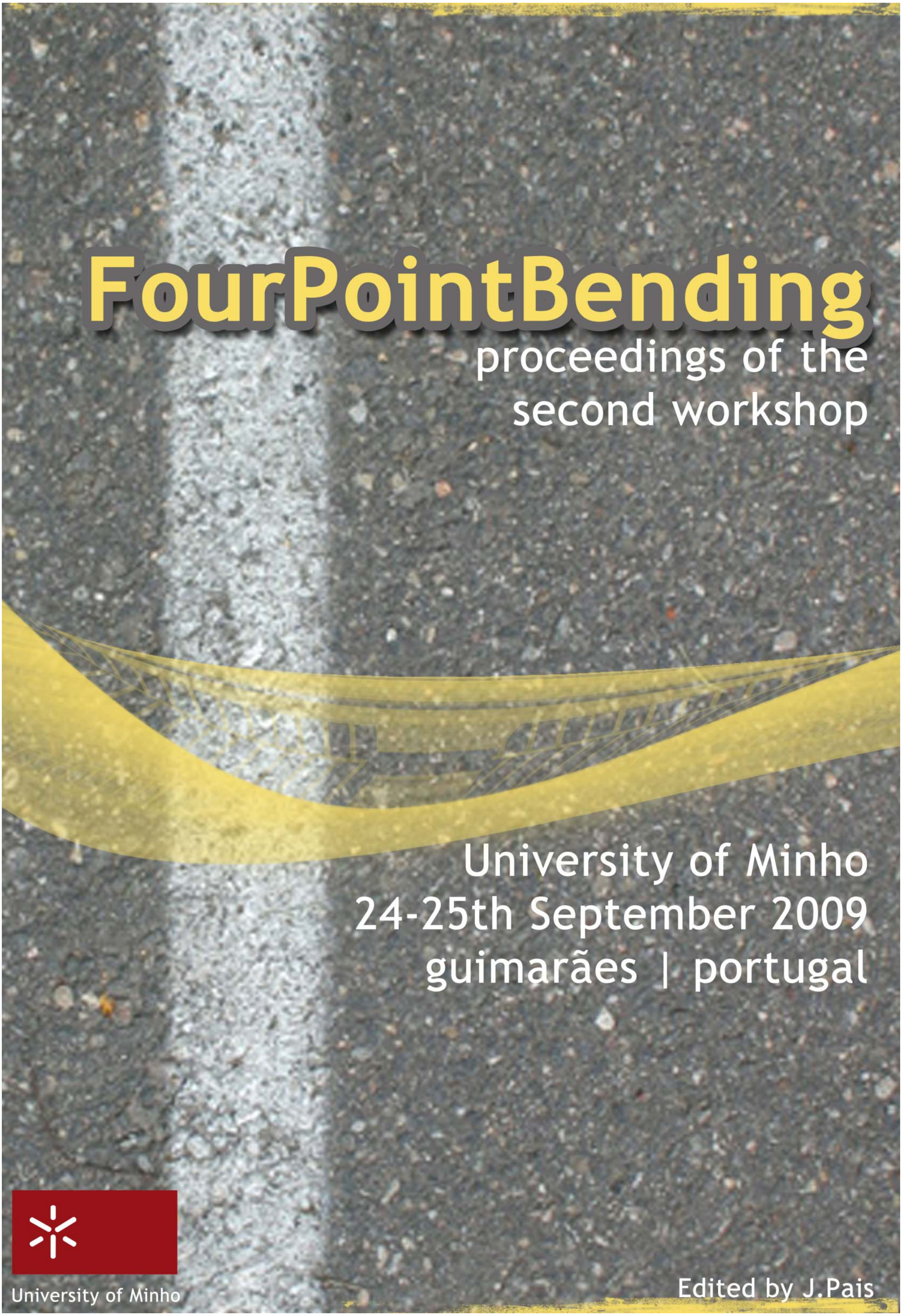

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Fatigue Laws for Brazilians Asphalt Rubber Mixtures Obtained in 4 Point Bending Tests

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ABSTRACT: The majority of Brazilian road pavements consists of thin pavement structures unable to resist the damage caused by heavy loads and an increasing traffic demand. The main structural distress modes found in Brazilians asphalt layers is fatigue cracking. One of the promising techniques to improve the pavement performance is through asphalt rubber mixtures, which make use of crumb rubber from scrap tires to modify and enhance the properties of the asphalt. The inexistence of fatigue laws for asphalt rubber mixtures to be applied in road design encouraged the study presented in this paper, aiming at the development of prediction models for fatigue and dynamic modulus from the results obtained in laboratory tests. Four mixtures (gap and dense graded) containing Brazilian terminal blend asphalt rubbers were assessed through four point bending tests to evaluate their fatigue and stiffness properties.

1 INTRODUCTION

The surface course of the highways in Brazil is generally constructed with dense graded hot mix asphalt prepared with conventional binder, in spite of the significant temperature variation throughout the year. Recent research conducted with the objective of analyzing the conditions of the Brazilian paved highways in relation to preservation aspects, safety and comfort to the users, revealed that 73,9% of the road pavements in relation to the total evaluated extension (87592 km) are either in regular or in bad condition (CNT, 2007).

In this context, the researchers' efforts in order to develop new materials and asphalt mixtures that may delay the main distress found, such as fatigue cracking, permanent deformation and crack propagation, and with this, to extend the service life of the Brazilian highways. Currently, one of the promising techniques under study is the incorporation of crumb rubber from waste tires into the asphalt, which is known as asphalt rubber.

Asphalt rubber mixtures have been used in the United States since the 1960's. In Brazil, the first applications of asphalt rubber mixtures in the surface courses began at the end of the 1990's.

Some beneficial effects from the addition of crumb rubber to asphalt include a decrease in the thermal susceptibility and permanent deformation as well as an enhanced resistance to fatigue and to low temperatures. There are also other benefits from the use of rubber from recycled scraps tires to build pavements (Caltrans, 2003; Baker *et al.*, 2003; Dantas Neto, 2004), which:

- reduces maintenance costs by extending the life of fatigued roads;
- allows reducing the overlays thickness by the half;
- reduces traffic noise;
- preserves natural resources as it uses old tires;
- improves skid resistance and drainage of road surfaces.

Blending methods through wet processes are in general divided into two main categories: continuous blend and terminal blend. The continuous blend is the most common method used to add crumb rubber to asphalt concrete and requires special equipment to blend crumb rubber with the asphalt prior to mixing it with the aggregate. The interaction process generally takes between 1 and 4 hours and it is facilitated by the mechanical action of a shaft (Visser & Verhaeghe, 2003).

The terminal blend process, which has been used in Texas since 1995, uses about half the amount of crumb rubber used in the wet process continuous blend.

Terminal blend asphalt rubber is produced by the digestion of rubber in asphalt rubber at high temperatures at an industrial plant (Takallou & Takallou, 2000). In Brazil, only asphalt rubber from terminal blend process is used and, in general, the percentage of crumb rubber varies between 15 to 20%.

The objective of this study is to evaluate laboratory fatigue laws for Brazilian asphalt rubber mixtures produced through the wet process, and develop a model to predict the fatigue life of asphalt rubber mixtures when applied in Brazilian pavements. A prediction model for the dynamic modulus was also developed from laboratory results in relation to stiffness.

In this study, two gradations were used (gap graded and dense graded) with different types of asphalt rubber (terminal blend with 15% and 20% of crumb rubber).

2 MATERIALS AND MIXTURES CHARACTERIZATION

2.1 *Rubber*

In this study, an ambient rubber was incorporated to a conventional asphalt (50/70 pen), at an industrial plant in Brazil, the result of which was a terminal blend asphalt rubber.

The rubber gradation, presented in Figure 1, was tested in accordance with the requirements of ASTM C136, amended Greenbook (2000) recommendations. The rubbers followed the ADOT (Arizona Department of Transportation) requirements Type B from ADOT Asphalt Rubber Specifications, Section 1009 (ADOT, 2005).

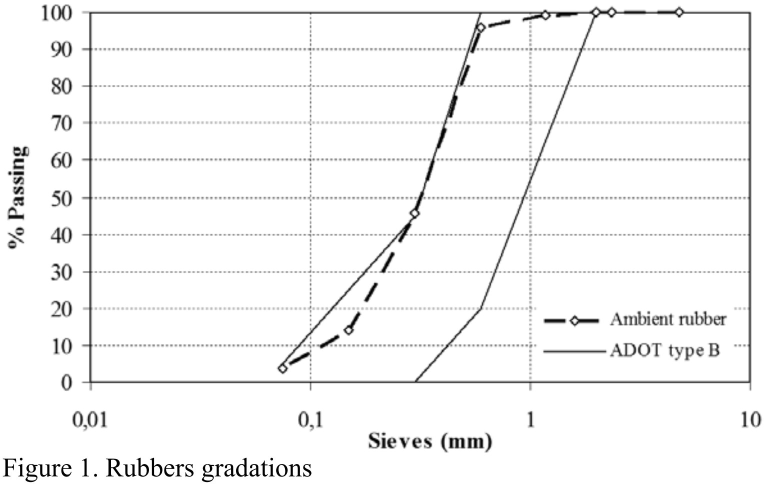

Figure 1. Rubbers gradations

2.2 *Asphalt rubbers*

The terminal blend asphalt rubbers were produced with two different rubbers content, 15% and 20%, and with a 50/70 pen asphalt, as presented in Table 1. Both the asphalt and rubber are from Brazil. The physical properties of the asphalt rubbers are presented in Table 2.

Table 1. Nomenclature of the asphalt rubbers

Type	Nomenclature	Asphalt base	Rubber type/content
Terminal blend	BB20	50/70 pen	Ambient (20%)
Terminal blend	BB15	50/70 pen	Ambient (15%)

Table 2. Physical properties of the asphalt rubbers

Test	Standard	BB20	BB15
Penetration (0,01 mm) *	ASTM D 5	40	42
Softening point (ºC)**	ASTM D 36	68,0	67,7
Apparent viscosity (cP)***	ASTM D 2196	2179	1644
Resilience (%)	ASTM D 5329	28	33

* 25 ºC, 100 g, 5 s; ** Ring and ball Method; *** Brookfield viscometer, spindle 27, 20 rpm.

The results presented in Table 2 show that asphalt rubbers present high viscosity due the addition of rubber into the conventional asphalt (50/70 pen). Also, the elevated softening point and resilience results could be an indicator that the asphalt rubber enhances the mechanical properties (high fatigue and permanent deformation resistance) of the mixtures produced with it.

2.3 *Aggregate and mixtures gradations*

The granite (100% crushed) aggregates used in this study are commonly used in asphalt concrete pavement constructions in Portugal. The characteristics of these aggregates are the same as the ones found in the South of Brazil. They include coarse aggregates (6/12 mm and 4/10 mm), fine aggregates (0/4 mm) and a mineral filler (limestone). The properties of aggregates are summarized in Tables 3 and 4 for coarse and fine aggregates, respectively. The aggregate laboratory tests confirmed that these aggregates have suitable properties to be used in pavement mixtures.

Table 3. Coarse aggregate properties

Test	Standard	Aggregate (mm)	Results
Particle shape (flat)	BS 812	6/12	23%
		4/10	17%
Particle shape (elongated)	BS 812	6/12	21%
		4/10	19%
Los Angeles	ASTM C 131	6/12	24%
Water absorption	NP 581	6/12	0,88%
		4/10	1,24%
Specific gravity	NP 581	6/12	2,55 g/cm^3
		4/10	2,65 g/cm^3

Table 4. Fine aggregate properties

Test	Standard	Results
Methylene Blue Test	EN 933-9	0,02 %
Sand Equivalent Test	EN 933-8	60%
Water absorption	NP 954	0,41 %
Specific gravity	NP 954	2,61 g/cm^3

Gap and dense graded asphalt rubber mixtures were produced using the following terminal blend asphalt rubbers:

- gap graded ARHM-GG mixture (Asphalt Rubber Hot Mix Gap Graded), designed in accordance with the California Department of Transportation (Caltrans) Standard Special Provisions, SSP39-400;
- dense graded Asphalt Institute mixture, specified in accordance with the mix type IV, following the Asphalt Handbook Manual Series nº 4.

The mixtures were designed through the Marshall Method to evaluate the binder and void content. Figure 2 illustrates the mixture gradations. The characteristics of the produced mixtures are presented in Table 5.

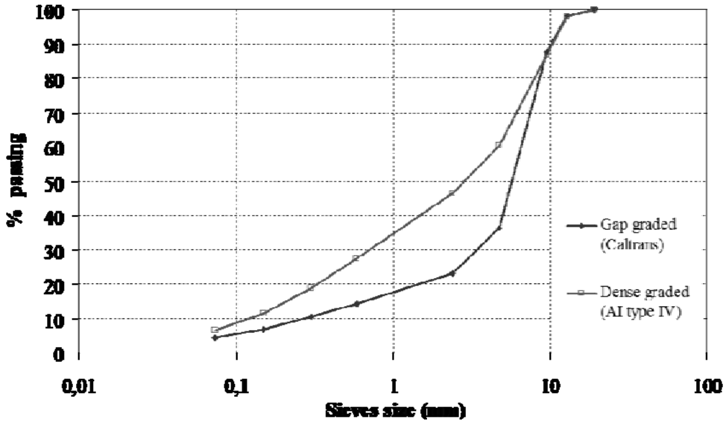

Figure 2. Aggregate gradation of the asphalt rubber mixtures

Table 5. Characteristics of the asphalt rubber mixtures

Mixture	Gradation	Specification	Asphalt type	Binder content (%)	Voids content (%)
CBB20	Gap graded	Caltrans	BB20	7,5	6,0
CBB201	Gap graded	Caltrans	BB20	8,5	6,0
IBB15	Dense graded	AI type IV	BB15	6,0	5,0
IBB151	Dense graded	AI type IV	BB15	7,0	5,0

The specimens prepared in laboratory for stiffness and fatigue tests were compacted in slabs by using a cylinder with vibration over the asphalt mixtures. Then, the slabs were sawed to produce prismatic specimens (50 mm x 63 mm x 380 mm) for stiffness and fatigue tests.

3 TESTS RESULTS

3.1 *Dynamic modulus*

The dynamic modulus of the asphalt rubber mixtures was evaluated at three temperatures; 15, 20 and 25 ºC. Prior to the tests, the specimens were placed in an environmental chamber for approximately 2 hours in order to reach the test temperature. The frequency sweep test measures the stiffness (dynamic modulus) of mixtures when subjected to different loading frequencies (10; 5; 2; 1; 0,5; 0,2; 0,1 Hz) in 100 cycles. Table 6 presents the dynamic modulus (E) and the phase angle, δ, of the mixtures at the frequency of 10 Hz for the three temperatures mentioned before.

Table 6. Dynamic modulus and phase angle at 10 Hz

Mixture	15º C		20º C		25º C	
	E (MPa)	δ (º)	E (MPa)	δ (º)	E (MPa)	δ (º)
CBB20	6368	14	4810	21	3249	27
CBB201	6352	16	4864	21	3208	29
IBB15	6729	14	5399	19	3735	26
IBB151	6207	15	4910	19	3524	25

From the dynamic tests results, the law of the modulus variation with the temperature can be expressed as follows:

$$E = a + b \times T \tag{1}$$

where:
E = dynamic modulus;
a and b = regression parameters;
T = temperature (ºC).

The application of the model, expressed by equation 1, led to the parameters presented in Table 7.

Table 7. Regression parameters of the modulus with the temperature variation

Mixture	a	b
CBB20	11046	-311,82
CBB201	11275	-299,36
IBB15	11095	-314,36
IBB151	10246	-268,29

The law of the dynamic modulus variation with the temperature and binder content is expressed by Equation 2:

$$E = K_1 \times B + K_2 \times T + K_3 \qquad (2)$$

where:
E = dynamic modulus;
B = binder content (%);
T = temperature (ºC);
K_1, K_2, K_3 = regression parameters.

Through the dynamic modulus in function of the temperature tests for the evaluated mixtures, Equation 2 can be reformulated as Equation 3. Figure 3 shows that the dynamic modulus measured in the tests (observed modulus) fitted the model expressed by Equation 3 (predicted modulus).

$$E = -176{,}85 \times B - 302{,}20 \times T + 12260{,}02 \qquad (3)$$

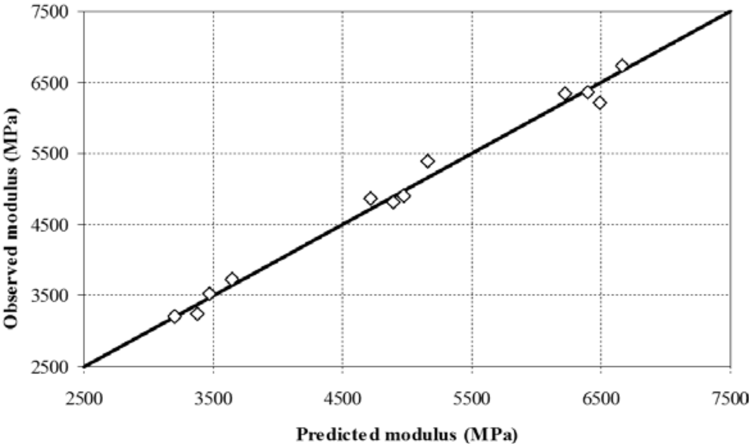

Figure 3. Predicted and observed dynamic modulus results

The air temperature was calculated through the Shell Method for Florianópolis (Santa Catarina State, Brazil), based on annual mean temperatures. The pavement temperature, designed by Witzack´s equation, resulted in 29,4 ºC (for 10 cm of asphalt surface, temperature considered at 3 cm depth).

3.2 *Fatigue*

The configuration to evaluate the fatigue resistance of the mixtures used in this study was the four-point bending test in controlled strain. Flexural fatigue tests were conducted according to the AASHTO TP 8-94 (Standard Test Method for Determining the Fatigue Life of Compacted HMA Subjected to Repeated Flexural Bending). The test apparatus used in this study, a Repetitive Loading Testing Machine (CS7800) equipped with a four point flexural beam device, is presented in Figure 4.

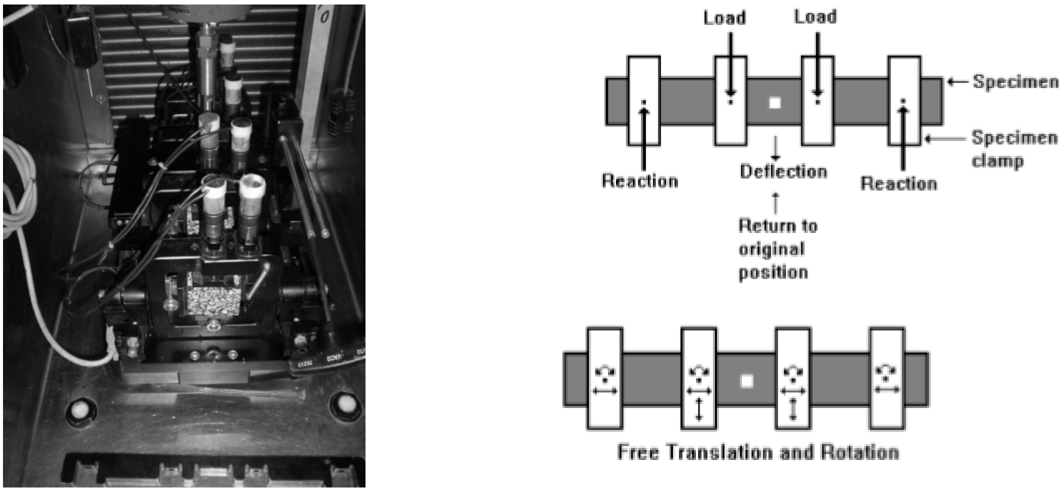

Figure 4. Repetitive loading testing machine and flexural four point beam device

The apparatus has free translation and free rotation at the reaction points and at load points, as represented in Figure 4. The equipment is controlled by a microcomputer using the ATS software to provide feedback closed-loop control to the servo-hydraulic system, as well as to test temperature and to acquire data This device was placed in a climatic oven that maintained the test temperature by circulating air and allowed the beam test.

The AASHTO TP 8-94 standard establishes that fatigue tests should be performed by applying a constant sinusoidal displacement to the specimen, which produces a constant sinusoidal strain at the bottom of it. This is a strain controlled test in which the stress and stiffness decrease as the specimen fails. The stiffness evolution during a strain controlled fatigue test is used to define the specimen failure.

All tests were executed at 20 ºC and at 10 Hz. For each mixture, three levels of strain were selected (200, 400, 800 x10-6), with three replicates. Before the fatigue test, the frequency sweep test was conducted in the same equipment, using the same specimen. The dynamic modulus and fatigue tests were carried out under controlled strain conditions in beam specimens with the dimension 380 mm (length) x 50 mm (height) x 63 mm (width).

The test results, expressed in terms of fatigue life as function of the strain level, are represented in Figure 5.

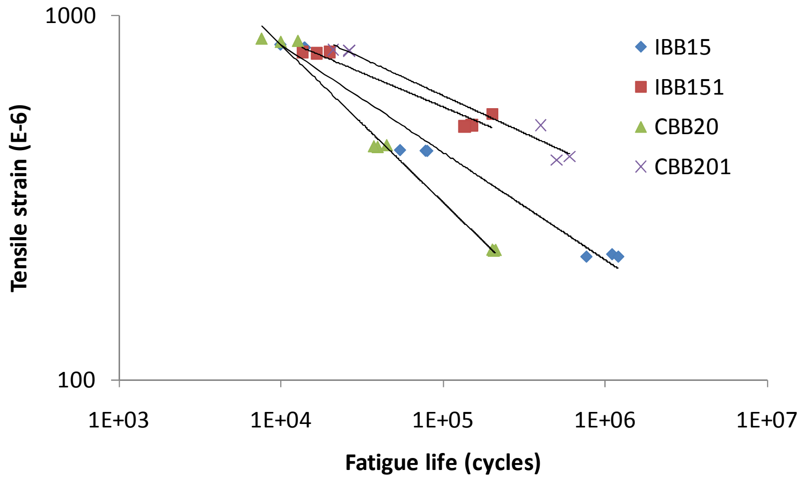

Figure 5. Fatigue life for studied mixtures

The fatigue tests of this study were used to develop a fatigue model to predict the performance of Brazilian asphalt rubber hot mixtures produced with terminal blend asphalt rubber with 15% and 20% of crumb rubber, respectively for dense-graded asphalt rubber mixtures and for gap-graded asphalt rubber mixtures.

The development of the fatigue models was based on the model developed by Tayebali et al. (1994), expressed in equation 4, where: N is the fatigue life; e is the Neper's number; VFB is the percentage of voids filled with bitumen; ε is the tensile strain; S'' is the loss stiffness and k_1, k_2 and k_3 are statistical coefficients.

$$N = k_1 \times e^{k_2 \times VFB} \times \varepsilon^{k_3} \times \left(S''\right)^{k_4} \tag{4}$$

The fatigue results of the dense graded asphalt rubber mixtures (IBB15 and IBB151) allowed to develop the model expressed in equation 5. The fatigue results of the gap graded asphalt rubber mixtures (CBB20 and CBB201) allowed to develop the model expressed in equation 6.

$$N = 2.22E8 \times e^{0.247 \times VFB} \times \varepsilon^{-3.470} \times \left(S''\right)^{-0.475}, \ \mathrm{R}^2=0.95 \tag{5}$$

$$N = 1.48E8 \times e^{0.276 \times VFB} \times \varepsilon^{-2.244} \times \left(S''\right)^{-1.626}, \ \mathrm{R}^2=0.99 \tag{6}$$

The best fit obtained for the developed models can be observed in Figures 6 and 7, for dense graded and gap graded asphalt rubber mixtures, respectively, where the values predicted by the fatigue models are very close to those observed in the fatigue tests.

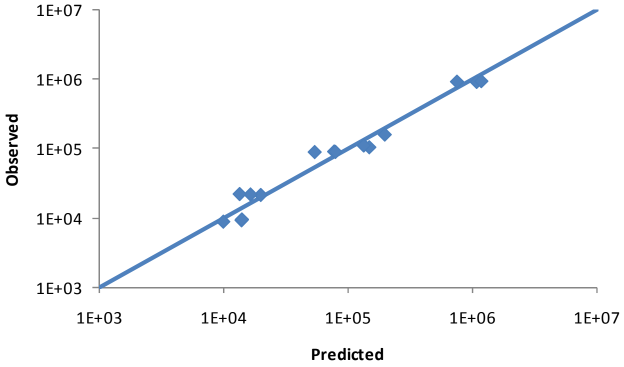

Figure 6. Quality of the model developed for dense graded asphalt rubber mixtures (IBB15 and IBB151)

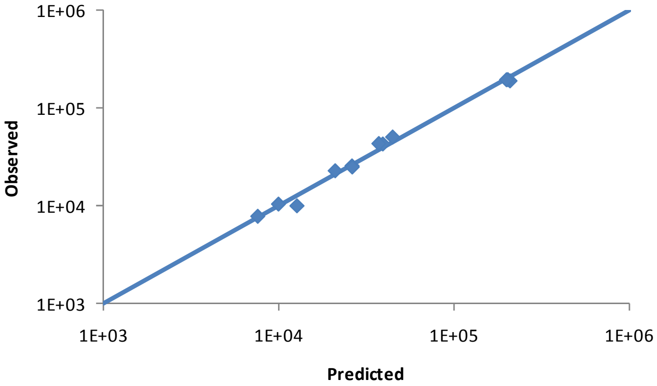

Figure 7. Quality of the model developed for gap graded asphalt rubber mixtures (CBB20 and CBB201)

4 CONCLUSIONS

Two types of asphalt rubber from terminal blend process, with 15% and 20% of ambient rubber and 50/70 pen bitumen were used to produce dense and gap graded mixtures. With each asphalt rubber binders, two asphalt rubber mixtures were produced, each one containing a different quantity of asphalt rubber.

The four mixtures studied in this work were tested to evaluate stiffness and fatigue resistance by using a four point bending device to develop stiffness and fatigue models to predict the behavior of Brazilian asphalt rubber mixtures.

With the testing results, a stiffness model was developed relating stiffness to the binder content and to temperature. The fatigue models developed in this work relate the fatigue resistance to the voids filled with bitumen, the tensile strain and the loss stiffness, as firstly used during SHRP programme.

The quality of the developed models allows its use to predict accurately the performance of Brazilian asphalt rubber mixtures.

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