PERFORMANCE OF ASPHALT RUBBER MIXTURES

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Abstract

Asphalt rubber mixtures are one of the most promising techniques to extend the service life of asphalt pavement overlays. Asphalt rubber binder is composed of crumb rubber from reclaimed tires and conventional asphalt. The asphalt rubber binder can be obtained through wet process in two different systems: terminal blending (produced at industrial plants) and continuous blending (produced in asphalt plants). This study presents a laboratory evaluation of asphalt rubber mixtures produced with different asphalt rubber binders, using gap and dense gradations. The mechanical behavior of the mixtures studied was established through several laboratory tests (stiffness, fatigue cracking and permanent deformation). A finite-element methodology was also employed to evaluate the fatigue life in terms of reflective cracking. Moreover, the morphologies of the crumb rubber and of the asphalt rubber binder were analyzed through scanning micrographs. The rheology of the asphalt rubber binder was characterized in order to predict the mechanical behavior of asphalt rubber mixtures. This study indicates that asphalt rubber mixtures improve the mechanical properties of asphalt pavements, enhancing their performance and increasing the service life of overlays in comparison to conventional mixtures.

Resumo

As misturas com asfalto-borracha constituem uma das mais promissoras técnicas utilizadas para aumentar vida de serviço dos pavimentos asfálticos reabilitados. O ligante asfalto-borracha é composto por borracha moída proveniente de pneus insersíveis e por asfalto convencional. O asfalto-borracha pode ser obtido através de dois sistemas diferentes: *terminal blending* (produzido em unidades industriais) e *continuous blending* (produzido em usinas de asfalto). Este estudo apresenta uma avaliação em laboratório de misturas com asfalto-borracha produzidas com diferentes tipos de ligantes asfalto-borracha, utilizando graduações *gap* e densa. O comportamento mecânico das misturas estudadas foi realizado através de diversos ensaios de laboratório (rigidez, fadiga e deformação permanente). Uma metodologia de elementos finitos também foi empregada para estimar a vida de fadiga em termos de reflexão de trincas. Adicionalmente, as morfologias da borracha moída e do asfalto-borracha foram analisadas através de micrografias por varredura. A reologia dos ligantes asfalto-borracha foi caracterizada de modo a prever o comportamento mecânico das misturas com asfalto-borracha. Este estudo indica que as misturas com asfalto-borracha melhoram as propriedades mecânicas dos pavimentos asfálticos, aumenta seu desempenho e também a vida de serviço da reabilitação em comparação com as misturas convencionais.

1. Introduction

The disposal of scrap tires is a serious environmental problem all over the world. In order to minimize its impact, crumb rubber from scrap tires have been used in the asphalt modification resulting the asphalt rubber binder, that have contributed to enhance the structural and functional behavior of road pavements.

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The objective of this paper is to evaluate the laboratory performance of asphalt rubber mixtures, produced using the wet process, in terms of fatigue life, permanent deformation and reflective cracking. Additionally, asphalt rubber binders were analyzed in terms of rheology and morphology.

Two gap-graded and two dense graded asphalt rubber mixtures were produced with different types of asphalt rubber binders (continuous blend and terminal blend). Continuous blend asphalt rubber binder was produced in laboratory with conventional 35/50 pen asphalt and crumb rubber by the ambient and cryogenic processes. Terminal blend asphalt binder was produced with 50/70 pen asphalt and crumb rubber by the ambient process, with two rubber percentages, 15% and 20%. A dense graded conventional mixture, produced with 50/70 pen asphalt, was used as control mixture.

The mechanical tests comprised the following: dynamic modulus and fatigue tests using a four-point bending test; permanent deformation thought Repeated Simple Shear Test at Constant Height (RSST-CH). The reflective cracking resistance was studied through the methodology proposed by Minhoto et al. (2007, 2008), based on finite elements.

2. Materials

2.1. Aggregate and mixtures gradations

The dense graded asphalt rubber mixture was specified in accordance with type IV of the Asphalt Institute (AI) mix and prepared with asphalt rubber binder from continuous blending (35/50 pen asphalt and ambient crumb rubber) and terminal blend with 15% of rubber. The gap gradation used to produce the asphalt rubber mixtures followed the Caltrans (California Department of Transportation) specifications. The mixtures were prepared with asphalt rubber binder from continuous blending (35/50 pen asphalt and cryogenic crumb rubber) and terminal blend with 20% of rubber. The dense gradation used to prepare the control mixtures with conventional asphalt (50/70 pen) was the “DNIT Grade C”, specified by the Brazilian Road Department. The sieve analyses followed the ASTM C 136 (1996) test method and the results are presented in Figure 1 and Table 1.

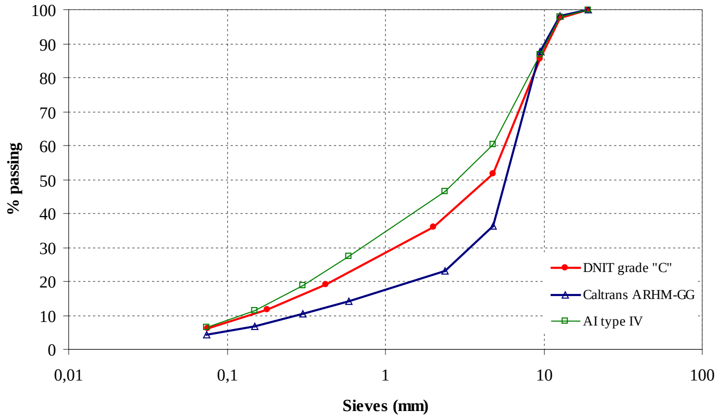

Figure 1. Mixtures curves

Table 1. Mixture gradations

Sieves size		% passing		
inch/nº	mm	Caltrans ARHM-GG	DNIT grade “C”	Asphalt Institute mix type IV
3/4"	19,0	100	100	100
1/2”	12,7	98	98	98
3/8”	9,5	88	86	87
nº 4	4,8	36	52	60
nº 8	2,4	23	36	46
nº 30	0,6	14	19	27
nº 50	0,3	10	12	19
nº 100	0,15	7	6	11
nº 200	0,075	4	100	7

2.2. Crumb rubber

Two crumb rubbers were used in this study. To produce continuous blending asphalt rubber binder, both cryogenic and ambient crumb rubber were introduced. To produce terminal blend asphalt rubber, only ambient crumb rubber was used. The crumb rubber was tested in accordance with the requirements of ASTM C 136, and the results are presented in Figure 2 with the Arizona Department of Transportation (ADOT) limits.

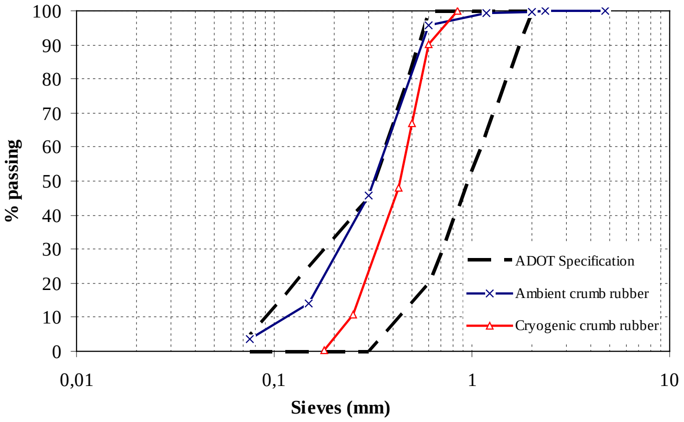

Figure 2. Crumb rubber gradations

Identification of the morphology of the crumb rubbers was conducted using a Scanning Electron Microscope (SEM), LEICA Cambridge S 360. The images in Figure 3 (50x magnification) indicate that the morphology of the particles from ambient and cryogenic processes is completely different.

The surface analysis of the crumb rubber obtained by the ambient process presents an irregular structure with several sizes and shapes, with rubber agglomerates, the smallest particles of which are adhered, having a spongy appearance. On the other hand, the surface of the cryogenic crumb rubber presents a flat texture with uniform and regular grains. The specific surface was calculated with a proportion of 19,27 m^2/kg for ambient crumb rubber and 13,61 m^2/kg for cryogenic crumb rubber.

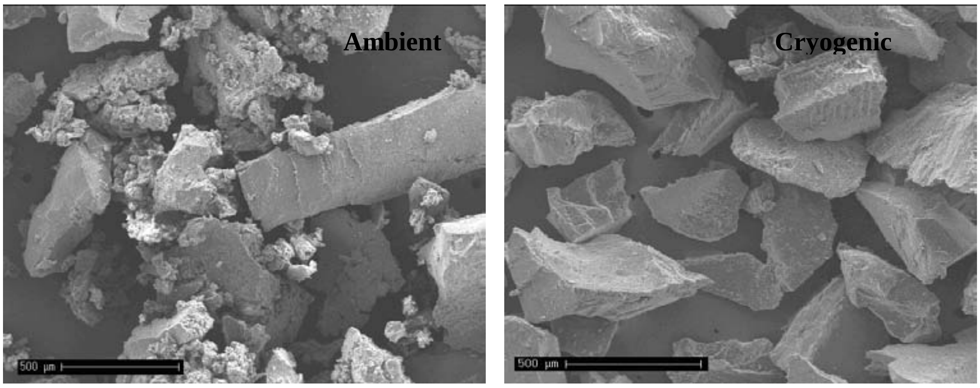

Figure 3. Morphology of the crumb rubbers

2.3. Physical properties of asphalts

Two conventional asphalts were tested in this study. The 50/70 pen (named as AB) was used to produce the control mixture and to produce the terminal blend asphalt rubber. The 35/50 pen asphalt (AP) was used to produce the continuous blending asphalt rubber binder.

The terminal blend asphalt rubber were produced at an industrial plant, herein named as TB1 (20% of crumb rubber) and TB2 (15% of crumb rubber). The continuous blending asphalt rubber binders CB1 (with cryogenic rubber) and CB2 (with ambient rubber) were produced as follows: 17% of cryogenic crumb rubber; 90 minutes of digestion time; 180ºC of digestion temperature.

The physical properties of the asphalts were evaluated in laboratory in terms of: softening point; penetration; resilience, apparent viscosity (Brookfield viscometer). The hardening of the asphalts due to oxidation was also tested through the Rolling Thin-Film Oven Test (RTFOT). The asphalt rubber binders tested followed the specifications of the ASTM D 6114 (1997), type II. The test results are presented in Table 2.

Table 2. Asphalts properties

Test	Standard	AB	AP	TB1	TB2	CB1	CB2
Penetration 25ºC, 100g, 5s (0,1 mm)	ASTM D5	51,5	33,0	40	42	16,8	19,7
Softening point, ring and ball (ºC)	ASTM D36	51,5	52,7	68,0	67,7	73,4	69,9
Apparent viscosity* (cP), 175ºC	ASTM D2196	127	175	2179	1644	2246	4058
Resilience (%)	ASTM D5329	0	9	28	33	49	52
RTFOT 163ºC, 85 minutes							
Change of mass (%)	ASTM D2872	0,3	0,2	0,3	0,3	0,9	0,2
Softening point** (ºC)		4,3	0,5	1,0	2,9	11,2	17,1
Penetration 25ºC, 100g, 5s (0,1 mm)		22,3	27,7	28,8	25,3	15,5	19,5
Retained penetration (%)		43,3	84,0	72,0	60,2	92,2	99,0
Apparent viscosity* (cP), 175ºC				5350	1962	3925	8813
Resilience (%)				39	36	56	52

* Brookfield viscometer, spindle 27, 20 rpm; **increment of softening point after RTFOT.

The test results showed that the modified asphalts were significantly more viscous than the conventional ones. The asphalt rubber binders TB1 and TB2 seemed to be similar, except for the fact that TB1 presented higher viscosity (more rubber content) and that TB2 had more elasticity. The differences between CB1 and CB2 were more evident. CB1 had lower viscosity and a higher softening point. The low viscosity of the continuous blending in relation to terminal blending can be explained by the fact that it was produced with more rigid asphalt than TB. Asphalt rubber binders CB (1 and 2) presented a high softening point than TB (1 and 2), what may indicate that mixtures produced with CB would be highly resistant to permanent deformation. In general, asphalt rubber binders are not very sensitive to hardening.

2.4. Compatibility of asphalt rubber binder systems

The compatibility of asphalt/polymer systems, such as asphalt rubber binder, may be defined in several ways (Brule, 1996). It may be in terms of the achievement of a particular morphology, i.e. the structural arrangement of the polymer (rubber) particles, chains or groups within the asphalt matrix. A reaction is claimed to occur when the asphalt and the rubber particles interact. Observation suggests that particles seem gel-coated (Van Kirk et al., 1998). Compatible systems usually have superior rheological characteristics, aging and stability properties than those of incompatible systems at the same polymer level (Holleran et al., 2001).

Despite the fact that ambient crumb rubber, due to the greater surface area, can interact with asphalt more easily and quickly than cryogenic asphalt, the compatibility of the system still depends on the other parameters, such as the asphalt base, the amount of the crumb rubber and the proportion of asphalt light fraction.

The SEM analysis was used to evaluate the compatibility of the asphalt rubber binder system through the interaction with the crumb rubber and the conventional asphalt after blending. Figures 4 and 5 illustrate the asphalt rubber binder microstructures (100x magnification). In both, the systems showed to be compatible.

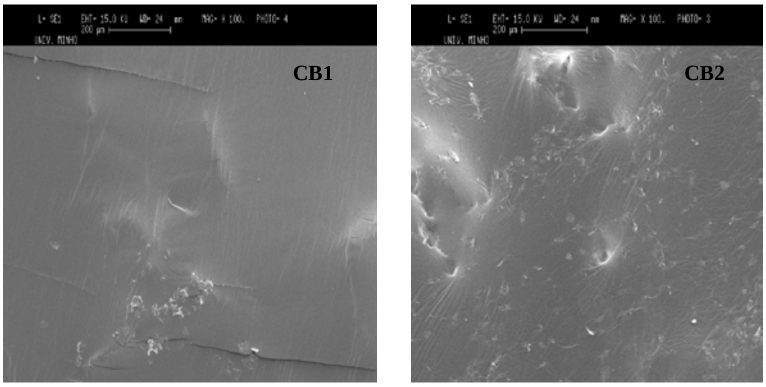

Figure 4. Microstructure of asphalts rubber binders CB1 and CB2

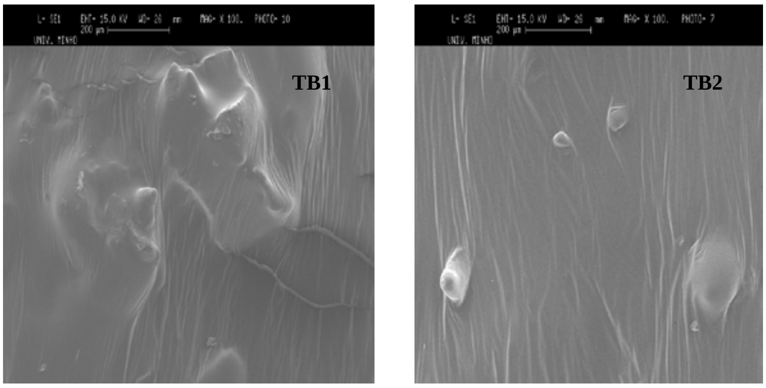

Figure 5. Microstructure of asphalts rubber binders TB1 and TB2

The configuration used in this study to produce continuous blending asphalt rubber binder resulted in a good interaction and, apparently, 35/50 pen asphalt reacted better with cryogenic than with ambient rubber (Figure 4). The terminal blend asphalt rubber system allows blending or combining asphalt and crumb rubber together to produce a long lasting product. Thus asphalt rubber binder produced through this system resulted in a compatible system and in a perfect interaction between asphalt (50/70 pen) and ambient and cryogenic rubbers (Figure 5).

2.5. Rheology of asphalts rubber binder

Asphalt is a viscoelastic material, meaning that it simultaneously shows the behavior of an elastic material and that of a viscous material. The relationship between these two properties is used to measure the capability of the binder to resist permanent deformation and fatigue cracking. A binder needs to be stiff and elastic to resist permanent deformation; to resist fatigue cracking, the binder needs to be flexible and elastic (FHWA, 1994).

The rheology tests with rheometers are used to characterize the viscous and elastic behavior of the asphalt. It is accomplished by measuring the viscous and elastic properties of a thin asphalt sample, between an oscillating and a fixed plate. As the force (shear stress) is applied to the asphalt by the spindle, the rheometer measures the response (shear strain) of the asphalt to the force. If the material was perfectly elastic, the response would coincide immediately with the applied force, and the time lag between the two would be zero. A perfectly viscous material would have a larger time lag between load and response.

The relationship between the applied stress and the resulting strain quantifies both types of performance, and provides the necessary information to calculate two important asphalt binder properties: the complex shear modulus (G*) and the phase angle (δ). The complex shear modulus, G*, represents the total deformation resistance when loaded or sheared and it is defined as the ratio of maximum shear stress (τ_{max}) to maximum shear strain (ε_{max}), expressed as follows:

$$G^* = \frac{\tau_{\max}}{\varepsilon_{\max}} \qquad (1)$$

The phase angle, δ, represents the relative distribution between the elastic response and the viscous response to loading. It indicates the delayed strain response, or lag, of the binder to the applied shear stress, during steady state conditions (Roberts et al., 1996). For a perfectly elastic material, δ is zero, and the whole deformation is temporary, whereas for a viscous material, δ approaches 90º, and the deformation is permanent.

The Superpave specifications define the rutting factor, G*/sin δ, that represents the maximum temperature that a binder can reach without permanent deformation. The fatigue cracking factor is G*.sin δ.

In this study, the rheological characterization of asphalt rubber binders was performed to estimate the mechanical behavior of the material. The rheological data were collected using a parallel plate rheometer (Rheological StressTech HR) (sample with a diameter of 40 mm and a thickness of 0,8 mm) which was capable of measuring the complex shear modulus and the phase angle for different stresses and strain rates (Figure 6).

In relation to the asphalt rubber binder obtained by the continuous blending (CB) and through the terminal blend processes (TB), the tests were conducted at 20ºC (intermediate service temperature) and 60ºC (high service temperature) with frequencies between 1 to 10 Hz. Figures 7 and 8 present the G*/sinδ, at 60ºC and G*.sinδ , at 20ºC. The phase angle is presented in Figure 9.

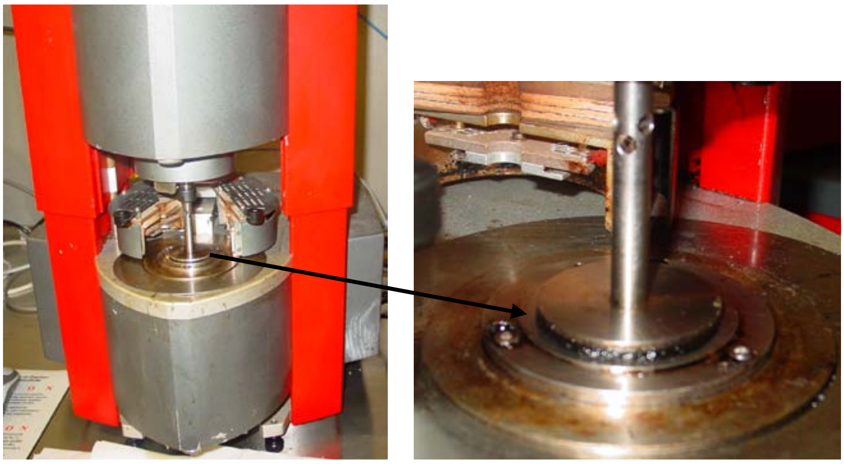

Figure 6. Rheometer and parallel plates

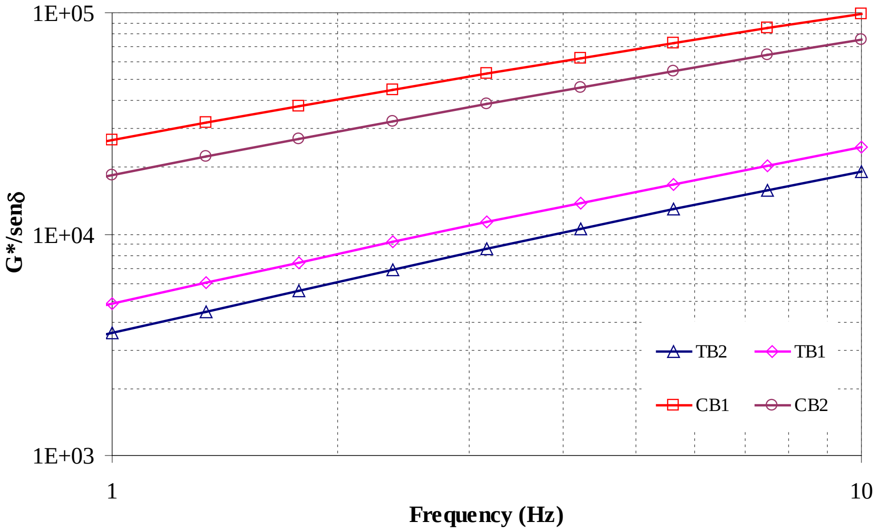

Figure 7. G*/sinδ at 60ºC

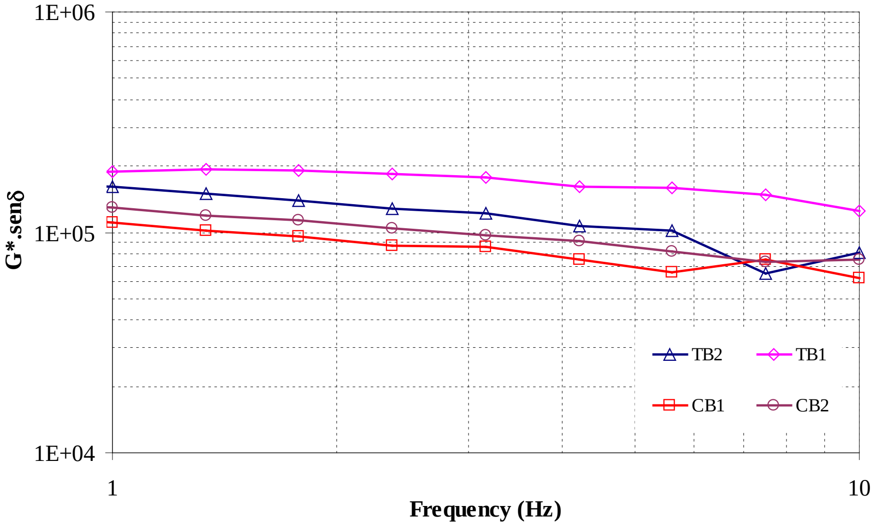

Figure 8. G*.sinδ at 20ºC

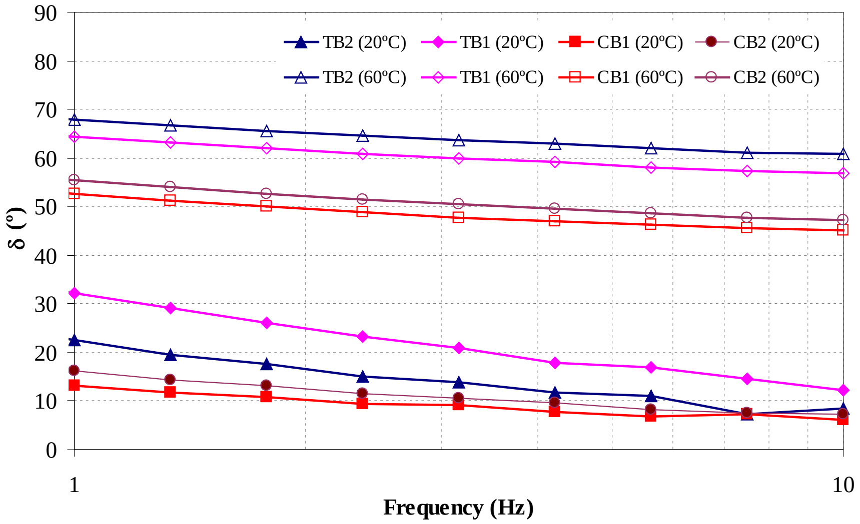

Figure 9. Asphalts rubber binder phase angles

The results of the rheology tests are an indicator of the properties of the asphalt rubber binder and can be used to predict the mixture performance. The results obtained allow concluding that, at high temperatures, the asphalt rubber binder CB1 and CB2 should acquire higher resistance to permanent deformation than TB1 and TB2, due to higher values of G* and lower values of δ. Furthermore, for intermediate temperatures, CB1 and CBs also present the properties of a soft elastic material (lesser G*.sinδ and lower δ), that probability would improve the fatigue properties.

The complex modulus of asphalt, at many levels of temperature and load time-rate, can be determined by a master curve constructed at a reference temperature (20ºC). Master curves are constructed using the principle of time-temperature superposition.

To construct the master curves of asphalt rubber binder, obtained by graphic translation of the isotherms aligning frequencies of same value, the rheology tests were conducted under five temperatures (20ºC, 30ºC, 40ºC, 50ºC and 60ºC) with applied frequencies between 0,0001 to 100 Hz. The master curves, at a reference temperature of 20ºC, are presented in Figure 10. The results show that CB1 and CB2 are more elastic than TB1 and TB2, what can be verified by the slope of the curves (a horizontal curve represents a purely elastic behavior). TB1 would be more susceptible to temperature variations.

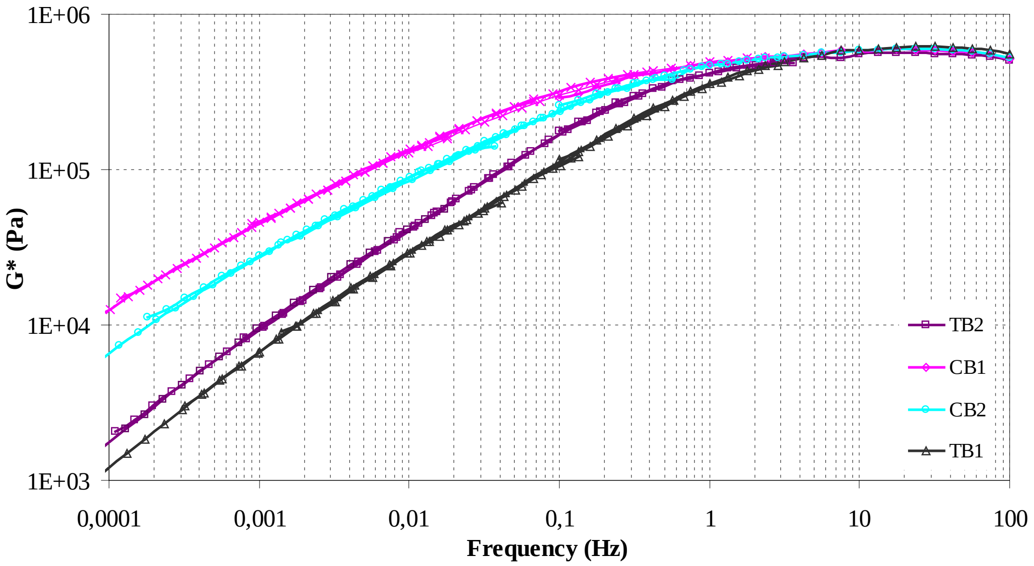

Figure 10. Master curves of the asphalt rubber binders

2.6. Asphalt mixtures

Gap and dense graded asphalt rubber mixtures were produced using continuous and terminal blending. A conventional dense graded mixture was produced with conventional asphalt 50/70 pen, as the control mixture. These mixtures were produced as follows:

– MCB1 – gap graded asphalt rubber mixture; Caltrans ARHM-GG gradation; 8,0% of asphalt content (continuous blending asphalt rubber binder, produced in laboratory, asphalt base 35/50 pen, 17% of cryogenic rubber content, 180ºC digestion temperature; reaction time of 90 minutes), and 6,0% of void content;

– MCB2 – dense graded asphalt rubber mixture; AI mix type IV gradation; 7,0% of asphalt content (continuous blending asphalt rubber binder, produced in laboratory, asphalt base 35/50 pen, 17% of ambient rubber content, 180ºC digestion temperature; reaction time of 90 minutes) and 5,0% of void content;

– MTB1 – gap graded asphalt rubber mixture, Caltrans ARHM-GG gradation; 8,5% of asphalt content (terminal blend asphalt rubber, produced at industrial plant, asphalt base 50/70 pen, 20% of ambient rubber content) and 6,0% of void content;

– MTB2 – dense graded asphalt rubber mixture, AI mix type IV gradation; 7,0% of asphalt content (terminal blend asphalt rubber, asphalt base 50/70 pen, produced at industrial plant, 15% of ambient rubber content) and 5,0% of void content;

– MCO – dense graded conventional mixture, DNIT Grade “C” gradation; 5,5% of asphalt content (50/70 pen) and 4,0% of void content.

Table 3 presents a summary of the studied mixtures, in which the aggregate gradation, binder content, binder type and void content can be observed.

The mixtures were compacted with a steel roller in a mould (75x49x8 cm^3). The compacted slabs were sawed and cored with the appropriate dimension for each type of test.

Table 3. Asphalts mixtures properties

Mixture	Aggregate gradation	Binder content (%)	Binder type	Void content (%)
MCB1	Caltrans, gap	8,0	Continuous blending, 35/50, 17% rubber	6,0
MCB2	AI, dense	7,0	Continuous blending, 35/50, 17% rubber	5,0
MTB1	Caltrans, gap	8,5	Terminal blending, 50/70, 20% rubber	6,0
MTB2	AI, dense	7,0	Terminal blending, 50/70, 15% rubber	5,0
MCO	DNIT, dense	5,5	50/70	4,0

3. Mechanical tests

3.1. Dynamic modulus and fatigue life

Four point bending tests were conducted to evaluate the dynamic modulus and fatigue life. Beam specimens of 38 cm long by 5 cm thick by 6,3 cm wide were used in frequency sweep test to measure the dynamic modulus and the phase angle when subjected to seven loading frequencies (10; 5; 2; 1; 0,5; 0,2; 0,1 Hz), at 20ºC.

Fatigue tests were conducted according to the AASHTO TP8/94, at 20ºC and at 10 Hz. Fatigue failure was assumed to occur when the dynamic modulus was reduced to 50 percent of the initial value. The tests were conducted at three strain levels of approximately 200, 400 and 800 microstrains, with three repetitions for each level. The test results considered bottom-up cracking to determine an empirical fatigue relationship of the simple power formula (Monismith et al., 1971) shown as:

$$N = a\left(\frac{1}{\varepsilon}\right)^{b} \tag{2}$$

where: N = number of repetitions until failure; ε = tensile strain applied (10^{-6}); a and b = experimentally determined coefficients.

The dynamic modulus of the mixtures for all the frequencies applied is shown in Figure 11 and the phase angle of the mixtures is depicted in Figure 12.

The results in Figure 11 show that the MCB2 has a higher dynamic modulus than the other mixtures, and at 10 Hz, this value is similar to MCO. It is noticed that the terminal blend mixtures (MTB1 and MTB2) presented lower dynamic modulus than the continuous blend mixtures. In Figure 12, the results of the phase angle, an indicator of viscoelastic properties of the mixtures, indicate that MCO is more viscous than asphalt rubber mixtures (continuous blend and terminal blend) what represents an improvement in the elastic response and, therefore, a better fatigue performance of the asphalt rubber mixtures.

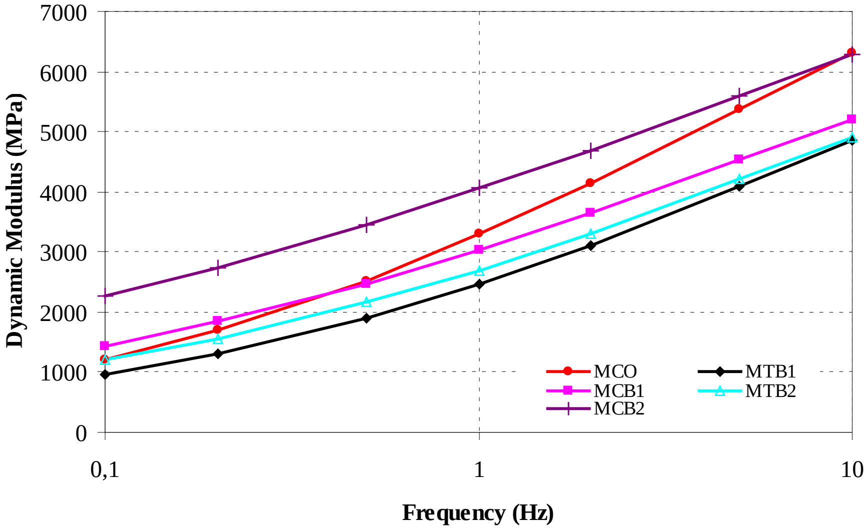

Figure 11. Dynamic modulus of the mixtures

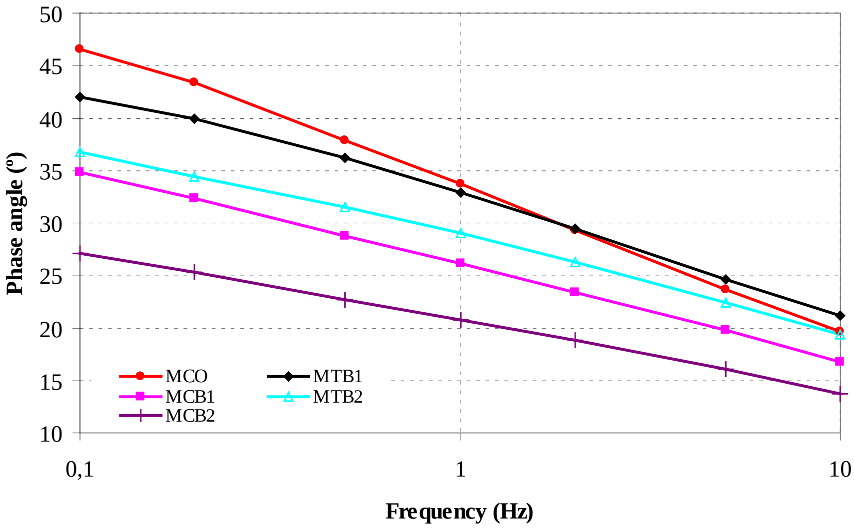

Figure 12. Phase angle of the mixtures

Table 4 shows the experimental parameters of fatigue laws of the mixtures, according to Equation 2, with the strain expressed in terms of microstrains. Figure 13 presents the results of the fatigue curves.

Table 4. Experimental fatigue parameters, according to Equation 2

Mixture	a	b	R^2
MCO	1,185E+15	4,037	0,99
MCB1	2,782E+17	4,597	0,96
MCB2	4,852E+19	5,463	0,99
MTB1	4,587E+20	5,623	0,99
MTB2	2,031E+21	5,915	0,99

According to Figure 13, asphalt rubber mixtures have an enhanced fatigue performance when compared to conventional mixtures. The terminal blend mixtures presented higher fatigue life than the continuous blend mixtures. However, it is important to consider that MTB1 has more asphalt content (8,5%) than MBC1 (8,0%). For terminal blend mixtures, it was also observed that the use of dense gradation (MTB2, 7,0% of asphalt content) improved the fatigue performance of the mixture better than the gap gradation (MTB1, 8,5% of asphalt content). The same occurred with continuous blend mixtures, in which the MCB2 (7,0% of asphalt content) presented a more extended fatigue life than MCB1 (8,0% of asphalt content). It was observed that lower air void contents improved the fatigue performance of all asphalt rubber mixtures.

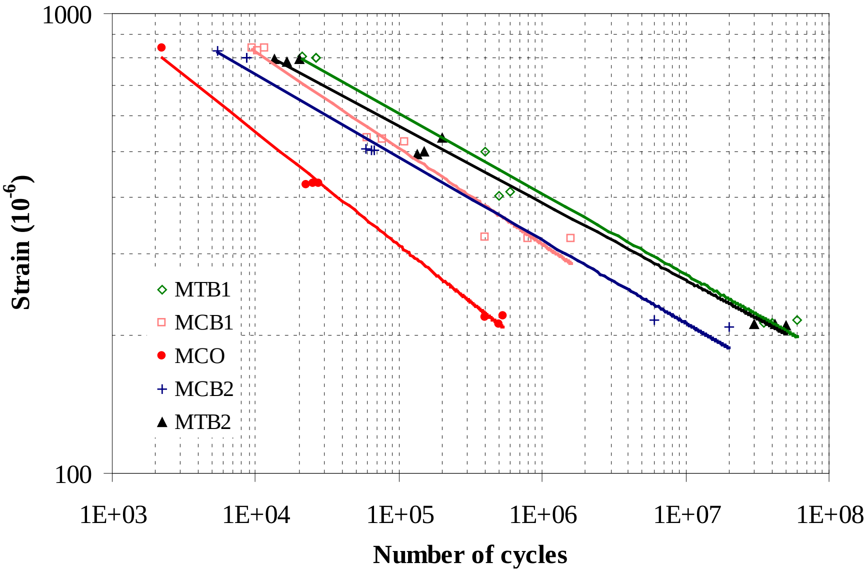

Figure 13. Fatigue curves

The rheology results, in terms of G*.sinδ, were confirmed by the fatigue tests. The greater G*.sinδ, the longer fatigue life, as in can be observed in Figure 14. Only the conventional mixture (MCO) does not follow the trend presented by the asphalt rubber mixtures.

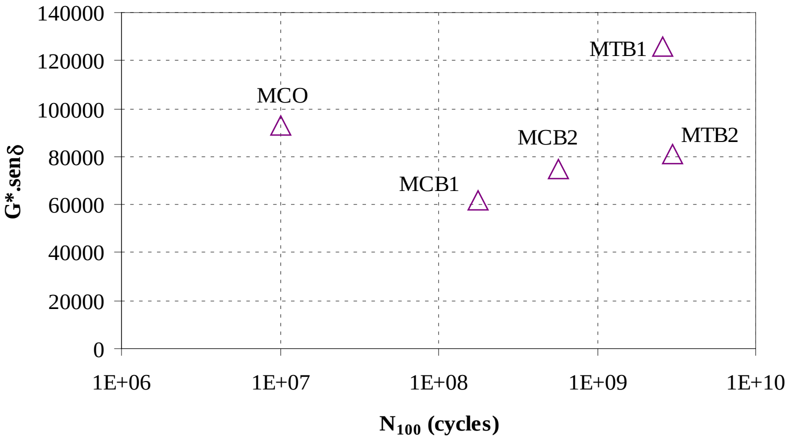

Figure 14. Fatigue life versus G*.sinδ

3.2. Permanent deformation

Cylindrical specimens with 5 cm thick and 15 cm diameter were used for permanent deformation tests through a Repeated Simple Shear Test at Constant Height (RSST CH) that consists of applying a repeated shear stress to a cylindrical specimen, while measuring the resulting plastic shear strains, at a given controlled temperature. During the test there is no change in volume (the height of the specimen is maintained constant). The applied load has a duration of 0,1 seconds, with an unload time of 0,6 seconds. A vertical load is applied to the sample during the test to ensure a constant height. The test procedure followed the AASHTO TP7-01, Test Procedure C. The shear stress is applied to the sample until the sample reaches 5% permanent shear strain. The RSCH-CH test is carried out until the specimens reach the maximum plastic shear strain of 0,04545, which is equivalent to the limit value of 12,7 mm rut depth (Sousa et al., 1994), expressed in Equation 3.
In this study, the asphalt rubber specimens were tested at 60°C. Figure 15 presents the permanent deformation results, expressed in terms of ESALs (80 kN Equivalent Single Axes Loads) to reach a rut depth of 12,7 mm.

$$\mathrm{ESAL} = 10^{\frac{4.36+\log N_{mpss}}{1.24}} \tag{3}$$

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.

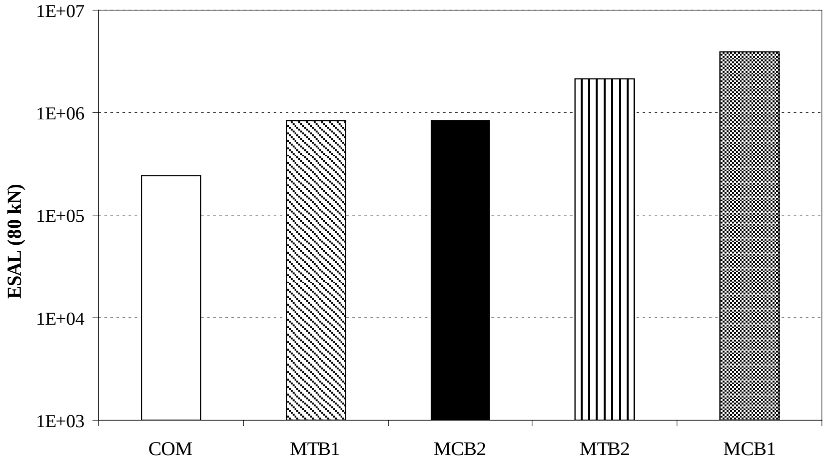

Figure 15. Permanent deformation test results

The permanent deformation results (Figure 15) give evidence that the asphalt rubber mixtures are more resistant than the conventional mixture. MCB1 showed a better performance than the other mixtures. The resistance to permanent deformation of MCB1 is justified by the greater softening point and large elastic recovery presented by the CB1 asphalt rubber binder. The gap graded gradation in continuous blending mixtures promoted an enhanced resistance to permanent deformation, associated with an excellent interaction between cryogenic rubber and 35/50 pen to resist rutting. In the case of the terminal blend mixtures, MTB2, with less asphalt and voids content and dense gradation, it performed better than MTB1.

The rheology results, in terms of G*/sinδ, were confirmed by the permanent deformation tests once the greater G*/sinδ, the greater the resistance to permanent deformation, as it can be observed in Figure 16.

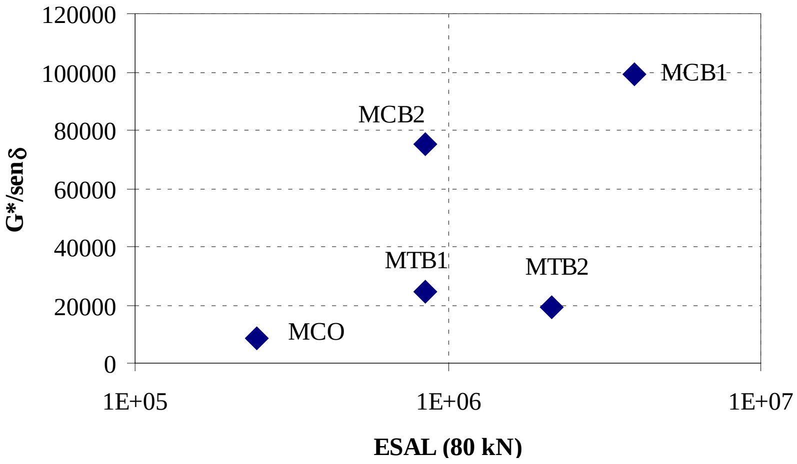

Figure 16. Permanent deformation versus G*/sinδ

3.3. Reflective cracking

The reflective cracking resistance of the studied mixtures was evaluated using the methodology proposed by Minhoto et al. (2007, 2008), based on finite elements, which takes into account the influence of temperature variation in the reflective cracking of asphalt pavements.

The numeric simulation used to predict the reflective cracking was accomplished by using the finite element program ANSYS, which allows evaluating the damage of a pavement overlay due to the effect of traffic and temperature variations. The temperature variations considered the temperatures verified in a sub-tropical climate (South of Brazil) and air temperature collected for 30 years in Florianópolis, Brazil.

The geometry adopted to evaluate the resistance to reflective cracking was based on a pavement with the following characteristics: (i) overlay = 0,12 m; (ii) existent cracked layer = 0,21 m; (iii) unbound layer = 0,20 m.

The application of the finite element model reproduced the pavement damage for the period of one year, as presented in Figure 17, in which the pavement life is also depicted.

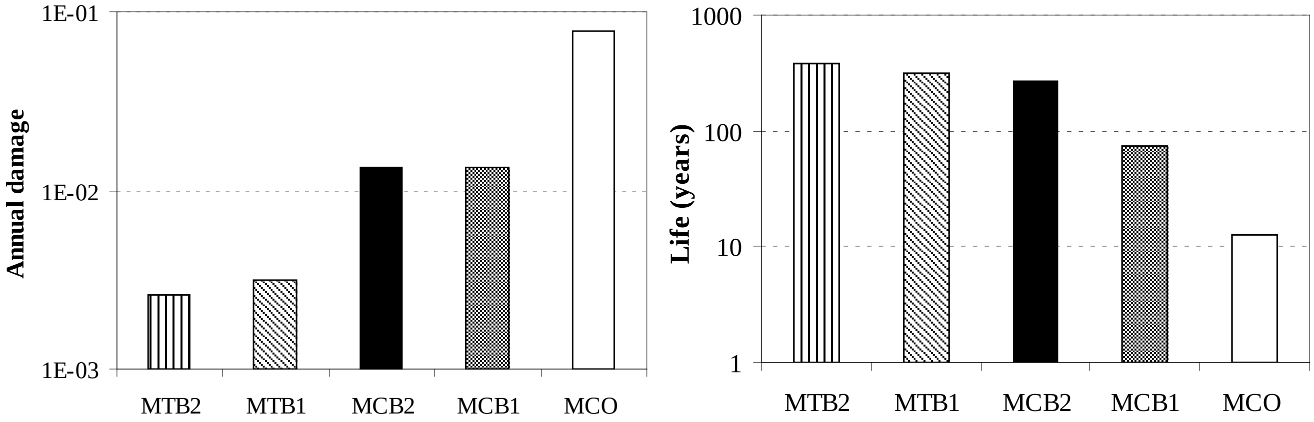

Figure 17. Annual damage and reflective cracking life of the mixtures

The results obtained through the numeric simulation showed a great difference between the asphalt rubber mixtures and conventional ones. Furthermore, extremely high life values for the modified mixtures were assessed. This can be explained by the weak performance obtained by MCO in fatigue tests in comparison to asphalt rubber mixtures.

4. Conclusions

The primary aim of this work was to evaluate the mechanical properties of asphalt rubber mixtures when compared to conventional ones. The mechanical tests included dynamic modulus, fatigue cracking and permanent deformation. The methodology developed by Minhoto et al. (2007, 2008), which assessed reflective cracking in pavement overlays through FEM analysis, was applied to evaluate the resistance to reflective cracking of asphalt rubber mixtures.

From the SEM analysis it can be observed that cryogenic and ambient crumb rubbers have different morphologies. While cryogenic has an angular smooth and cracked appearance surface, ambient has a porous surface. The SEM morphology of asphalts rubber binder systems also showed that all binders result in compatible systems. These analyses are significant and helpful to make a decision when evaluating the digestion time requested to produce asphalt rubber binders.

Asphalt rubber binders were characterized rheologically to estimate the mechanical behavior of the material, following the SUPERPAVE parameters $G^*.\sin\delta$ and $G^*/\sin\delta$, which are good indicators of fatigue performance and resistance to permanent deformation. However, the mixture variables such as asphalt and void content and type of gradation also need to be considered in the prediction.

The continuous blend mixtures presented higher dynamic modulus than terminal blend. The MCB2 presented a higher dynamic modulus and, at 10 Hz, the value was similar to that of conventional mixtures. The results of the phase angle indicated that the conventional mixture is more viscous than asphalt rubber mixtures independently of the process used, what represents an improvement in its elastic response and, consequently, a better fatigue performance.

Fatigue tests showed that asphalt rubber mixtures exhibit significantly more fatigue performance than conventional mixtures. Terminal blend mixtures presented a higher fatigue life than continuous blend mixtures.

The results of permanent deformation tests demonstrated that asphalt rubber mixtures were more resistant to the development of plastic shear strains than the conventional mixture. Although similar, the MCB1 presented a better performance, followed by the MTB2. This behavior was also predicted through rheology tests.

The FEM method used to simulate reflective cracking was a valuable tool to evaluate the performance of asphalt overlays under traffic and thermal loading conditions. The results of the FEM method showed that the mixture MCB presented a more extended fatigue life in relation to reflective cracking than the others.

The most important conclusion drawn from this study states that asphalt rubber mixtures present better mechanical properties and a superior performance than conventional mixtures, what allows asphalt pavement layers have a more extended life cycle.

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