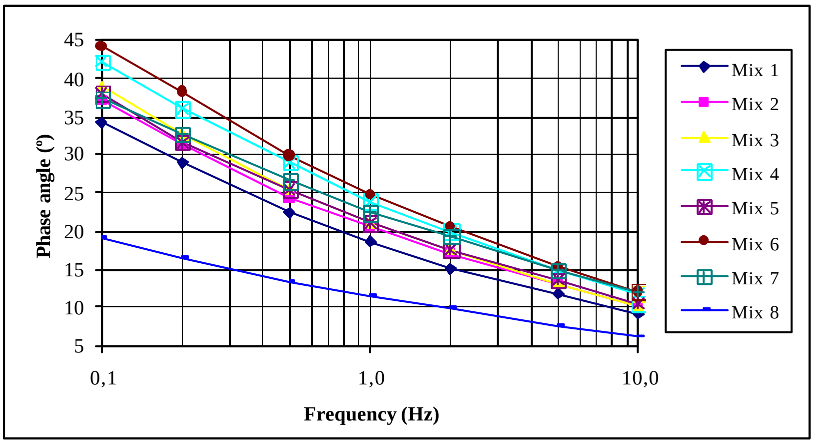

Figure 3. Phase angles obtained in four points bending test at 15 ºC

Table 2. Stiffness modulus and phase angles of the bituminous mixtures

	Temperature	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7	Mix 8
Stiffness Modulus (MPa)	5 ºC	16252	14011	15773	14706	13988	15453	11710	16863
	15 ºC	12966	10744	12224	11420	11553	12010	8045	13679
	25 ºC	7675	7341	6968	6537	6560	6243	4959	10162
Phase Angle (º)	5 ºC	4.0	4.2	4.4	5.4	4.2	4.6	4.5	2.7
	15 ºC	9.1	10.2	10.1	11.7	10.6	11.9	12.1	6.1
	25 ºC	21.9	22.1	25.1	26.9	24.3	28.8	23.4	12.4

The procedures used during the fatigue test were based on the European norm EN 12697-24 [10]. The repetitive four points bending test was used to determine the fatigue life of the bituminous mixtures. The specimen used in this type of test is presented in Figure 1.

The test configuration used in this work consisted in the application of a repetitive cyclical loading in controlled strain, at two strain levels: 300E-6 and 700E-6. Three repetitions for each strain level were done. Based on the number of cycles which cause the fatigue failure of the specimen, defined by the decrease of the stiffness modulus to half of its initial value, and by knowing the applied strain, it is possible to obtain series of points related to the fatigue behaviour of the bituminous mixtures. The best adjustment line for these points corresponds to the fatigue law of the bituminous mixture and it follows the following equation:

$$e_t = a \cdot N^b \qquad (7)$$

Where:
e_t = tensile strain;
N = number of cycles;
a, b = statistical constants.

Based on this law, it is possible to extrapolate the number of load applications that the bituminous mixture support until the fatigue failure, when it is subjected to a strain level of 100E-6 (N_{100}).

In Figure 4 the results obtained in the fatigue tests are presented as well as the fatigue laws for each mixture. The determination of the fatigue laws corresponds to the adjustment of a potency function to the results obtained in the tests. By using the fatigue laws, and by extrapolation, it is possible to determine the number of applications for an applied strain of 100E-6, which a bituminous mixture can support (N100), before the occurrence of failure by fatigue cracking. Based on this value, it is possible to distinguish the fatigue resistance of the different bituminous mixtures, as shown in Figure 5.

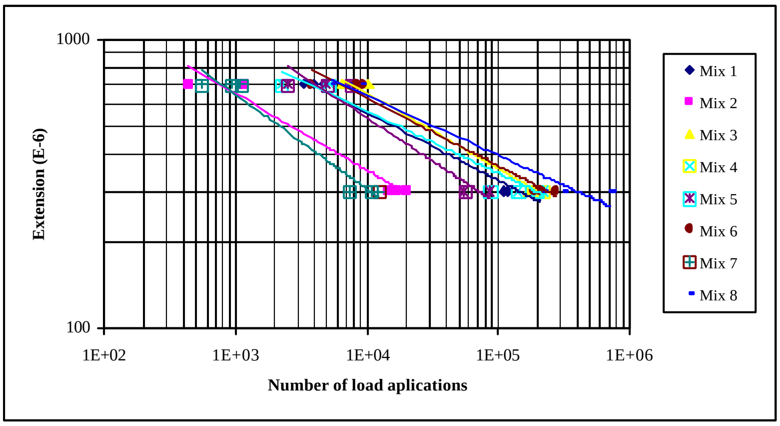

Figure 4. Fatigue laws obtained in four points bending test at 15 ºC

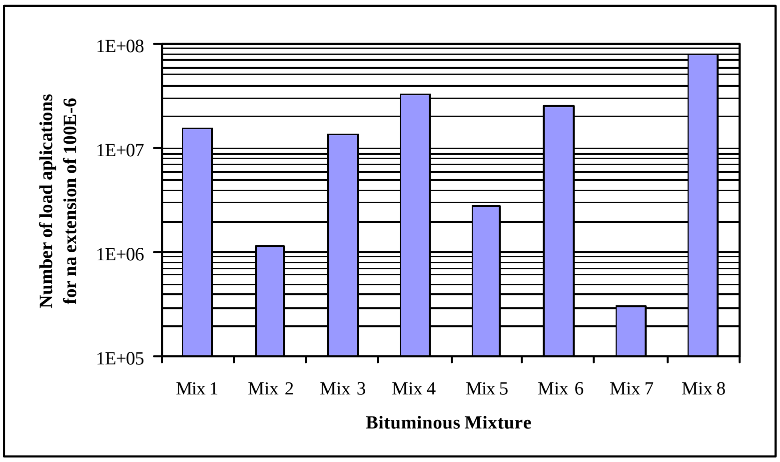

Figure 5. Number of load applications, untill the fatigue failure, for a tensile strain of 100E-6, at 15 ºC

3.3 Repetitive Simple Shear Test at Constant Height – RSST-CH

In order to obtain the permanent deformations resistance of the bituminous mixtures, the norm TP7-01 (ASSHTO [11]) was applied. The specimen type used in the tests is presented in Figure 6.

Figure 6. Cylindrical specimen used in the RSST-CH test

A repetitive loading was applied, with the suitable configuration (0.1 seconds of loading and 0.6 seconds of rest), in load control, for a tension value of 69±5 kPa. The tests were done at a temperature of 50 ºC. The specimen was maintained at constant height during the test. The result of this test consists in measuring the permanent shear deformation accumulated during the several load cycles. The knowledge of the evolution of the permanent deformations during the test, allows the prediction of the accumulated number of standard axes (NAEP) which will originate the permanent deformation, using he following equations:

$$\text{Rutting depth (mm)} = 280 \cdot \text{Maximum permanent shear extension} \quad (8)$$

$$\log(\text{number of cycles in the RSST-CH test}) = -4.36 + 1.24 \cdot \log(\text{NAEP}) \quad (9)$$

To estimate the NAEP, which causes a rutting, Expression 8 is used, initially, to know the maximum acceptable permanent shear strain in the RSST-CH test. After the test, it is possible to know the number of load applications, which caused the maximum acceptable permanent shear strain. By knowing that number of cycles in the RSST-CH test, it is possible to calculate the number of standard axes (NAEP), by using Expression 9.

The results of the repetitive simple shear test at constant height, for the different studied bituminous mixtures, are presented in Figure 7.

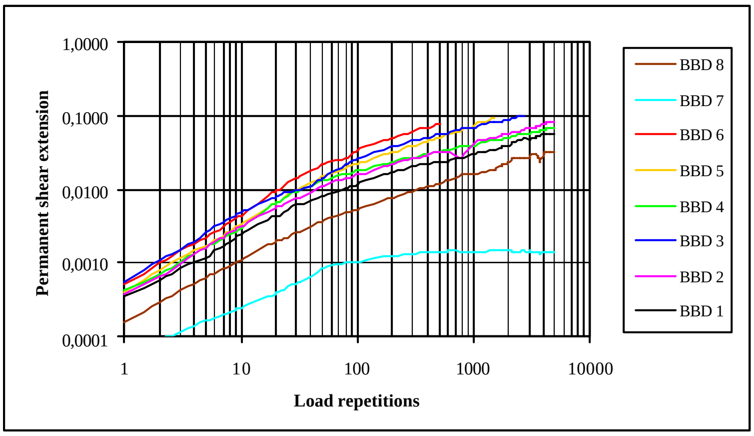

Figure 7. Permanent shear strain in the RSST-CH test at 50 ºC

In order to distinguish the different mixtures, according their permanent deformations resistance, Figure 8 presents the permanent deformation resistance of the studied mixtures.

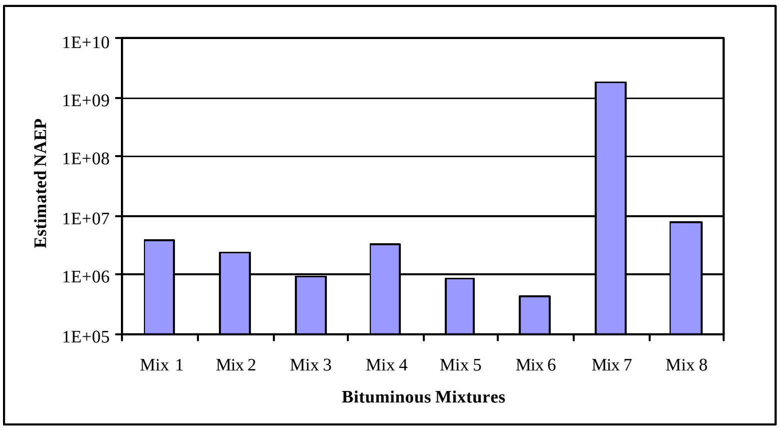

Figure 8. NAEP to produce a rut depth of 20 mm at 50 ºC

4. CONCLUSIONS

The stiffness modulus of the different bituminous mixtures produced with different type of mastic binder presents values greater than the usual for this type of mixtures due the void content obtained for these mixtures (below 2%).

Concerning the differences between the mixes, it was observed that the aged mixture (mix 8) was the one with higher modulus and lower phase angles, and the mixture with coarse mastic (mix 7) was the one with the worst results. The mixtures with higher binder contents have shown a high modulus at low temperature. The opposite occurs with the mixtures with low binder content.

The analysis of the results of the repetitive fatigue test demonstrated that the bituminous mixtures with smaller fatigue life were those with smaller binder content (mixes 7 and 2) and with granite filler (mix 5). On the other hand, the aged mixture (mix 8), the mixes with higher binder content (mixes 6 and 3) and the one with softer bitumen type (mix 4) were the ones that had the longest fatigue life.

Concerning the rutting, the bituminous mixtures with higher binder contents (mixes 3 and 6) and the ones which used granite filler (mix 5) had a minor rutting resistance. The bituminous mixture with a better resistance was the one which had a smaller amount of fines and bitumen (mix 7). However, this mixture presented disaggregating problems due to the reduced amount of mastic which bonded the coarser aggregates. Another bituminous mixture with a good performance concerning the rutting resistance is the aged mixture (mix8). This is easily understood because of the hardening of the bitumen during the aging.

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