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Dense Graded Hot Mixes using Asphalt-Rubber Binders with High Rubber Contents

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ABSTRACT. *This paper shows the results of a study about the mechanical behavior of dense graded asphalt-rubber hot mixes prepared with two different types of asphalt-rubber binders. These asphalt-rubber binders were obtained with penetration grade asphalt (AC 50/70) mixed with 21% and 25% of crumb rubber in weight. The rubber was recycled from unserviceable tires using the ambient grinding process. Hot mixes made with the conventional binder AC 50/70 were also studied for comparison. The mechanical behavior of hot mixes was evaluated through laboratory tests for fatigue life, permanent deformation and indirect tensile strength. The results showed that asphalt-rubber hot mixes presented better mechanical behavior for fatigue life and permanent deformation than those obtained with the straight binder.*

KEYWORDS: *Asphalt-rubber, Crumb Rubber, Asphalt Hot Mixes.*

1. Introduction

The experiences obtained with the use of asphalt-rubber hot mixes in several countries showed the excellent structural and functional behavior of this type of material. In general, improvements can be observed in the fatigue life of wearing courses, reduction of maintenance costs, increase of skid resistance, decrease of reflective cracking in overlays, and reduction of noise levels.

In addition to the improvement of mechanical behavior of asphalt hot mixes there is also an environmental benefit. Asphalt-rubber hot mixes incorporate to the conventional binder approximately 20%, by weight, of crumb rubber recycled from ground tires.

Crumb rubber recycled from ground tires is composed of different constituents capable of conferring better mechanical properties to the conventional binder (Holleran *et al.*, 2000). The rubber content incorporated to the conventional binder is one of the main factors that influence the mechanical behavior of asphalt-rubber hot mixes (Dantas-Neto *et al.*, 2003). Increase of the rubber content produces a substantial increase in the viscosity of binders modified with crumb rubber recycled from ground tires. This increase of viscosity reduces the workability of the modified binders limiting, in general, the rubber contents to 20%, by weight.

The objective of this paper is to study the influence of increasing rubber content on the mechanical behavior of asphalt-rubber hot mixes, in terms of indirect tensile strength, fatigue life and resistance to development of permanent deformations. In this study, asphalt-rubber hot mixes obtained with dense gradation (grading envelope C of DNER-ES 313/97) were made with two different types of asphalt-rubber binders. Modified binders were produced, mixing straight asphalt of penetration grade 50/70 (AC 50/70), produced in Portugal, and crumb rubber obtained by the ambient grinding process, for rubber contents of 21% and 25%, by weight. The evaluation of the mechanical behavior of the asphalt-rubber hot mixes was made through laboratory tests for indirect tensile strength, resilient modulus, fatigue life and permanent deformation.

2. Background

The use of binders modified with crumb rubber recycled from ground tires in asphalt hot mixes began in the 1940's. The objective of the incorporation of the crumb rubber to conventional binders was to improve the mechanical behavior of the asphalt hot mixes and to reduce environmental pollution levels (Mohammad *et al.*, 2000).

In the 1960's, engineer Charles McDonald began studying about the incorporation of crumb rubber to conventional binder, denominated as asphalt-

rubber. The method of production of the asphalt-rubber was patented then and known as the McDonald process or wet process (Way, 2000).

In 1964, Arizona Department of Transportation (ADOT) began to use asphalt-rubber hot mixes in maintenance services, mainly in seal coats for deteriorated pavements. From 1968 to 1972, the ADOT executed a series of chip seals using asphalt-rubber. From 1974 to 1989, asphalt-rubber hot mixes were applied in several highways as Stress Absorbing Membrane Interlayer (SAMI), with the objective of reducing reflective cracks in the pavements (Way, 2000).

In the 1980's, asphalt binders modified with crumb rubber recycled from ground tires began to be used in chip seals and overlays in South Africa. Currently, asphalt-rubber hot mixes have been executed with open, gap and dense gradation. The results showed that the asphalt-rubber hot mixes have superior fatigue life when compared with asphalt hot mixes executed with conventional binders (Visser, Verhaeghe, 2000; Potgieter *et al.*, 2000).

2.1. *Asphalt-rubber: production methods*

Modified binders with crumb rubber recycled from ground tires are obtained through the incorporation of crumb rubber to conventional binders under certain temperature conditions. The resulting asphalt-rubber presents the mechanical properties of the conventional binder and the elasticity of the crumb rubber (Huang *et al.*, 2000).

There are two methods for the manufacture of asphalt-rubber denominated wet process and dry process. In the wet process, the conventional binder is heated up to temperatures about 190ºC in a super-heating tank in hermetic conditions, being transported soon after to an adapted mixture tank. In the mixture tank, crumb rubber is added to the preheated conventional binder. The digestion process, which is the mixture of the conventional binder with the crumb rubber, takes place over a period of 1 to 4 hours, at a temperature of 190ºC. This mixture process is assisted by the action of a horizontal single shaft in-line paddle agitator (Visser and Verhaeghe, 2000).

In the dry process, dry particles of crumb rubber are added to preheated aggregate, before the addition of conventional binder (Visser and Verhaeghe, 2000). The aggregate is heated up to temperatures of approximately 200ºC, then the crumb rubber is added and the mixture proceeds for approximately 15 seconds or until the formation of a homogeneous composition of aggregate-crumb rubber. Then, conventional binder is added to mixture aggregate-crumb rubber by conventional methods in a mixing plant.

In general, there is not a standard procedure for production of modified binders with crumb rubber recycled from ground tires (Antunes *et al.*, 2000; Oliver, 2000; Visser and Verhaeghe, 2000; Mohammad *et al.*, 2000; Huang and Yan, 2000). There is no fixed criterion for the choice of the content and type of crumb rubber, or for the time and temperature of digestion. These parameters are sometimes chosen as a function of the production capability of the available equipment in different countries and they influence directly the behavior of the modified binders.

2.2. *Mechanical properties of asphalt-rubber hot mixes*

The structural performance of the wearing courses of flexible pavements is directly related to the mechanical properties of the asphalt hot mixes employed. (Sousa *et al.*, 2000) studied the behavior of dense graded asphalt-rubber hot mixes made with modified binders, in terms of fatigue life and resistance to reflective cracks. Mixtures made with asphalt-rubber, for a rubber content of 18% by weight, and conventional binders presented an optimum binder content of 8% and 5%, in relation to the total mixture, respectively. The fatigue tests were carried under controlled strain, as well as under controlled stress.

The results for tests under controlled strain and controlled stress showed that asphalt-rubber hot mixes had a fatigue life superior to those mixtures made with conventional binders. This behavior is attributed to the larger flexibility of the mixtures provided by the incorporation of crumb rubber into the conventional binder (Sousa *et al.*, 2000)

Several studies indicate a satisfactory performance of asphalt-rubber hot mixes in terms of resistance to the development of permanent deformations, in relation those asphalt hot mixes produced with conventional binders (Antunes *et al.*, 2000).

3. Materials

3.1. *Crumb rubber and conventional binder*

Crumb rubber used in this study was recycled from ground tires using the ambient grinding process. Approximately 20% of truck tires and 80% of car tires of different types and origins were used in the crumb rubber fabrication process. The crumb rubber particle diameter varies between 0, 5 to 2, 0 mm. Table 1 describes the grain size distribution curves for the crumb rubber samples and the grading envelope specified by Arizona Department of Transportation (ADOT). Table 2 presents the results of physical properties characterization tests of the conventional binder AC 50/70.

Table 1. *Grain size distribution of crumb rubber samples and grading envelope specified by Arizona Department of Transportation (ADOT)*

Sieve size		%Passing		
#	mm	ADOT		Rubber
N° 4	4.75	100	100	100
N° 8	2.36	100	100	99.9
N° 10	2.00	100	100	96.8
N° 16	1.18	65	100	47.7
N° 30	0.60	20	100	18.7
N° 50	0.30	0	45	7.5
N°200	0.075	0	5	0

Table 2. *Characterization of conventional binder AC 50/70*

Physical properties	AC 50/70
Penetration, ASTM D 5-95 (1/10 mm)	52.0
Softening point, ASTM D36-97 (°C)	50.6
Brookfield viscosity at 175°C, ASTM D 4402-87 (cP)	87.5
Resilience, ASTM D5329 (%)	14.0

3.2. *Aggregates*

Mineral aggregates from 3 different stock piles were used for producing the asphalt hot mixes studied in this paper. These mineral aggregates comprised:

– Grade 1 crushed granitic stone: particle size 11 - 16 mm;

– Grade 0 crushed granitic stone: particle size 4 - 11 mm;

– Fine crushed granitic aggregate: particle size < 4 mm.

Granitic filler was also used. The aggregate mixture presents a dense graded curve specified by DNER-ES 313/97 as grade envelope C.

Figure 1 presents the grain size distribution curves of the specified grade envelope and of the theoretical mixture designed for the asphalt hot mixes according to the aggregate mixture composition.

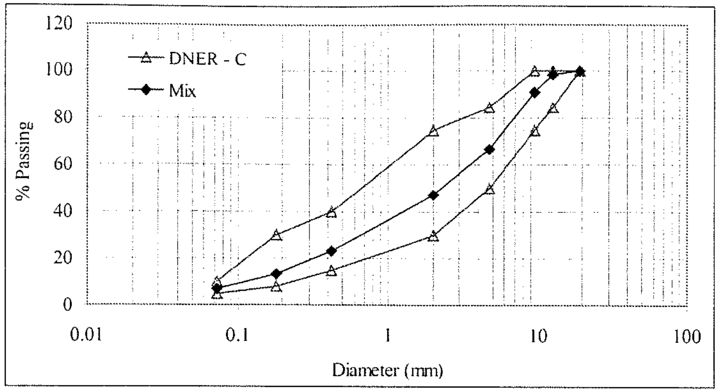

Figure 1. *Grain size distribution curves for dense graded mix*

4. Asphalt hot mixes: design and production

4.1. *Modified binders used in the asphalt-rubber hot mixes*

The following modified binder configurations were chosen for the study of the mechanical behavior of the dense graded asphalt-rubber hot mixes:

– Asphalt-rubber 1 (AR-1): straight binder AC 50/70 + 21% of crumb rubber, digestion time of 300 minutes and digestion temperature of 210°C;

– Asphalt-rubber 2 (AR-2): straight binder AC 50/70 + 25% of crumb rubber, digestion time of 300 minutes and digestion temperature of 210°C.

The use of these asphalt-rubber configurations allows evaluating the mechanical behavior of asphalt-rubber hot mixes made with modified binders obtained with rubber content higher than 20%, by weight. Hot mixes were also prepared with the straight binder AC 50/70 in order to compare with the mechanical properties of mixes with modified binders. Table 3 presents the physical properties of the modified binders used in the asphalt-rubber hot mixes.

The digestion time of 300 minutes was chosen due the high initial Brookfield viscosity presented by the modified binder with a rubber content of 25%, by weight. The modified binders with rubber contents above 21% present high initial Brookfield viscosity, mainly in the first 120 minutes of digestion. The increase of the digestion time produces a decrease of the modified binder viscosity due to the softening of the rubber particles (Dantas-Neto *et al.*, 2003).

Even so, penetration grades for AR-1 and AR-2 were slightly below the limit of 25 (0.1mm) suggested by ASTM D6114-97 and Brookfield viscosity of AR-2 was well above the limit of 5.000 cP suggested by the same standard, but still workable for practical purposes.

Table 3. *Characterization of binders AR-1, AR-2 e AC 50/70*

Physical properties	AR-1	AR-2	AC 50/70
Penetration, ASTM D5 (1/10 mm)	23.0	24.5	52.0
Resilience, ASTM D5329 (%)	39.0	48.0	14.0
Softening point, ASTM D36 (°C)	89.8	96.6	50.6
Brookfield Viscosity at 210°C, ASTM D 4402 (cP)	4280	8000	-

4.2. *Design and production of conventional and asphalt-rubber hot mixes*

Marshall method was used for the determination of the optimum binder content of the asphalt hot mixes. Table 4 presents the values of temperatures of the binders, aggregates and of compaction of the asphalt hot mixes obtained with the AC 50/70, AR-1 and AR-2 binders. These temperatures were chosen in consideration of the workability of the asphalt-rubber binders and the experience of local producers in application of this type of material.

Table 4. *Temperatures used in the production of conventional and asphalt-rubber hot mixes*

Temperatures	AC 50/70	AR1/AR2
Binder heating (°C)	160	170
Aggregates heating (°C)	177	190
Compaction of the mix (°C)	160	164

The dense graded mixture made with the conventional binder AC 50/70 presented an optimum binder content of 7.05%, in relation to the total weight of the mixture, and a void content of 4.5%, as described in Table 5. The mix design of the dense graded asphalt-rubber hot mixes indicated an optimum binder content of 9.61%. However, for these bitumen contents the volumetric parameters of the mixes obtained were different.

The mechanical behavior of asphalt hot mixes depends, among other factors, on their volumetric properties, as for example, the void content. Thus, for the mixtures made with the asphalt-rubber AR-1 and AR-2, the optimum binder content of 9.61% in total weight was used, but with a void content of 4.5%. In this way, it is guaranteed that all asphalt hot mixes presented the same volumetric parameters, and the type of binder is the only variable affecting the mechanical behavior of the mixes.

Table 5 presents the volumetric parameters of the specimens of asphalt hot mixes used in the mechanical tests. The rather high binder content for both conventional and asphalt-rubber mixes is due to the high percentage of filler and fines in the mineral aggregates as described in tables 3 and 4.

Table 5. *Properties of the dense graded asphalt hot mixes studied*

Mix properties	AC 50/70	AR-1/AR-2
Apparent density (g/cm^3)	2.249	2.251
Void content (%)	4.5	4.5
Void in the mineral aggregate – VMA (%)	19.3	19.2
Void filled with asphalt binder – VFA (%)	76.7	76.7
Optimum binder content (%)	7.05	9.61

After the mix design, several specimens of asphalt hot mixes with AC 50/70, AR-1 and AR-2 binders were prepared. A mechanical device with production capability of 50 kg of asphalt mixture was used to accomplish the mixture between the mineral aggregates and asphalt binders. Compaction of the asphalt hot mix was performed in a metallic mold with dimensions (7.3 x 49.2 x 75.2 cm), and a vibratory wheel roller was used to achieve the apparent density of the asphalt hot mixes defined in the design.

5. Asphalt hot mixes: tests, results and discussion

5.1. *Indirect tensile strength tests*

The indirect tensile test is carried out through the application of a vertical force F in the diametrical plan of the specimen until failure. The indirect tensile strength is calculated by Equation [1], as a function of the geometric characteristics and of the maximum vertical load applied diametrically to the specimen.

$$\sigma_t = \frac{2F}{\pi t \phi} \qquad [1]$$

Where:

σ_t: indirect tensile strength;

F: maximum vertical load applied;

t: height of the specimen;

ϕ: diameter of the specimen.

Indirect tensile tests were carried out at a temperature of 20°C, using specimens submitted to an aging process at 85°C for 5 days in an oven. Non-aged specimens were also tested for comparison. This laboratory aging process, normalized by AASHTO PP2/94, simulates the long-term aging that occurs in asphalt hot mixes in field. The tests were carried out in accordance with the recommendations of DNER-ME 138/94 standard. Figure 2 shows a picture of a specimen at the moment of failure during the indirect tensile test.

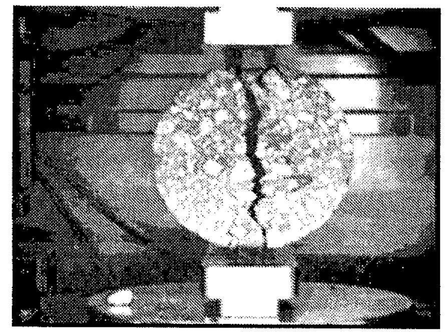

Figure 2. *Indirect tensile test*

Figure 3 shows the results from indirect tensile tests for the dense graded asphalt hot mixes made with AC 50/70, AR-1 and AR-2 binders. The aging process produced an increase in the indirect tensile strength of the dense graded asphalt hot mixes due to the increase of binder stiffness.

For specimens submitted to the aging process, the results show that the dense graded asphalt-rubber hot mixes present indirect tensile strength slightly (10%) lower than those obtained for conventional asphalt hot mixes with AC 50/70 binder. By comparing, the results of the dense graded asphalt hot mixes obtained with asphalt-rubbers AR-1 and AR-2, it is verified that the increase of rubber content incorporated to the conventional binder produces a slight decrease in the indirect tensile strength. However, the differences in tensile strength in all cases were not significant.

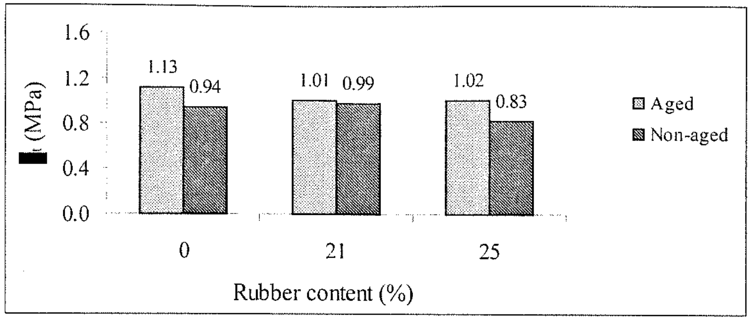

Figure 3. *Indirect tensile strength of the dense graded asphalt hot mixes*

5.2. *Resilient modulus, phase angle and fatigue life tests*

The resilient modulus of asphalt hot mixes is defined as the ratio between the tensile stress applied to the specimen and the tensile strain produced. This value depends on several factors such as intensity, frequency and time of load application. In this paper the values of resilient modulus of the asphalt hot mixes will be presented for different load application frequencies (f).

The fatigue life of asphalt hot mixes in controlled strain tests is defined as the number of load applications (N) that reduces by 50% the initial stiffness of the specimen.

The phase angle is calculated as a function of the time lag between the application of a certain load (F) and the displacement (δ) produced in the specimen. Therefore, the phase angle, calculated by Equation [2], is a quantitative measure of elastic capacity of the constituent material of the specimen.

$$\phi = 360.f.t \qquad [2]$$

Where:

ϕ: phase angle, in degrees (°);

t: time lag between F and δ, in seconds (s);

f: load frequency, in Hertz (Hz).

The resilient modulus and fatigue life tests were carried out under controlled strain conditions in beam specimens of bituminous concrete with the following dimensions: 381 ± 6.35 mm in length, 50.8 ± 6.35 mm in height and 63.5 ± 6.35 mm in width. These tests are normalized by AASHTO TP8/96 standard. The tests were

performed at 20ºC. The following frequencies were used in the resilient modulus tests: 0.1, 0.2, 0.5, 1.0, 2.0, 5.0 and 10.0 Hz. Fatigue tests are carried out only for the frequency of 10 Hz.

The specimens obtained from asphalt hot mixes made with AC 50/70, AR-1 and AR-2 binders were submitted to the long-term aging process described previously, and normalized by AASTHO PP2/94.

Figure 4 presents the results from resilient modulus tests of the specimens obtained from dense graded asphalt hot mixes with AC 50/70, AR-1 and AR-2 binders. The results show the variation of the resilient modulus with the frequency of load application. Figure 5 presents the results of phase angle of the asphalt hot mixes studied, as a function of the load application frequency.

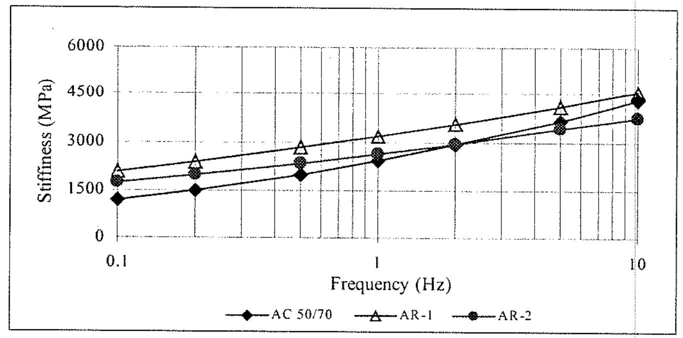

Figure 4. *Resilient modulus of the dense graded asphalt hot mixes*

The results in Figure 4 show higher resilient modulus for the mixes with asphalt-rubber if compared to the conventional. When comparing the two asphalt-rubber mixes, it is noticed that the mix with higher rubber content (AR-2) presented lower resilient modulus, at higher load frequencies (10 Hz) usually adopted in pavement design, in relation to conventional asphalt hot mix made with AC 50/70.

Figure 5 shows that the values of phase angles of the asphalt hot mix made with asphalt-rubber AR-1 are slightly lower than those made with the asphalt-rubber AR-2. If compared with the conventional binder AC 50/70, significant differences can be observed. This indicates improvements on the elastic response of the asphalt-rubber hot mixes in relation to those produced with conventional binders.

Figure 6 presents the results of fatigue life tests of asphalt hot mixes made with the AC 50/70, AR-1 and AR-2 binders. The results are expressed as a function of a parameter denominated α_{rubber} and defined by Equation [3]. This parameter represents the relationship between the fatigue life of the asphalt-rubber hot mix and the fatigue life of the mixture made with the conventional binder, for each tensile strain induced in the specimen.

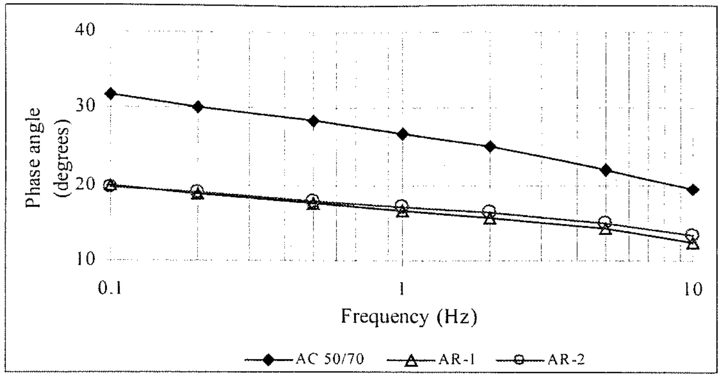

Figure 5. *Phase angles of the dense graded asphalt hot mixes*

$$\alpha_{rubber} = \frac{N_{ARHM}}{N_{AHM}} \qquad [3]$$

Where:

N_{ARHM}: fatigue life of the asphalt-rubber hot mix;

N_{AHM}: fatigue life of the conventional asphalt hot mix.

This parameter measures the gain or loss of fatigue life of the asphalt-rubber hot mixes in relation to the conventional mixtures. For the conventional mixtures, taken as reference, α_{rubber} values will always be equal to one.

During fatigue life tests, tensile strains of 400 and 800 microns were induced in the bituminous concrete beam specimen. The results presented in Figure 6 show that the asphalt-rubber hot mixes made with the AR-1 and AR-2 binders present fatigue lives superior to that of the conventional asphalt hot mix, for the tensile strains induced in the specimens.

The increase of rubber content to 25% produces a further increase in the fatigue life of the mixture made with asphalt-rubber AR-2 in relation to the mixture obtained with AR-1 binder. The asphalt-rubber hot mixes obtained with AR-1 and AR-2 were, respectively, 2 and 3 times more resistant to cracking by fatigue than the conventional asphalt hot mix, for a tensile strain of 800 microns.

For a tensile strain of 400 microns, the results of the fatigue life tests for AR-1 with 21% of rubber content indicate a gain above three times higher than that for the mix with conventional binder. The results obtained for the tensile strain of 400 show that the gain in the fatigue life of the asphalt-rubber hot mix obtained with AR-2 binder in relation to AC 50/70 and AR-1 was even more significant. The mix with 25% of rubber content (AR-2) presented a fatigue life more than 12 times that of the conventional mix with AC 50/70.

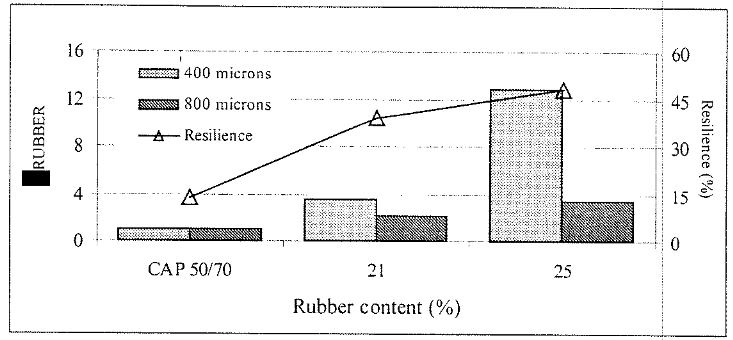

Figure 6. *Fatigue life of dense graded asphalt hot mixes*

The gain in fatigue life of the mixes follows the same trend as the increase of resilience of the asphalt binders with the increase of crumb rubber content, as shown superimposed in the same Figure 6

The analysis of the overall results of resilient modulus and phase angle tests of the studied asphalt hot mixes shows that the incorporation of rubber up to 25% produces an improvement in the elastic and viscoelastic properties of these mixtures. This improvement of elastic properties reflects in longer fatigue life for the asphalt hot mixes.

5.3. *Permanent deformation*

In general, rutting (permanent deformation) in pavements occurs initially due to a densification of the bituminous layers in the first load cycles, and later due to the plastic shear strains produced in the bituminous layers. These plastic shear strains cause displacements in the material of the bituminous layer without volumetric variation forming upheaval zones adjacent to the wheel paths (Sousa *et al.*, 1994).

Based on several studies, the Strategic Highway Research Program (SHRP) established a procedure to evaluate rutting in pavements through the evaluation of the evolution of the plastic shear strains that occur in asphalt hot mixes. The main assumption of this procedure it is that rutting is the result of a phenomenon of plastic shear flow under constant volume of the mixture, caused by the shear stress produced below the edge of the truck tires (Sousa *et al.*, 1994).

The determination of plastic shear strains is made by means of the repeated simple shear test at constant height (RSST-CH). This test consists of applying a repeated shear stress to a cylindrical specimen with 15 cm diameter and 5 cm thickness, while measuring the resulting plastic shear strains, at a given controlled temperature.

The RSST-CH is executed using a horizontal and a vertical mechanical actuator. The horizontal actuator controls the magnitude of the applied shear stress; while the vertical actuator guarantees that the specimen is tested with constant height.

Tests were performed at controlled temperatures of 50°C and 60°C, which represent average critical pavement temperatures typical in countries of temperate and tropical climates, respectively.

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 [4] presents the evolution law of the plastic shear strain (γ_p) with the number of applied load cycles in the RSST-CH.

$$\gamma_p = a.N^b \qquad [4]$$

Where:

γ_p: plastic shear strains measured in the specimen during RSST-CH;

a, b: laboratory parameters;

N: number of applied load cycles to the specimen during RSST-CH.

The rut depth in the wheel path can be estimated from plastic shear strains measured in the RSST-CH. Equation [5] shows a relationship between the rut depth and the plastic shear strains in the RSST-CH (Sousa *et al.*, 1994).

$$\delta_{\text{rut depth}} = 279.40. \quad \gamma_p \qquad [5]$$

Where:

$\delta_{\text{rut depth}}$: rut depth in the wheel path, in mm;

γ_p: plastic shear strain measured in the specimen during RSST-CH.

Equation [6] shows the relationship between the number of passes of the equivalent standard axle load of 82 kN ($ESAL_{mrd}$) as a function of the number of applied load cycles in the RSST-CH (N_{mpss}) for the specimen to reach the maximum plastic shear strain of 0.04545.

$$ESAL_{mrd} = 10^{\frac{4.36+\log N_{mpss}}{1.24}} \qquad [6]$$

Where:

– $ESAL_{mrd}$: number of cycles of the equivalent standard axle load of 82 kN correspondent to the maximum rut depth of 12.7 mm;

– N_{mpss}: number of applied load cycles in the RSST-CH for the specimen to reach the maximum plastic shear strain of 0.04545.

Figure 7 shows the results of the RSST-CH tests for the asphalt hot mixes made with the AC 50/70, AR-1 and AR-2 binders and test temperatures specified in Table 9. The results are expressed in terms of number of cycles of the equivalent standard axle, calculated by Equation [6], for the mixture to reach the maximum plastic shear strain or a limit rut depth of 12.7 mm.

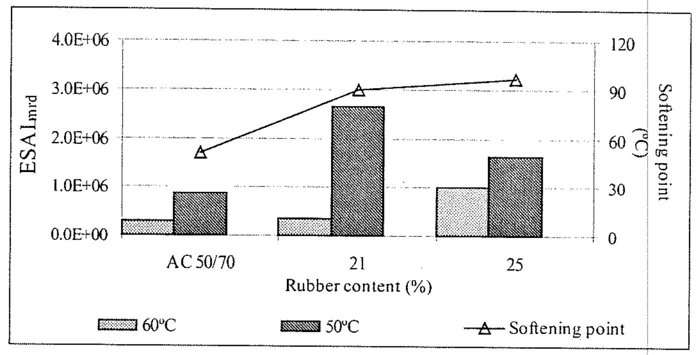

Figure 7. *Results of RSST-CH tests for dense graded asphalt hot mixes*

The results show that the asphalt-rubber hot mixes made with the AR-1 and AR-2 binders present larger resistance to the development of the plastic shear strains than the conventional asphalt hot mixes made with AC 50/70 binder, for both test temperatures used. For the temperature of 50°C, mixes made with AR-1 and AR-2 resisted, respectively, three times and two times more cycles to suffer the limit rut depth when compared with mixes prepared with the conventional binder. For 60°C, the gain was of 1.3% and three times, respectively, for mixes with binders AR-1 and AR-2.

This improvement of the behavior of the asphalt-rubber hot mixes occurred due to the larger elastic recovery of AR-1 and AR-2 binders in relation to the conventional binder AC 50/70, during the RSST-CH tests. The RSST-CH test temperatures of the asphalt-rubber hot mixes are well below the values of softening points for AR-1 and AR-2 binders shown in Table 5. Therefore, the elastic component of the binders AR-1 and AR-2 prevails in the behavior of the asphalt hot mixtures during the RSST-CH tests, resulting in larger resistance to the development of plastic shear strains.

For the conventional asphalt hot mixes, the softening point of the conventional binder AC 50/70 is practically equal or less then the test temperatures used.

Therefore, this binder is already in a quite viscous state, presenting little resistance to the development of the plastic shear strains.

For the test temperature of 60°C, the increase of the rubber content incorporated to conventional binder of 21% to 25% caused an increase in the resistance to the development of the plastic shear strains. However, for the test temperature of 50°C, the resistance to plastic shear strains of the asphalt hot mixes made with the asphalt-rubber AR-2 decreased in relation to mixture obtained with the asphalt-rubber AR-1.

The elevation of the test temperature had a greater impact in hot mixes made with AR-1 binder due to its lower softening point when compared with AR-2, as shown in Table 5.

6. Conclusions

The incorporation of the crumb rubber recycled from ground tires to conventional binders produces a slight reduction in the indirect tensile strength at 20°C of the asphalt-rubber hot mixes, in relation to those made with the conventional binders. The aging process produced a slight increase of tensile strength for all mixes investigated. However, the difference in tensile strength was not significant when compared to other aspects, such as fatigue life and rutting resistance.

The results of resilient modulus and of phase angle values, at higher load frequencies, showed that an increase of rubber content produces an improvement in the elastic and viscoelastic properties of the asphalt hot mixtures studied. This improvement of the elastic properties reflected in the increase of laboratory fatigue life at 20°C of the asphalt-rubber hot mixes, in relation to the conventional mixtures. The gain in fatigue life was of approximately 2 times for AR-1 and 3 times for AR-2 with a tensile strain of 800 microns. For a tensile strain of 400 microns, fatigue life increased more than three times for mixes with AR-1 and twelve times for AR-2.

The mixtures made with the asphalt-rubber AR-1 and AR-2 presented larger resistance to the permanent deformations, obtained in repeated simple shear test at constant height (RSST-CH), than those made with AC 50/70 binder. This increase of the resistance to the permanent deformations was observed for the test temperatures of 50°C and 60°C. For the temperature of 50°C, mixes made with AR-1 and AR-2 resisted, respectively, three times and two times more cycles to suffer the limit rut depth when compared with mixes prepared with the conventional binder. For 60°C, the gain was of 1.3 and three times, respectively, for mixes with binders AR-1 and AR-2.

The softening point can be defined as the temperature above which the binders behave as a viscous fluid. Asphalt hot mixes, made with the asphalt-rubber AR-1 and AR-2, were tested at typical temperatures, which are below the softening point of these binders.

The asphalt hot mixes made with AC 50/70 were tested at temperatures equal or superior to the softening point this binder. However, for the test temperatures used, asphalt-rubber AR-1 and AR-2 were more viscous, with higher elasticity, and consequently more resistant to development of the plastic shear strains than the mixtures made with the conventional binder AC 50/70.

The production of asphalt-rubber binders with rubber contents up to 25% was only possible due to the decrease of the specific surface of the crumb rubber recycled used in the experiments. For this purpose, it was necessary to use crumb rubber with particle dimensions slightly larger than those usually acceptable in the specifications of crumb rubber for use in asphalt-rubbers. It was also necessary to adopt longer digestion time (300 min) to bring the binder viscosity down to acceptable workability levels.

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A Dissipated Energy Approach to Fatigue Evaluation

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ABSTRACT. *The fatigue behaviour of bituminous binders and/or bitumen-filler mastics has been postulated as having a strong correlation with the fatigue behaviour of asphalt mixtures. The binder is one of the major factors controlling fatigue of the asphalt mixture and is considered as the leading media of energy dissipation. It is verified in this paper that the application of the Ratio of Dissipated Energy Change (RDEC) approach in terms of the fatigue characteristics of bituminous binders and mastics produces a unique energy parameter, known as the Plateau Value (PV), similar to the PV previously identified for asphalt mixtures. The relationship between PV and fatigue life (Nf) is found to be unique for asphalt mixtures and binders (mastics). This suggests the RDEC approach is a fundamental approach for fatigue analysis of HMA. Furthermore, the two PV-Nf curves for asphalt mixtures and binders are strongly related, which provides a new way to explain mixture fatigue behaviour from a binder's rheological characteristics.*

KEYWORDS: *Ratio of Dissipated Energy Change (RDEC), Dynamic Shear Rheometer, Plateau Value (PV), Fatigue, Asphalt Mixtures, Bitumen-filler Mastics, Bituminous Binders.*