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CONSTRUCTING BETTER ROADS WITH ASPHALT RUBBER

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Abstract

Brazilians mixtures containing asphalt rubber were evaluated by mechanical laboratory tests. A conventional mixture with asphalt CAP-50/70 was produced as a mixture control. With the aim of compare the Brazilians mixtures performance, a Portuguese asphalt rubber mixture was tested as well. The testing set involved the determination of the mechanical properties, fatigue and permanent deformation, of asphalt rubber produced by wet process through two different systems: continuous blend and terminal blend. The asphalt rubber morphology was evaluated in order to determine the compatibility of the systems. The asphalt rubber mixtures exhibit good resistance to permanent deformation and prolonged fatigue life in relation to mixture control. Therefore it is concluded that the application of asphalt rubber alters the characteristics of asphalt mixture in a very beneficial way.

Keywords: Asphalt rubber, fatigue, permanent deformation, asphalt mixtures

1. INTRODUCTION

Asphalt mixtures are designed to resist aging and distress induced by traffic loading and changing environmental conditions. The most common asphalt distresses include rutting and fatigue cracking that occurs when an asphalt layer is subjected to repeated loading under the passing traffic. While fatigue cracking is one of the major load-related distresses experienced in asphalt pavements, permanent deformation or surface rutting is due to volume change (densification) as well as plastic flow (shear) in one or more pavement layers (Artamendi et al., 2004; Gossain et al., 2006).

In Brazil, the last study carried out by Confederação Nacional do Transporte, which the focal objective was to analyze the conditions of the paved Brazilian highways in relationship to the conservation, safety and comfort of the users, shown that in 73557 km of highways under state administration, some level of degradation was found in 60.8% of the total of the extension investigated (CNT, 2006). The main distresses that occur in Brazilian's pavement are fatigue cracking and permanent deformation.

In Brazilian highways the growth of heavy road traffic and the use of conventional materials in pavement surface layers, have been contributing to accelerated degradation process in the asphalt pavements. In addition, the lacks of investments and means that be able to assure the mechanical performance of the new and existent materials are factors that step up this process.

In this way, the emphasis of highway construction has gradually shifted from construction activities to maintenance and rehabilitation of the existing highways. This important change in highway projects clearly reveal necessitates in development and availability of new materials such as asphalt modifiers that will be capable to promise an expected life performance.

During many years, Brazil focused research efforts on improving mixture design to preclude rutting and fatigue cracking in the early life of the pavement through the mechanical tests. However, the lack of appropriate equipments for the accurate characterization of the mechanical behaviour of asphalt and asphalt mixtures has limited the development of researches in Brazil. Therefore, throughout a partnership between Portugal and Brazil, in 2004 initiated a research study with the following objectives: (i) accomplish the mechanical tests (fatigue and permanent deformation) in asphalt mixtures using Brazilian's materials; (ii) performance evaluated of asphalt rubber produced in Brazil; (iii) fatigue curves development of Brazilian's mixtures using four point bending test; (iv) asphalt mixtures performance comparison.

In this research, laboratorial set tests were done to evaluate Brazilian's asphalt rubber and asphalt mixtures through the performance tests. A control mixture using conventional asphalt was available as well. In order to compare the results, a Portuguese asphalt rubber mixture was used in the study.

First, the concepts about asphalt rubber are reviewed. After, presenting a brief references concerning fatigue and permanent deformation mechanisms and tests used to predict the asphalt mixtures behaviour, the experimental tests on asphalt and asphalt mixtures were performed.

The results obtained in this research showed that the Brazilian's asphalt mixtures produced with asphalt rubber presented a superior performance in relation to the mixture control usually applied in Brazil surface pavements.

Moreover, these mixtures had the same quality when compared to the Portuguese mixture.

2. RUBBER FROM WASTE TIRES AND ASPHALT RUBBER

Around the world, billions tires are added to stockpiles, landfills or illegal dumps. In Brazil, the large number of tires accumulated over the years creates disposal problems in the cities. The introduction of crumb rubber from waste tires into asphalt has the potential to solve the disposal problem and mainly contribute to improve the mechanical characteristics of the asphalt mixtures produced with this product (asphalt rubber).

Highway engineers around the world have tried to incorporate scrap tire rubber in asphalt pavements since the 1950's (Hanson, 1994). Some of the earliest experiments involved incorporating natural rubber with bitumen in the 1840s' (Heitzman, 1992). In 1960's, the engineer Charles McDonald, in the United States, initiated the studies on the granulated rubber incorporation to the conventional binders. The results from the study was a success, the product was named asphalt rubber and the manufacture method was known as McDonald's process or wet process (Way, 2000).

By 1968, the Arizona Department of Transportation (ADOT) began numerous researches and development projects involving asphalt rubber, as a consequence, in 1975, crumb rubber was successfully incorporated into asphalt mixtures (Epps et al., 1980). From this time, many agencies in other American states were able to follow the progress and development of asphalt rubber. California (Caltrans) and Texas (TXDOT) placed chip seal test sections in the 1970's and hot mix applications in the 1980's. Since then, extensive researches have been tested and applied asphalt rubber mixtures in several countries in the world.

In Brazil, the Centro de Pesquisas e Desenvolvimento da Petrobrás (CENPES) and some universities began in 90's to investigate the behaviour of the asphalt modified with rubber. Currently, further investigations have been done in many universities and researches centres. Some companies of petroleum distribution developed, with advanced technology, the asphalt rubber from terminal blend system.

Besides the use of crumb rubber as an additive in conventional asphalts and the use of asphalt rubber is an attractive from the standpoint of environmental preservation, the performance of asphalt rubber mixtures must be evaluated.

2.1. Crumb rubber production

To produce rubber from waste tires, it is usually necessary to further reduce the size of the tire shred. First the tyres are coarsely shred so the steel belts and fibres can be separated from the rubber. The coarse rubber shreds are then shredded again to a smaller size. For use in asphalt the rubber shreds must then be ground up to produce crumb rubber.

Crumb rubber is a general term used to identify a group of concepts that incorporate scrap tire rubber into asphalt paving materials. The terminologies associated with these crumb rubber mixtures are based on the percentage composition of crumb rubber and asphalt, and the mix production process (Heitzman, 1992).

Crumb rubber obtained from waste tires can either be ambient ground (grinding at room temperature or above) or cryogenically ground (grinding below embitterment temperature, liquid nitrogen is often used). Ambient ground crumb rubber has a sponge-like surface. Due to very high surface area this rubber reacts with asphalt reasonably fast. Cryogenically ground rubber usually has undesirable particle morphology. This process produces clean flat surfaces which, in turn, reduce the reaction rate with hot conventional asphalt. Cryogenically ground rubber also gives lower elastic recovery compared to the ambient ground rubber (Roberts et al., 1989).

The differences in crumb rubbers are critical variables in the success or failure of asphalt rubber binders. Asphalts rubber produced with rubber from the different grinding processes have measurable differences in properties and storage characteristics; these differences are critical to the performance of the binder in the mixtures (Baker et al., 2003).

The ASTM 6114 (1997) specification the following requirements for crumb rubber:

– less than 0.75% moisture;
– specific gravity of 1.15 ± 0.05;
– no visible nonferrous metal particles;
– no more than 0.01% ferrous metal particles by weight;
– fiber content shall not exceed 0.5% by weight;
– recommends no rubber particles retained on the 2.36 mm particles sieve.

2.2. Asphalt rubber

Asphalt rubber is obtained through the incorporation of the crumb rubber into the conventional binders in controlled temperature conditions. The purpose of blending crumb rubber with asphalt was to enhance the elastic and aging properties of the asphalt. There are two processes to produce asphalt rubber: wet process and dry process.

In the wet process, rubber and asphalt are digested together at high temperature to produce the asphalt rubber. The asphalt rubber is added to aggregate in a mixing plant in the same way as any conventional asphalt. In the dry process, however, dry rubber particles are added to aggregate and asphalt in a pug mill at the asphalt mixing plant. The rubber is usually mixed with the aggregate prior to asphalt addition (Austroads, 1999).

The wet process can be divided into two systems: continuous blend and terminal blend. In the continuous blend system, the asphalt is heated at high temperatures (in general 180 to 190 ºC), in a tank of overheating in anaerobic conditions, being carrying after that, to an appropriate tank of mixture. In this tank, the addition of the crumb rubber to the previously heated asphalt occurs. The digestion process is accomplished in a period of 1 to 4 hours, under a controlled temperature. This process of mix is facilitated by the action of a mechanical action, generally a vane, introduced into the mix tank (Visser et al., 2000). Accordingly to Takallou et al. (1992) the asphalt rubber from continuous blend system has short stability to the storage and must to be used until four hours after the blending. In this system, some modifications in asphalt mixing plant have to be done.

The asphalt rubber produced in terminal blend system follow the same procedure of continuous blend, which means that the asphalt and crumb rubber are mix in an appropriated tank at high temperatures. However, in the terminal blend system, the asphalt rubber is produced in an industrial plant, whose the main characteristic is that the incorporation of the crumb rubber to the asphalt is processed through potent cut mills, in time (in general 6 hours) under controlled temperature and pressure. The asphalt rubber from terminal blend has stability to the storage and can be trucked to the job site, without loss of their original characteristics and properties.

To produce adequate asphalt rubber is necessary to establish the digestion temperature and time for a specific combination of conventional asphalt and crumb rubber. Viscosity of the blend is checked at different time intervals during the blending and digestion process. Viscosity of the blend increases with digestion time and then levels off. Achieving a reasonably constant viscosity indicates that the initial reaction is nearly complete and the binder are ready to use (Kandhal, 1992).

The physical properties of an asphalt rubber mixture depend on the physical and chemical properties of the materials used, the reaction between these materials, and the interaction conditions. Therefore, to obtain desired properties, appropriate materials and interaction conditions which will produce desired properties need to be identified. Specific items which should be addressed are: (i) conventional asphalt source and grade, (ii) crumb rubber source and gradation, (iii) crumb rubber content, (iv) interaction conditions of time, temperature, and mixing intensity (Hicks, 2002).

The physical properties of asphalt rubber binders are controlled by several factors, related to the base materials and mixture process. Therefore, guidelines should be set so that producers of asphalt-rubber can choose the appropriate base materials, find the proper dosage between the ingredients, and specify the appropriate process of mixing (Dantas Neto et al., 2006).

ASTM 6114 (1997) specifications for asphalt rubber specifies the required properties for the asphalt rubber as shown in Table 1.

Table 1. ASTM 6114 specifications for asphalt rubber

Binder designation		Standard	Type I	Type II	Type III
Apparent viscosity, 175 ºC (cp)	min. max.	ASTM 2196	1500 1500	1500 5000	1500 5000
Penetration, 25 ºC, 100 g, 5 s	min. max	ASTM D5	25 75	25 75	50 100
Softening point (ºC)	min.	ASTM D36	57.2	54.4	51.7
Resilience, 25 ºC (%)	min.	ASTM D5329	25	20	10
Flash point (ºC)	min.	ASTM D93	232.2	232.2	232.2

ASTM 6114 provides recommendations for asphalt rubber type based on climatic conditions. For average monthly maximum ambient temperatures of 27 ºC or lower and average monthly minimum ambient temperatures of -9 ºC or lower at Type III is recommended. For average monthly maximum ambient temperatures of 43 ºC or lower and average monthly minimum ambient temperatures of -9 ºC or greater a Type II is recommended. For average monthly maximum ambient temperatures of 43 ºC or greater and average monthly minimum ambient temperatures of -1 ºC or greater a Type I is recommended.

Asphalt rubber is used as a binder in chip seal or stress-absorbing membrane (SAM), stress-absorbing membrane interlayer (SAMI), crack or joint sealing and in various types of flexible pavement construction including surface treatments and asphalt mixtures (Caltrans, 2003; Baker et al., 2003).

3. FAILURE MECHANISMS

Under traffic loading, the asphalt mixtures as surface pavements are subjected a repeated tensile strains which tend towards increased pavement deterioration. The two major distress conditions affecting the performance of asphalt pavements are permanent deformation or rutting and fatigue. The assessment of fatigue and permanent deformation characteristics is normally done through laboratory tests.

3.1. Fatigue

The fatigue resistance of an asphalt mixture is its ability to withstand repeated bending without fracture. Fatigue, a common form of distress in asphalt pavement, manifests itself in the form of cracking from repeated traffic loading. It is important to have a measure of the fatigue characteristics of specific mixtures over a range of traffic and environmental conditions so that fatigue considerations can be incorporated into the process of designing asphalt pavements. The fatigue characteristics of asphalt mixtures are usually expressed as relationships between the initial stress or strain and the number of load repetitions to failure, determined by using repeated flexure, direct tension, or diametral tests performed at several stress or strain levels (Tayebali et al., 1994).

Fatigue tests are carried out in two modes, controlled strain and controlled stress. In controlled strain mode, the strain is kept constant by decreasing the stress during the test whereas in controlled stress the stress is maintained constant which increases the strain during the test. In general, controlled stress testing has been related to relatively thick pavement construction where high stiffness is the fundamental parameter that underpins fatigue life. Controlled strain testing, on the other hand, has been associated with thin conventional flexible pavements where the elastic recovery properties of the material have a fundamental effect on its fatigue life (Artamendi et al., 2004).

The fatigue behaviour of a specific mixture can be characterized by the slope and relative level of the stress or strain versus the number of load repetitions to failure (N) and can be defined by a relationship of the following form proposed by Monismith et al. (1971), in Equation 1:

$$N = a\left(\frac{1}{\varepsilon_t;\sigma_t}\right)^b \quad (1)$$

Where N is the number of repetitions to failure; ε_t; σ_t are tensile strain applied and stress applied; a, b are experimentally determined coefficients.

The stiffness at any number of load repetitions is computed from the tensile stress and strain at that specific value. The fatigue life to failure (N) is dependent on the mode of loading condition. For controlled stress tests, failure is well defined since specimens are cracked through at the end of the test. In controlled strain testing, failure is not readily apparent; accordingly, the specimen is considered to have failed when its initial stiffness is reduced by 50% (Tayebali et al., 1994).

One of the most common methods used to evaluate fatigue life in laboratory is the flexural bending beam test. Flexural fatigue four bending tests were conducted according to the AASHTO TP 8-94 (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. They also determine fatigue life, dynamic modulus, and the phase angle of the beams.

3.2. Permanent deformation

Rutting or permanent deformation on the asphalt pavement surface generally results from one of two conditions. Permanent deformation throughout the entire asphalt pavement structure is caused by overstressing the underlying layers or subgrade. This overstressed condition can be the result of inadequate thickness design for the applied traffic or for the strength properties of the underlying materials. A more common form of pavement permanent deformation occurs in the asphalt mixture itself. In this case, the underlying layers perform fine and their boundary lines are unaffected by the distress occurring near the surface of the asphalt pavement and permanent deformation can be the result of an unstable asphalt mixture, heavy vehicle traffic, and/or high pavement temperatures (Santucci, 2001).

Permanent deformation that occurs in the asphalt mixture is the focus on in this research.

Permanent deformation in asphalt concrete layers develops gradually as the number of load applications increases, usually appearing as longitudinal depressions in the wheel paths accompanied by small upheavals to the sides. It is caused by a combination of densification (decrease in volume and hence, increase in density) and shear deformation (Sousa et al., 1994).

Eisenmann et al. (1987) concluded that permanent deformation was mainly caused by deformation without volume change. From this study, two conclusions were drawn:

– in the initial stage of trafficking, the increase of irreversible deformation below the tires is distinctly greater than the increase in the upheaval zones. In this initial phase, therefore, traffic compaction has an important influence on rutting;

– after the initial stage, the volume decrement beneath the tires is approximately equal to the volume increment in the adjacent upheaval zones. This is an indication that compaction under traffic is completed for the most part and that further rutting is caused essentially by displacement with constancy of volume. This phase is considered to be representative of the deformation behaviour for the greater part of the life of a pavement.

Considering that for properly compacted pavements, shear deformations, caused primarily by large shear stresses in the upper portions of the asphalt-aggregate layer(s), are dominant, repetitive loading in shear is required in order to accurately measure, in the laboratory, the influence of mixture composition on resistance to permanent deformation (Sousa et al., 1991).

Sousa et al. (1994) developed a test procedure to evaluate the permanent deformation in asphalt specimens in laboratory. The Repetitive Simple Shear Test at Constant Height (RSST-CH) followed AASHTO TP7-01, Test Procedure C. The RSST-CH was used as the accelerated laboratory test for evaluating the permanent deformation susceptibility of the mixture. This test is performed at the critical pavement temperature at 5 cm. depth. For the purpose of this test analysis, the critical pavement temperature was defined as the 7-day maximum pavement temperature at 5 cm. depth. This depth was selected because computations have shown that the maximum shear stresses, causing the permanent deformation in the pavements, are encountered at 5 cm. depth near the edge of the tires.

The fundamental relation among the laboratory tests and the field performance was derived from determining a relationship between the number of cycles in the RSST-CH to reach a given permanent shear strain and the number of ESAL (number of cycles of the equivalent standard axle load of 80 kN) to cause the same permanent shear strain in the pavement section. The RSST-CH test is carried out until the specimen reaches the maximum plastic shear strain of 0.04545, which is equivalent to the limit value of 12.7 mm of rut depth in the wheel path.

Equation 2 shows the relationship between the number of passes of the equivalent standard axle load of 80 kN (ESAL) as a function of the number of applied load cycles in the RSST-CH (Nmpss) for the specimen to reach the maximum plastic shear strain of 0.04545.

$$ESAL = 10^{\frac{4.36 + \log N_{mpss}}{1.24}} \quad (2)$$

Where ESAL is the number of cycles of the equivalent standard axle load of 80 kN correspondent to the maximum rut depth of 12.7 mm; Nmpss is the number of applied load cycles in the RSST-CH for the specimen to reach the maximum plastic shear strain of 0.04545.

4. EXPERIMENTAL TESTS

In this study, four asphalt mixtures were tested using asphalt rubber from terminal blend and continuous blend systems. A control mixture with conventional asphalt was also tested.

The terminal blend asphalts rubber were produced in an industrial plant and come from Brazil. The continuous blend asphalts rubber were manufactured in laboratory using crumb rubber and conventional asphalts from Portugal and Brazil. Initially, laboratorial tests were carried out to evaluate the physical properties of the conventional asphalts. The tests are also used to characterize the asphalts rubber.

Finally, the performance of asphalt rubber mixtures were evaluated through the fatigue and permanent deformation tests.

4.1. Crumb rubber and asphalt materials characterization in laboratory

4.1.1. Crumb rubber

Crumb rubber from Brazil was recycled in the ambient process and was used to produce the terminal blend asphalt rubber and, in laboratory, the continuous blend asphalt rubber. The Portuguese continuous blend asphalt rubber was produced in cryogenic process.

The rubber gradations were tested in accordance with the requirements of ASTM C136, amended the Greenbook (2000) recommendations. Both crumb rubber followed the Arizona Department of Transportation (ADOT) requirements type B (ADOT, 2005). Table 2 describes the grain size distribution curves for grading envelope specified by ADOT and Figure 1 presents the crumb rubber gradations.

Table 2. Crumb rubber type B from ADOT requirements

Sieve size		ADOT Specifications
nº	mm	% passing
10	2.00	100 – 100
16	1.18	65 – 100
30	0.60	20 – 100
50	0.30	0 – 45
200	0.075	0 – 45

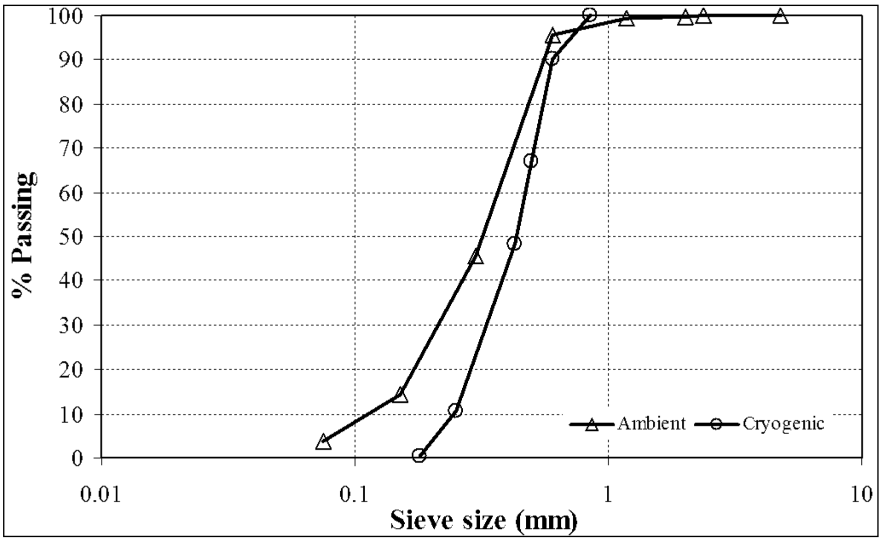

Figure 1. Crumb rubber gradations

The crumb rubber production process influences the physical shape and the surface area of the rubber particles. In this study, the ambient particles surface area are lower than the cryogenic (ambient surface area is 19.3 m^2/kg and the cryogenic is 13.6 m^2/kg). Scanning Electron Microscopy (SEM) micrographs of ambient and cryogenic crumb rubber were used in order to evaluate the particles morphology. As result, ambient size reduction resulted in rough shredded particles surfaces, while cryogenic size reduction presented in smoother glassy surfaces, as shown in Figure 2.

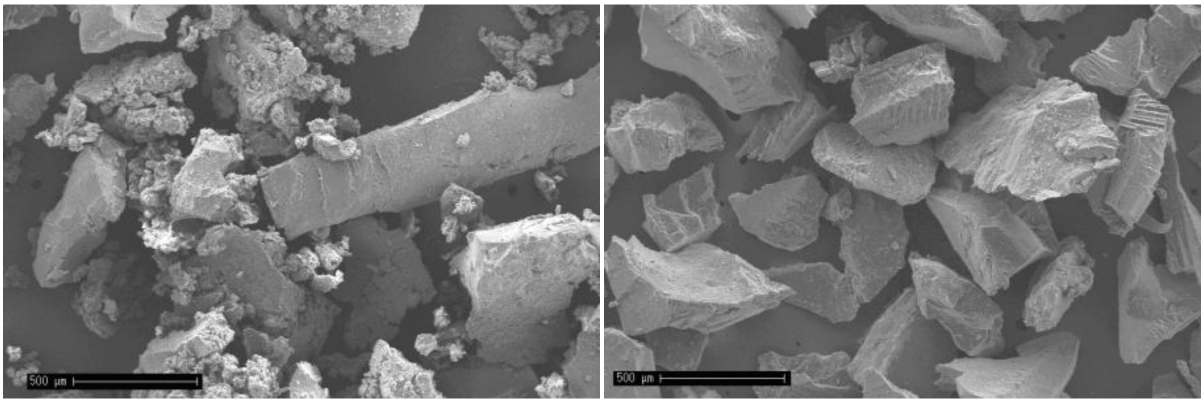

Figure 2. SEM micrographs of ambient and cryogenic crumb rubber (50X magnification)

4.1.2. Conventional asphalts

In this study, two conventional asphalts were employed to produce asphalts rubber. The Portuguese conventional asphalt was a PEN 35/50 (classified by penetration), used in continuous blend Portuguese asphalt rubber. The asphalt base to produce the mixture control and Brazilian asphalts rubber terminal blend and continuous blend was a CAP 50/70 (classified by penetration). CAP-50/70 is specified by DNIT 095/2006 – EM (Departamento Nacional de Infra-Estrutura de Transportes, Cimentos Asfálticos do Petróleo – Especificação de Material).

The following asphalt tests were conducted to obtain the material characteristics that affect the asphalt rubber produced with them: (i) penetration; (ii) softening point; (iii) resilience; (iv) apparent viscosity (Brookfield viscometer); (v) aging test (RTFOT – Rolling Thin Film Oven Test). The physical properties of the conventional asphalts are presented in Table 3.

In spite the conventional asphalt PEN 35/50 presented in penetration test the result a slight high the inferior limit, it consider workable for the purpose. The Portuguese conventional asphalt PEN 35/50 is more rigid then Brazilian CAP-50/70.

Table 3. Characterization of conventional asphalts

Test	Standard	CAP-50/70	PEN 35/50
Penetration (1/10 mm)	ASTM D 5	51.5	33.0
Softening point (ºC)	ASTM D 36	51.5	52.7
Apparent viscosity at 175ºC (cP)	AASHTO TP 48	127	175
Resilience (%)	ASTM D 5329	0	9
RTFOT 163 ºC, 85 min	ASTM D2872		
Change in mass (%)		0.3	0.2
Change in softening point (ºC)		4.3	0.5
Penetration (1/10 mm)		22.3	27.7
Retained penetration (%)		43.3	84.0

4.1.3. Asphalts rubber

Crumb rubber and conventional asphalt CAP-50/70, from Brazil, were used to produce the terminal blend and, in laboratory, the continuous blend asphalt rubber. The Portuguese continuous blend asphalt rubber was produced in laboratory using rubber from cryogenic process and conventional asphalt PEN 35/50.

Continuous blend asphalts rubber were produced in laboratory using conventional asphalts PEN 35/50 and CAP-50/70 as asphalt base. The equipment used to production of asphalt rubber was composed by an oven, capable of temperature control and an assembly of engine and paddle that facilitates blending of the conventional asphalt and the crumb rubber. The paddle velocity was chosen in order to produce a homogeneous mixture and its values ranged from 250 to 300 rpm.

In continuous blend process, the conventional asphalt was heated until the prior established temperature chooses. Then, the crumb rubber is added in conventional asphalt and the blend process starts when the asphalt rubbers swelling. The blend process until the time reaction and the asphalt rubber is ready to be applied.

In order to obtain the asphalt rubber to produce the continuous blend mixtures from conventional asphalts (PEN 35/50 and CAP-50/70), several percentages of rubber, digestion time and temperature digestion were tested through the tests: softening point; penetration; resilience and apparent viscosity. CAP-50/70 was tested with ambient rubber to obtain the optimized asphalt rubber.

Considering that the characteristics of asphalt rubber are very dependent on the important variables such as amount of rubber and digestion time and temperature, in this study, asphalt rubbers properties were evaluated over a range of these variables. The testes were conducted varying the following variables: (i) amount of rubber: 19, 21, 23, 25% (by weight); (ii) digestion time: 30, 45, 60, 90, 120, 150, 180, 210 minutes; (iii) temperature digestion: 180, 190 ºC.

The selection of desirable asphalt rubber was done according the tests results, based in ASTM D 6114 (1997) specifications. As consequence, the follow desirable variables were choosing: 21% of rubber content; digestion time of 90 minutes; 180 ºC of temperature digestion. The asphalt rubber with PEN 35/50 and cryogenic rubber were produced using the same configuration. No additives were used.

Terminal blend asphalts rubber were produced in an industrial plant in Brazil and sent to Portugal in cans of 20 litters. In Brazil, two types of terminal blend asphalts rubber are applied in asphalt mixtures, with 15% and 20% amount of rubber.

To sum up the asphalts rubber characteristics, obtained through the same tests used to evaluate the conventional asphalts, the results are presented in Table 4 for continuous blend and in Table 5 for terminal blend.

Four asphalt rubbers were tested in this study and are following designated:

– CBB – Brazilian continuous blend asphalt rubber produced at laboratory with conventional asphalt CAP 50/70 and ambient crumb rubber;

– CBP – Portuguese continuous blend asphalt rubber produced at laboratory with conventional asphalt PEN 35/50 and cryogenic crumb rubber,

– TB1 – Brazilian terminal blend asphalt rubber produced in an industrial plant with conventional asphalt CAP 50/70 and 20% of ambient crumb rubber;

– TB2 – Brazilian terminal blend asphalt rubber in an industrial plant with conventional asphalt CAP 50/70 and 15% of ambient crumb rubber.

Table 4. Characterization of continuous blend asphalts rubber

Test	Standard	CBB	CBP
Penetration (1/10 mm)	ASTM D 5	26.0	16.8
Softening point (ºC)	ASTM D 36	65.0	73.4
Apparent viscosity at 175ºC (cP)	AASHTO TP 48	2829	2246
Resilience (%)	ASTM D 5329	40	49
RTFOT 163 ºC, 85 min	ASTM D2872		
Change in mass (%)		0.3	0.9
Change in softening point (ºC)		8.5	11.2
Penetration (1/10 mm)		18.5	15.5
Retained penetration (%)		71.1	92.2
Resilience (%)		46	45

Table 5. Characterization of terminal blend asphalts rubber

Test	Standard	TB1	TB2
Penetration (1/10 mm)	ASTM D 5	40.0	42.0
Softening point (ºC)	ASTM D 36	68.0	67.7
Apparent viscosity at 175ºC (cP)	AASHTO TP 48	2179	1644
Resilience (%)	ASTM D 5329	28	33
RTFOT 163 ºC, 85 min	ASTM D2872		
Change in mass (%)		0.3	0.3
Change in softening point (ºC)		1.0	2.9
Penetration (1/10 mm)		28.8	25.3
Retained penetration (%)		72.0	60.2
Resilience (%)		39	36

The results of the tests showed that independently of the conventional asphalt type, the incorporation of the crumb rubber resulted in reduction of the penetration value, in increase of the softening point and also increase of the resilience (Tables 3, 4, 5).

When the crumb rubber is added in conventional asphalt CAP-50/70 by continuous blend system, the value of the softening point was increased in 13.5 ºC and the resilience was 40%, whereas through the terminal blend, the enhances were 16.0 ºC and 28% respectively (Tables 3, 4). Relatively to conventional asphalt PEN 35/50, the increase of the softening point was 18.7 ºC and the resilience was 40% (Tables 3, 5). These results demonstrate the improvement of the properties when the crumb rubber is added to the asphalt.

Accordingly to the Tables 4 and 5, all asphalts rubber assist to the constant specifications in ASTM D 6114 (1997), (Table 1). Comparatively, the asphalt rubber TB1 presented a penetration value inferior to TB2, which could be explained because TB1 containing a larger amount of rubber in relation to TB2. For the same reason, TB1 have a higher viscosity than the TB2, which can consider in a smaller workableness when of the production of the asphalt mixtures. Relatively to the softening point, the result of both it was practically the same (Table 5).

The results of the RTFOT aging test had led to the following considerations:

– for TB1 and TB2, the value of change in softening point demonstrated that, in spite of the severity of the RTFOT, the aging didn't affect in a significant way these asphalts rubber;

– for CBB and CBP the value of change in softening point was more elevated;

– the change in mass showed that the modification of the asphalts rubber assured the fixation of the oils maltenes and aromatics oils during the aging process;

– the retained penetration value was higher for TB1 than TB2, which means that TB! Become hardening that TB2 in the RTFOT aging test;

– the same occur between CBB and CBP;

– for all asphalts rubber, the increase of the resilience (elastic recovery) was due that the heating associated to the fine film formed during the aging test provided an interaction among the rubber molecules and of rubber (continuity of the fusion process), and consequently, improving this property.

Scanning Electron Microscopy (SEM) micrographs were used to evaluate the final asphalts rubber morphology and are presented in Figures 3 to 6.

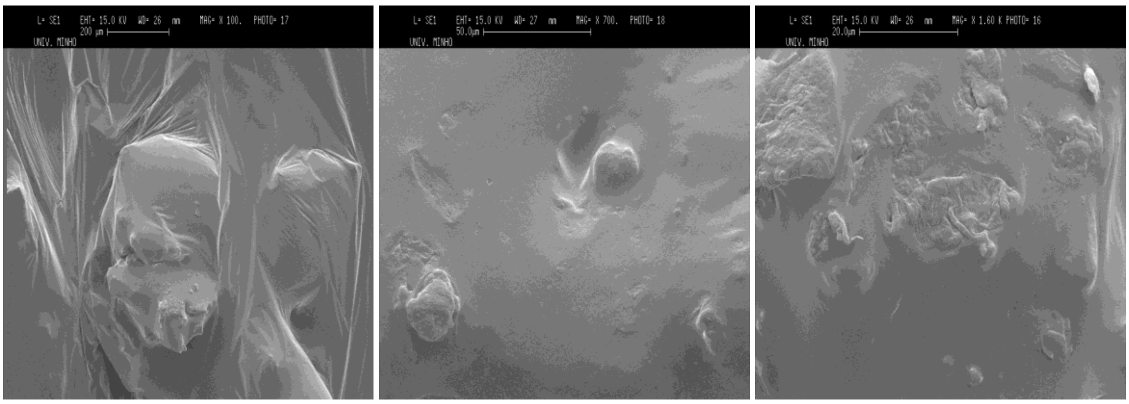

Figure 3. SEM micrographs of asphalt rubber CBB (50, 700, 1600X magnification)

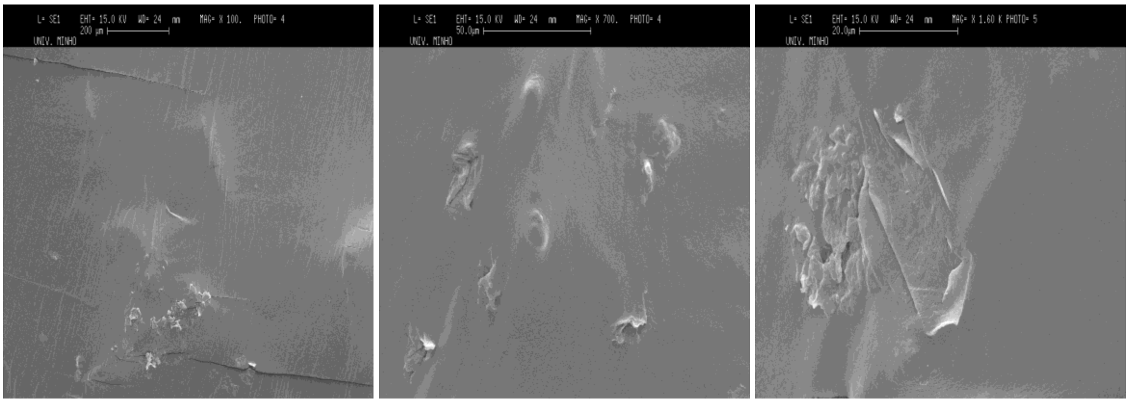

Figure 4. SEM micrographs of asphalt rubber CBP (50, 700, 1600X magnification)

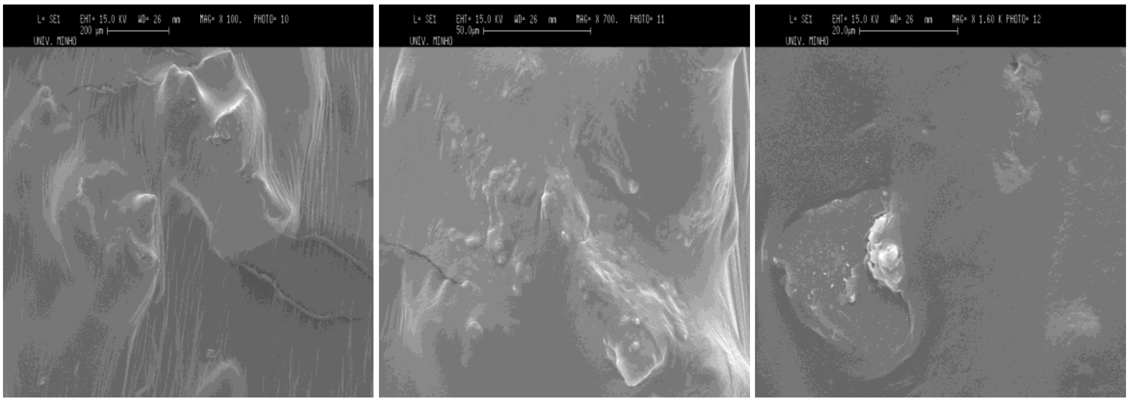

Figure 5. SEM micrographs of asphalt rubber TB1 (50, 700, 1600X magnification)

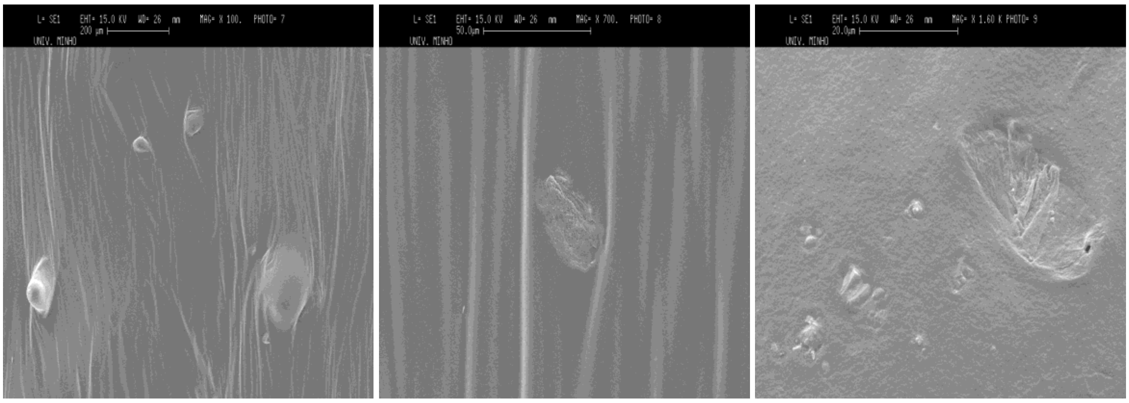

Figure 6. SEM micrographs of asphalt rubber TB2 (50, 700, 1600X magnification)

The micrographs of asphalts rubber morphology (Figures 3 to 6) shown that the all systems are compatible and the asphalt has been blended with crumb rubber. However, in micrograph of asphalt rubber CBB (Figure 3) it can be seen some chunks of rubber still dispersed in the system and it appears more than in the other asphalts rubber. Considering that the asphalts rubber CBB, TB1 and TB2 were made with the same asphalt base and crumb rubber, in spite of the different amount of rubber added, in the terminal blend system (Figures 5, 6) it was possible to observe that the rubber particles are best incorporated into the asphalt than in the continuous blend system (Figure 3). The Portuguese asphalt rubber CBP presented a very good compatibility system (Figure 4).

4.2. Aggregates and mixtures design

4.2.1. Aggregates

The physical properties and the gradation of the aggregates have great influence in performance of the asphalt mixtures as a pavement material. In this study, the granite aggregates were used to produce the asphalt mixtures and come from the northern of Portugal, which have similar characteristics as the ones using in southern of Brazil (Santa Catarina State). Limestone filler was also used to attempt the mixtures gradations. The aggregates have the following gradations:

– crushed granite stone with particles size between 6 and 12 mm;
– crushed granite stone with particles size between 4 and 10 mm;
– fine crushed granite stone with particles size smaller than 4 mm.

The characterization of the aggregates was done through the laboratory tests and is summarized in Table 6. Figure 7 shows the aggregates gradation curves.

Table 6. Characterization of the aggregates

Test	Standard	Aggregate	Test results
Particle shape (flat)	BS 812	6/12	23 %
		6/12	17 %
Particle shape (elongated)		4/10	21 %
		4/10	19 %
Abrasion Los Angeles	ASTM C 131	6/12	24%
Water absorption	NP 581	6/12	0.88 %
		4/10	1.24 %
Specific gravity		6/12	2.66 g/cm^3
		4/10	2.65 g/cm^3
Methylene blue test	EN 933-9	0/4	0.02 %
Sand equivalent test	EN 933-8	0/4	60%
Water absorption	NP 954	0/4	0.41 %
Specific gravity	NP 954	0/4	2.61 g/cm^3

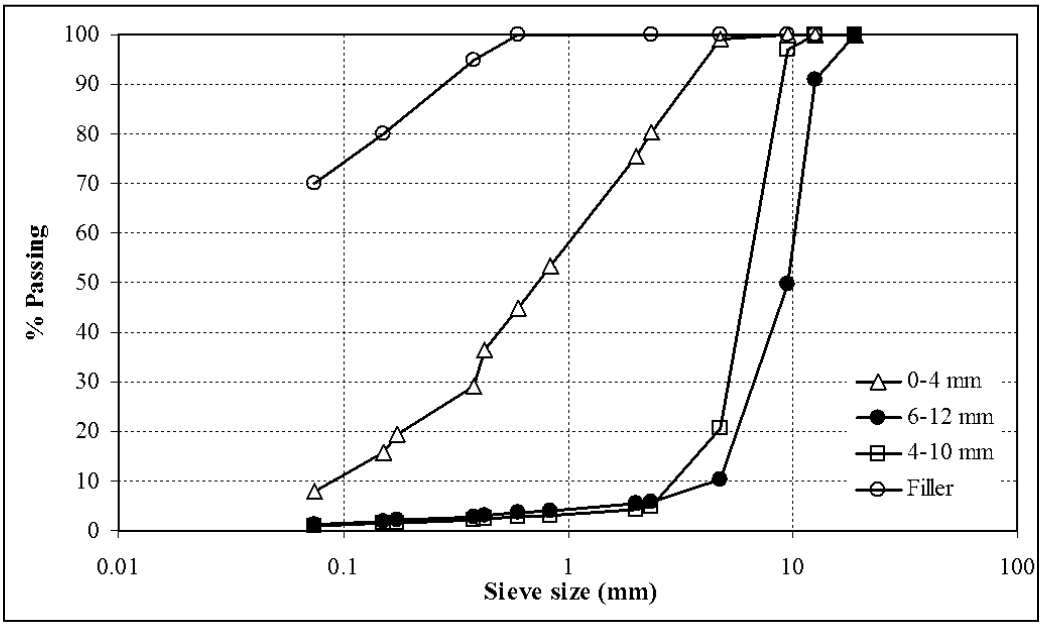

Figure 6. Aggregates gradation curves

4.2.2. Mixtures design

In this study, the performance of asphalt mixtures were evaluated using dense and gap graded gradations. Dense graded mixtures have an aggregate structure that is continuously graded (sized) from the largest to the smallest aggregate in the system. This gradation is the most common type used in Brazil surface pavements.

A gap-graded mixtures contains aggregate that is not continuously graded for all size fractions, in which usually missing one or two of the fines sizes. This is intended to allow for stone on stone contact for deformation resistance, extra binder required has been found to aid in fatigue and reflection cracking resistance, and in the cases in which asphalt rubber is used, the gap helps to accommodate the larger rubber particles present in this binder.

The control mixture was a dense graded DNIT grade C specified by the Departamento Nacional de Infra-Estrutura de Transportes DNIT 031/2006-ES (in Portuguese). For asphalt rubber mixtures, dense and gap graded were tested. The Asphalt Institute dense graded mixture was specified accordance mix type IV and meets in The Asphalt Handbook Manual Series nº 4 (AI, 1989). The Caltrans ARHM-GG mixture (asphalt rubber hot mix gap graded) was designed according to the Standard Special Provisions, SSP39-400 (Caltrans, 2003). In all mixtures, 3% of limestone filler was used by weight. The ADOT AR-AC (asphalt rubber asphaltic concrete) was performing in accordance with ADOT Construction Manual, section 414 (ADOT, 2005).

Tables 7 to 10 presents the operations ranges from mixtures specifications and the mixtures designed. Figure 7 presents the grain size curves of the mixtures.

Table 7. Asphalt Institute mix type IV specifications and mixture designed

Sieve size		AI "IV" specifications		% passing
inch	mm	min.	max.	
3/4	19.0	100	100	100
1/2	12.7	80	100	98
3/8	9.5	70	90	87
nº 4	4.8	50	70	60
nº 8	2.4	35	50	46
nº 30	0.6	18	29	27
nº 50	0.3	13	23	19
nº 100	0.15	8	16	11
nº 200	0.075	4	10	7

Table 8. Caltrans ARHM-GG specifications and mixture designed

Sieve size		ARHM-GG specifications		% passing
inch	mm	min.	max.	
3/4	19.0	100	100	100
1/2	12.7	90	100	98
3/8	9.5	78	92	88
nº 4	4.8	28	42	36
nº 8	2.4	15	25	23
nº 30	0.6	10	20	14
nº 50	0.3	7	15	10
nº 100	0.15	5	10	7
nº 200	0.075	2	7	4

Table 9. DNIT grade C specifications and mixture designed

Sieve size		DNIT "C" specifications		% passing
inch	mm	min.	max.	
3/4	19.0	100	100	100
1/2	12.7	85	100	97
3/8	9.5	75	100	86
nº 4	4.8	50	85	52
nº 10	0.42	30	75	36
nº 30	0.6	15	40	19
nº 80	0.18	8	30	12
nº 200	0.075	5	10	6

Table 10. ADOT AR-AC specifications and mixture designed

Sieve size		ADOT AR-AC specifications		% passing
inch	mm	min.	max.	
3/4	19.0	100	100	100
1/2	12.7	90	100	98
3/8	9.5	79	89	88
nº 4	4.8	34	42	36
nº 10	2.0	15	23	22
nº 40	0.4	4	14	12
nº 200	0.075	1	5	4

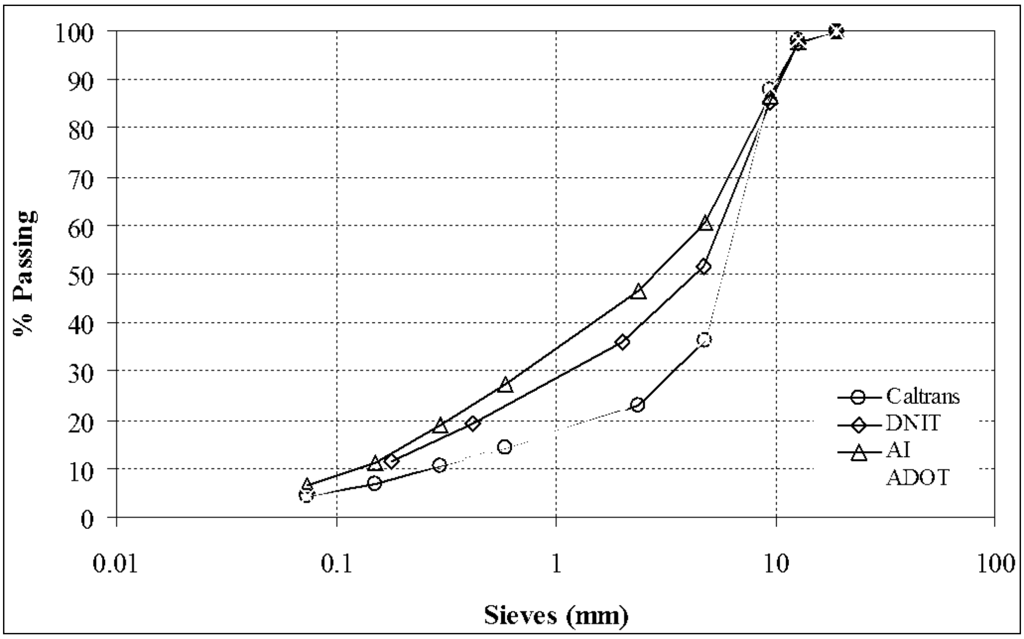

Figure 7. Mixtures grain size curves

In this study, four asphalt rubber mixtures and a mixture control (with conventional asphalt) were evaluated. The mixtures are following designated:

– MBBB – dense graded conventional mixture DNIT grade C with CAP-50/70;

– MCBB – gap graded mixture ADOT AR-AC with asphalt rubber CBB;

– MCBP – gap graded mixture Caltrans ARHM-GG with asphalt rubber CBP;

– MTB1 – gap graded mixture Caltrans ADOT AR-AC with asphalt rubber TB1;

– MTB2 – dense graded mixture AI type IV with asphalt rubber TB2.

In order to determine the optimum binder content and volumetric properties, the mixtures were compacted by Marshall method using number of presses according to heavy traffic criteria (75 blows on each face). The air voids and optimum binder content are presented in Table 11.

Table 11. Asphalt mixtures design

Mixture	Air voids (%)	Optimum binder content (%)
MBBB	5.0	5.5
MCBB	6.0	8.5
MCBP	6.0	8.0
MTB1	6.0	8.5
MTB2	5.0	7.0

After establishing the mixtures design, the materials were weighed and mixed in the laboratory to produce slabs from which the specimens were cored. A mechanical device with production capability of 50 kg of asphalt mixture was used to accomplish the mixture between the mineral aggregates and asphalts. Compaction of the asphalt mixtures was performed in a metallic mould with dimensions (75 x 49 x 8 cm^3), and a vibratory wheel roller was used to achieve the apparent density of the asphalt mixtures defined in the design.

For each mixture, two specimens were produced. A total of 9 beams (5.1 x 6.3 x 38.1 cm^3) and 8 cores (15 cm diameter and 5 cm height) were extracted The beams were used in four point bending tests, to determine the dynamic modulus and fatigue life, and the cores were used in the repeated simple shear test at constant height (RSST-CH), to determine the resistance to permanent deformation. Before performing the modulus tests, the beams were used to determine the apparent density of the mixtures.

4.3. Dynamic modulus and fatigue tests

The four point bending tests were carried out in controlled strain using four strain levels. A four point flexural beam device was placed in a climatic oven that maintains the test temperature by circulating air and allows for the testing of beams. The distance between reaction points was set to 355.6 mm and between load points to 118.5 mm. In these tests, the beams are subjected to simple flexure between the two central points where the load is applied (Figure 8).

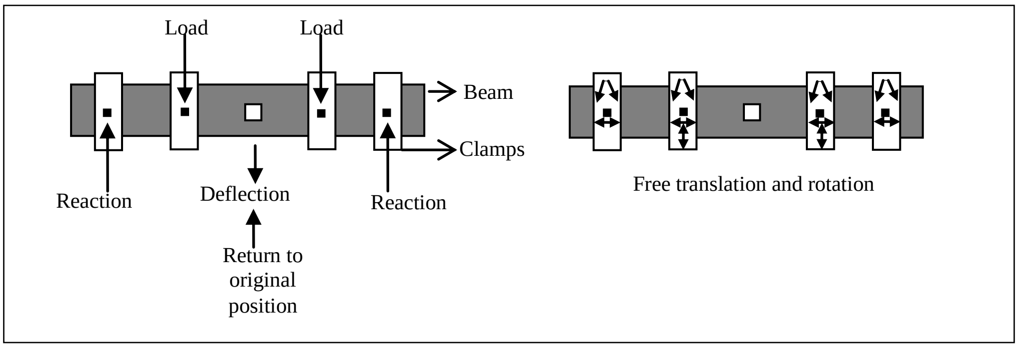

Figure 8. Flexural four point beam device (Pais et al., 2002)

In the middle section the bending moment is constant and the shear force is zero, hence this section is subjected to pure bending or flexing. Therefore, the failure of the specimens starts in a zone where the stress conditions are constant, decreasing the scatter results.

Flexural fatigue tests were conducted according to the AASHTO TP 8-94 and established that fatigue tests should be performed applying a constant sinusoidal displacement to the specimen, which produces a constant sinusoidal strain at the bottom of the specimen. This is a strain controlled test and the stress (and stiffness) decreases as the specimen fails. Stiffness evolution during a strain controlled fatigue test is used to define specimen failure. In this test failure is obtained by checking in each load cycle, if stiffness has decreased 50% from the initial stiffness (usually defined at cycle number 100) to take specimen heating as the beginning of the test into account.

Besides the determined fatigue life, dynamic modulus and the phase angle of the beams was evaluated as well. Thus, to determine the dynamic modulus a peak-to-peak strain value of 100 μm/m was used (low value, to prevent damaging the beans). The fatigue tests were done at 200, 400 and 800 □m/m (peak-to-peak). To determine the dynamic modulus the frequency sweep test was used and the modulus was measured at 0.1; 0.2, 0.5, 1, 2, 5 and 10 Hz. In the fatigue tests the frequency used was 10 Hz. The temperature of the tests was

20 ºC and for each strain level, three beams were tested. Prior the tests, the beams were placed in an environmental chamber for approximately 2 hours to reach the test temperature.

Figure 9 presents the results from dynamic modulus tests of the asphalt mixtures with asphalt rubber and the mixtures control with CAP-50/70. A set of values was obtained for each mixture at different frequencies at 20 ºC

Figure 10 presents the results of phase angle of the asphalt mixtures, as a function of the load application frequency.

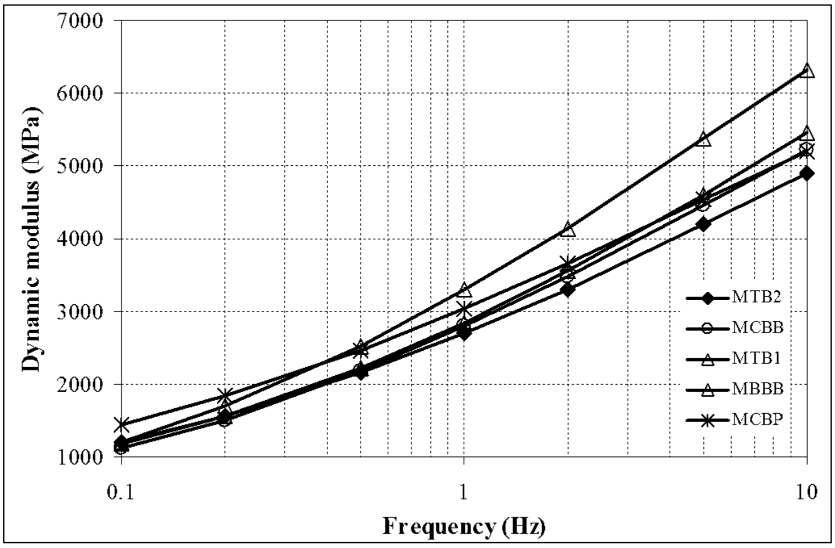

Figure 9. Dynamic modulus

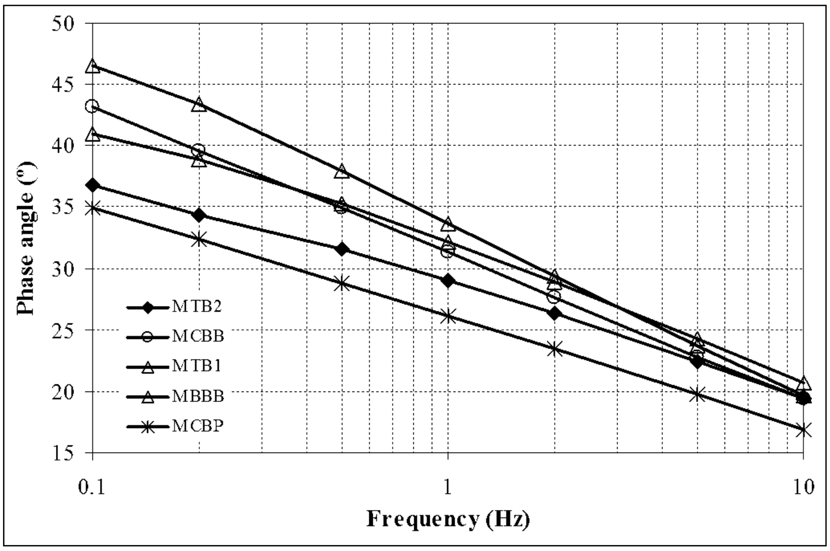

Figure 10. Phase angle

The results of dynamic modulus (Figure 9) showed that the asphalt mixture control is stiffer than asphalt rubber mixtures. Thus the lower dynamic modulus of the asphalt rubber could indicate that these mixtures have a lower stress to strain ratios than stiffer materials such conventional mixtures and consequently, enclose more elastic response to the same level of loading, which represents more flexibility to relieve stresses and to repair many of the cracks. The MCBP mixture presented higher dynamic modulus that the others asphalt mixtures due the stiffer asphalt base (PEN 35/50) in relation the CAP-50/70. Among the terminal blend asphalts rubber mixtures, the MTB2 that contain 15% of the crumb rubber presented a lower dynamic modulus that MTB1 with 20% of crumb rubber added.

From the phase angle (Figure 10), that is an indicator of the viscous or elastic properties of the mixtures, the results shown that asphalts rubber mixtures exhibited a lower phase angle at measured frequencies than a mixture control. It is an indicator that the additions of the crumb rubber into the asphalts enlarge the elastic properties of the binder. In general, the asphalts rubber with larger amount of rubber had the elastic properties increase (MCBP and MTB2).

The results obtained in the four point bending tests to determine the fatigue life of the studied asphalt mixtures are presented in Figure 11. As the fatigue tests results showed, when the asphalt rubber is applied in the mixtures, the fatigue life is increased. The asphalt rubber mixtures proved that the addition of crumb rubber conventional asphalt is capable to change and turn the mixtures able to withstand repeated loading and unloading exhibiting later fatigue failure than conventional mixtures.

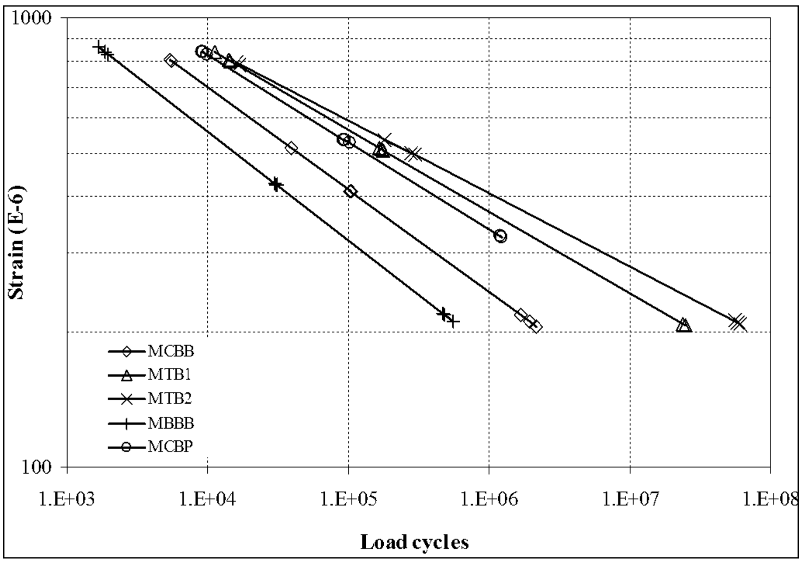

Figure 11. Fatigue life

The control mixture MBBB presented the lower fatigue life in relation to asphalt rubber mixtures. The results presented also that Brazilian mixtures produced with terminal blend asphalt rubber have fatigue life higher than the mixtures in which continuous blend asphalt rubber was used. The mixture MTB2 exhibited better fatigue life, despite is important to remind that this mixture presents lower air voids content than mixtures MTB1 and MCBB.

In comparison to Portuguese mixture MCBP, that obtained a longer fatigue life, the Brazilian mixtures had very similar behaviour.

4.4. Permanent deformation tests

The RSST-CH (Repetitive Simple Shear Test at Constant Height) test used to determine the resistance of the mixtures to permanent deformation is described by Sousa et al. (1994) and followed AASHTO TP7-01, Test Procedure C. In this test the specimen is repeatedly loaded (horizontal haversine loads corresponding to a 700 kPa shear stress magnitude), with a loading period of 0.1 s and rest period of 0.6 s, while the height of the compacted specimen (15 cm diameter by 5 cm height) is maintained constant. The test simulates the permanent deformation of the asphalt mixtures during the hottest days of the year, with a low viscosity of the asphalt. The maximum allowable rut depth was established to be 12.5 mm for one million Equivalent Standard Axle Loads (ESALs) of 80 kN. The test was accomplished either to 5000 load cycles or until five percent permanent strain is incurred by the sample. In this study, the RSST-CH was preformed at 60 ºC and the results are presented in Figure 12.

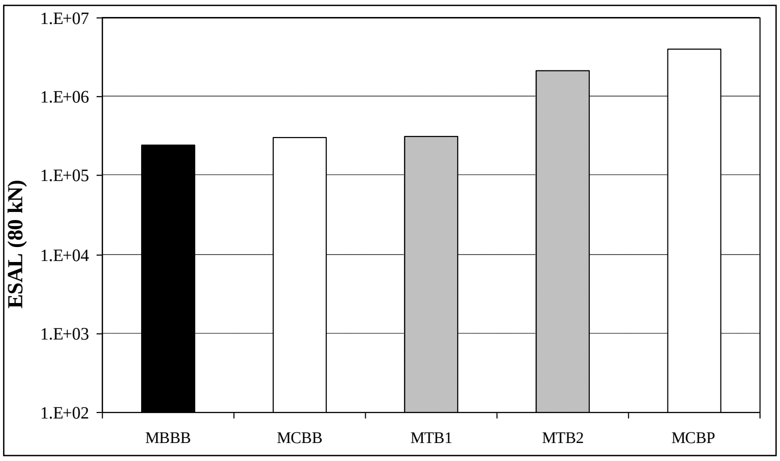

Figure 12. Permanent deformation

From the RSST-CH tests results, mixtures containing asphalt rubber improved resistance to permanent deformation. The Portuguese mixture MCBP presented the better performance, what takes to conclude that increasing the amount of crumb rubber content and the use of as asphalt base stiffer (higher viscosity) leads to reduce the permanent deformation. Considering the Brazilians mixtures, those mixtures produced by terminal blend systems (MTB1 and MTB2) presented higher performance than the mixture MCBB (by continuous blend). This improvement of the behaviour of the asphalt rubber mixtures at higher temperatures, as RSST-CH tests was performed, was also due to the larger elastic recovery and the softening points results of these binders (Tables 4 and 5) in relation to conventional asphalts (Table 3).

5. CONCLUSIONS

Asphalt rubber modified mixtures indicated outstanding enhancement over the conventional mixture. The study conducted proved the improvement in mechanical properties of asphalt rubber mixtures produced with Brazilian materials. This indicated that the use of these materials increased the project life when applied in pavements surface layers.

The asphalt tests accomplished in laboratory can to expect the behaviour of the mixtures. However, the performance of the mixtures should be evaluated through mechanical tests, such as fatigue and permanent deformation.

The morphology analyses of the asphalt rubber systems established a good technique to evaluate the compatibility between asphalt and crumb rubber. These analyses showed that asphalts rubber CBT1, CBT2 and CBP systems presented a homogeneous mixture among asphalt base and crumb rubber, in which represented the better performance in mechanical tests.

The conventional mixture obtained stiffer than asphalt rubber mixtures, as presented in dynamic modulus test at 20 ºC, which allows the pavement with asphalt rubber to exhibit lower strain levels.

All asphalt rubber mixtures presented better performance in mechanical tests (fatigue and permanent deformation) in relation to conventional mixture. The Brazilian mixtures using terminal blend system performed better than the mixtures produced by continuous blend system.

The Portuguese mixtures presented excellent mechanical properties. The results of mechanical tests proved that Brazilian asphalt rubber mixtures can be compared in terms of mechanical behaviour as mixtures produced in countries that have high developed technology.

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