Behaviour of Asphalt Rubber Mixtures with Different Crumb Rubber and Asphalt Binder Sources

Liseane P.T.L. Fontes* — Paulo A.A. Pereira* — Jorge C. Pais* — Glicério Trichês**

** University of Minho*
Department of Civil Engineering, Campus of Azurém
4800-058 Guimarães, Portugal
liseane@civil.uminho.pt
ppereira@civil.uminho.pt
jpais@civil.uminho.pt

*** University Federal of Santa Catarina*
Rua João Pio Duarte da Silva, 205
88040-970 Florianópolis, SC, Brasil,
ecv1gtri@ecv.ufsc.br

ABSTRACT. *This study evaluates the performance in laboratory of gap graded mixtures prepared with different crumb rubber types and different conventional grade asphalt binders. The asphalt rubbers were prepared via wet process (continuous blend) and their properties were measured through the current tests: (i) penetration; (ii) softening point; (iii) resilience; (iv) apparent viscosity using a Brookfield viscometer. The rheological properties for conventional asphalts were measured too, in order to evaluate their mechanical behaviour. The gradation used for the asphalt rubber mixtures was a gap graded (ARHM-GG) specified by Caltrans. ARHM-GG is a surface course with an aggregate gradation that has a gap in the continuous grading. Using this gradation, from the mix combination of rubber types and conventional asphalts, six asphalt rubbers were made from which resulted six asphalt rubber mixtures. All mixture selected were evaluated through complex modulus and fatigue test. The results showed that the mixture prepared with crumb rubber from cryogenic process with asphalt binder with higher grade performed better than the other mixtures.*

KEYWORDS: *Crumb rubber, Gap-graded, Rheology, Fatigue.*

1. Introduction

Scrap tires are still a serious disposal problem in the world. However, the use of scrap tires in asphalt pavements, known as asphalt rubber pavements, can minimize environmental impact and maximize conservation of natural resources.

There are two processes to introduce the crumb rubber in asphalt mixtures: i) dry process; ii) wet process. In the dry process mixes, the crumb rubber is mixed together with the aggregates prior to the addition of the asphalt. In this process, the crumb is used as an aggregate.

Asphalt rubber in a wet process is a chemically reacted mix of liquid asphalt binder with 15 to 22% crumb rubber obtained from used tires and added to liquid asphalt. It reacts at high temperatures prior to being mixed with aggregate.

Both asphalt and crumb rubber source can affect the properties of the asphalt rubber. It must be emphasized that the physical properties of asphalt binders even with the same grades are substantially variable. It is also important to evaluate how the process of crumb rubber production influences the mixture properties. The performance of an asphalt rubber mixture depends on the physical and chemical properties of the materials used and the interaction of these materials.

Hicks *et al.* (2000) concluded that there is no guarantee that current procedures to produce asphalt rubber will result in consistent binders as time and temperature of digestion can easily affect the properties of the binder produced. Furthermore, the original asphalt and the crumb rubber and their gradation can also produce binders with different properties.

Potential benefits of asphalt rubber have been reported from several researchers as a result of thinner layer thicknesses, reduced reflective cracking and longer service lives. Jorgenson (2002) corroborates that the researches have confirmed the success of the reduced thickness design approach for Asphalt Rubber Hot Mix – Gap Graded (ARHM-GG). The gap graded mixtures allows for higher asphalt content, and when combined with the crumb rubber, results in a pavement with much greater flexibility and durability.

This study intends to evaluate the performance of gap graded mixtures prepared from different sources of rubber and asphalt binder. Two types of rubber were used, obtained from different methods, ambient grinding and cryogenic process. Three different grade of asphalt binders were modified by the crumb addition. In order to evaluate the binders, the properties of the asphalts binder were evaluated through the conventional tests.

Additionally, in this study, the rheological characterization of the conventional asphalt was performed allowing the evaluation of the mechanical behaviour of the material. The characterization was carried out through the following parameters: i) G' (storage modulus that corresponds to the elastic response of the material); ii) G" (loss modulus that corresponds to the viscous response of the material); iii) tanδ (that represents an association between the viscous part and the elastic part of the material); iv) η (viscosity).

The matrix of crumb rubber and asphalt binders resulted in six different asphalt rubber. For these six asphalt rubbers, asphalt rubber mixtures were produced and tested in laboratory to evaluate the stiffness modulus and fatigue resistance.

2. Literature review

2.1. *Crumb rubber*

Scrap rubber, crumb rubber and reclaimed rubber are all terms describing recycled rubber. The largest recycled rubber source is car and truck tires and is referred to as crumb rubber modify. This rubber is not a pure polymer but a blend. Car tires are made of mainly Styrene Butadiene Rubber (SBR) or polyisoprene and carbon black. Other polymers are included in some blends, and tires are not uniformly formulated or compounded. Truck tires generally contain a higher percentage of natural rubber than car tires (up to 30% of the combined polymer content) (Caltrans, 2003).

To produce crumb rubber it is usually necessary to reduce the size of the tire. This is accomplished by two techniques: (i) ambient grinding; (ii) cryogenic process.

Ambient grinding can be accomplished in two ways: granulation and crackermills. Ambient describes the temperature of the rubber or tire as it is being size reduced. Typically, the material enters in the crackermill or granulator at ambient or room temperature. The temperature of the rubber will rise significantly during the process due to the friction generated as the material is being torn apart. Granulator's size reduces the rubber by means of a cutting and shearing action. Rubber particles produced in the granulation process generally have a cut surface shape, rough in texture, with similar dimensions on the cut edges (RRI, 2005).

According to Baker *et al.* (2003) the advantages of mechanical grinding are various: the system is well developed, with a variety of components available to reduce the tire into crumb at relatively low cost. The system is comparatively easy to maintain and requires few people to operate and service, and replacement parts are generally easy to obtain and install. On the other hand, the considerable added cost and energy required to produce the extremely fine mesh sizes, such as 0,25 mm are higher.

Cryogenic processing uses liquid nitrogen or other materials/methods to freeze (-87 °C to -162 °C) tire chips or rubber particles prior to size reduction. The surface is glasslike, and thus has a much lower surface area than ambient ground crumb rubber of similar gradation. Cryogenic grinding is a cleaner, slightly faster operation resulting in the production of fine mesh sizes. A disadvantage is the slightly higher production cost due to the added cost of liquid nitrogen (Baker *et al.*, 2003).

Asphalt rubber binders produced with rubber from the different grinding processes have measurable differences in properties. Ground tire rubber materials with greater specific surface area and more irregular-shaped particles produced asphalt rubber binders having higher viscosities (Baker *et al.*, 2003).

Table 1 presents the general properties of the materials produced by two techniques.

Table 1. *Properties of ambient and cryogenically crumb rubbers*

Physical property	Ambient grinding	Cryogenic process
Specific gravity	same	same
Particle shape	irregular	regular
Fiber content	0,5%	0%
Steel content	0,1%	0%

(Source: CWC, 1998)

Many of the characteristics of the crumb rubber can influence properties of asphalt rubber such as rubber quantity in the blend and particle size distribution. Additional factors include (Hicks *et al.*, 2000): i) crumb rubber surface area; ii) grinding process; iii) crumb rubber chemical composition; iv) contaminants (water, fibre, metal).

The amount of crumb rubber added to the asphalt will influence blend properties with higher amounts providing greater changes in properties. Generally, as the rubber content increases: (i) the viscosity of the material at 175 °C increases; (i) the resilience increases; (iii) the softening point increases; (iv) penetration at 25 °C decreases.

The particle size distribution of the crumb rubber has influence on the physical properties of asphalt and crumb rubber blends. Generally, small differences in the particle sizes do not affect blend properties significantly, but large differences in crumb rubber size can produce larger differences. Finer sized crumb rubber materials will generally experience quicker swelling due to their increased surface area and will produce higher viscosities than crumb rubber with larger particle sizes. Additionally, very small particle size crumb rubber will tend to more quickly viscosity reduction with storage due to its quicker and more thorough swelling and subsequent depolymerisation.

Surface area of the crumb rubber can influence physical properties. In some ways, this is similar to gradation; however, surface area differences can exist even for crumb rubber with similar gradations.

The crumb rubber production process may influence the physical shape and surface area characteristics of the rubber particles. Additionally, ambient temperature size reduction results in rough shredded particles surfaces, while cryogenic size reduction results in smoother glassy surfaces.

Finally, tires are composed of several different types of rubber compounds. The major crumb rubber compositional effect on asphalt rubber physical properties is the total rubber hydrocarbon content of the rubber with additional effects from the natural rubber content.

2.2. *Asphalt binder*

Asphalt binders are derived from the atmospheric and vacuum distillation of crude oil followed by subsequent processes (air blowing, solvent deasphalting, and for some residues, thermal conversion) to achieve the appropriate product characteristics. The chemistry of asphalt products is very complex because of the complex nature of the petroleum crude oils from which they are derived. The chemistry is also affected by the varying refining processes designed to meet specifications of performance rather than of a set chemical composition (Petroleum HPV, 2003).

Asphalt binders used in this study are graded by either penetration or viscosity. Penetration graded asphalts are specified by a measurement by a standardized penetrometer needle under a standard load at a standard temperature. The higher the penetration, the softer the asphalt binder is. Viscosity graded asphalts are specified by determining the viscosity of asphalt binder. A temperature of 60°C is considered to be a typical summer pavement temperature, and at this temperature, the unit of viscosity used is the poise. Many additives can be incorporated in conventional asphalts. Rubber from old car tires are used to increase the properties of the asphalt binders.

The physical properties of the asphalt binder influence the properties of asphalt rubber blends. The stiffness, temperature susceptibility and aging characteristics of the asphalt will affect the high temperature and low temperature performance of the blend. Use of stiffer asphalts will produce asphalt rubber (hereafter referred as AR) materials that have greater high temperature stiffness than obtained with softer asphalts. However, stiffer asphalts will produce AR materials that are harder at lower temperatures than those AR binders made with softer asphalts. Chemical properties of the asphalt binder can also influence the characteristics of the asphalt rubber by affecting the reaction of the rubber. Asphalts that have lower levels of components which are absorbed by the rubber can tend to produce asphalt rubber materials with lower viscosities and lesser degrees of modification of properties (Hicks *et al.*, 2000).

Asphalt binder must be compatible with the crumb rubber. Compatibility is controlled by the chemical composition of both the asphalt binder and the crumb rubber as demonstrated by an increase in the viscosity of the asphalt rubber blend with time. Most of the crumb rubber produced nowadays is a homogenous blend of different rubber polymers; hence, compatibility is primarily dependent on the properties of the asphalt binder rather than the composition of the crumb rubber material (*Hicks et al.*, 2002).

Ideally, any pavement layer must be capable of placement and compaction to provide an even and strong riding surface and appropriate mix density (air voids). An asphalt binder, together with the mixture design, must be able to withstand loading to prevent pavement deformation (wheel path rutting). Asphalt must be able to withstand low temperatures and the resulting thermal stresses that develop as the pavement contracts. Asphalt must be able to withstand repeated loading and unloading without exhibiting fatigue failure. At last, ideal asphalt will be able to sustain these performance criteria over an extended period of time (*Baker et al.*, 2003).

2.3. *Wet process – continuous blend*

The wet process defines any method that adds the rubber to the asphalt before the addition of aggregate. During the mix, a chemical and physical change occurs in the two constituents that allow a distinction to be made between asphalt-rubber and a simple mixture of asphalt binder and crumb rubber. Furthermore, the reaction of asphalt and rubber during the wet process is affected by the digestion time and temperature, the type and amount of mechanical energy, weight percentage and mesh size of rubber, and the aromatic content of the asphalt (Heitzman, 1992).

According to Caltrans (2005), the wet process is the method of modifying asphalt binders with crumb rubber produced from scrap tire rubber and, if required, other components. The wet process requires thorough mixing of the crumb rubber in hot asphalt binder (175 °C to 226 °C) and holding the resulting blend at high temperatures (163 °C to 218 °C) for a designated minimum period of time, the digestion time, (at least 45 minutes) to allow an interaction between the rubber and asphalt. Other components may be included, depending on applicable specifications. The interaction (also referred to as reaction) includes swelling of the rubber particles and development of specified physical properties of the asphalt and crumb rubber blend to meet requirements. Typical specification requirements include an operating range for rotational viscosity, and minimum values of softening point, resilience, and penetration.

Hicks *et al.* (2000) referred some considerations about the continuous blend asphalt rubber tests:

– pumping consistency at typical placement temperatures (150 to 200 °C) can be monitored using rotational type viscometers such as Brookfield viscometer (ASTM D2669). While this test is being performed, it is important to ensure that the rotating probes are conditioned to the test temperature and that readings are taken at specific intervals because of a tendency with some asphalt rubber blends for viscosity readings to reduce due to rubber particle migration away from the probe while it is rotating;

– stiffness can be measured at typical high-range pavement surface temperatures by several different testing procedures. The Ring and Ball Softening Point (ASTM D36) procedure provides an indication of relative stiffness of materials. A high softening point temperature indicates materials that are more resistant to softening at high temperatures. Results are mainly influenced by asphalt grade, rubber type and content, and degree of digestion;

– moderate temperature consistency (25 °C) can be evaluated using the standard ASTM D5 penetration test. The standard D5 test with the needle is most appropriate for finer rubber. The addition of crumb rubber to asphalt binder decreases the penetration at 25 °C;

– the elastic characteristics of asphalt and crumb rubber blends can be evaluated using the ASTM D5329 resilience procedure. This procedure indicates the percentage of rebound of the material at 25 °C under a load after the material is compressed. The addition of the crumb rubber into the asphalt increases resilience.

2.4. *Gap graded mixture*

Gap graded mixtures specified in Caltrans as ARHM-GG are used with asphalt rubber binders. The gap (missing fraction) is used to accommodate the asphalt rubber binder. The purpose of gap grading is to provide improved stone-to-stone contact by reducing the fine aggregate content so as to provide a strong aggregate skeleton that creates space for more engineered binder than a dense graded mix can hold. Gap grading is also a good way to increase the Voids in Mineral Aggregate (VMA) of a mixture. Beside this, is intended to allow for stone to stone contact for deformation resistance and the extra binder has been found to aid in fatigue and cracking propagation resistance. The crumb rubber increases the viscosity of the binder allowing high binder contents without bleeding. The increase in voids allows the mix to accommodate the larger particulate rubber present in asphalt rubber binders. The binder content may be 7 to 9% (*Caltrans*, 2005).

The design of gap graded mixture with asphalt rubber can also reduce the thickness in pavement rehabilitation. The Caltrans conducted research between 1980 and 1992, which compared asphalt rubber concrete to conventional asphalt concrete in field evaluations. It was determined through field evaluations that the asphalt rubber gap graded pavements could be significantly reduced in thickness while providing the same service life as thicker conventional asphalt concrete pavements (Van Kirk *et al.*, 2000).

2.5. *Rheology*

Rheology is the study of flow and deformation that concerns the relationship between shear stress, shear strain and time (Barnes, 2000).

Rheological measurements are understood through parameters such as storage modulus (G'), loss modulus (G"); which are indicators for elastic and viscous properties; respectively, and viscosity (η). G' represents the mechanical energy stored and recovered (analogous to elastic solid) and G" represents the mechanical energy dissipated whilst overcoming frictional effects (analogous to fluid like behaviour) (Jackson *et al.*, 2005).

In order to collect rheological data, in this study the parallel plate rheometer was used (Rheologica StressTech HR). This type of rheometer was suggested by Mooney that undertook specific study of polymers, rubbers and viscous materials.

The parallel plate rheometer has capability to measure strain; viscosity; loss and storage modulus for varying stresses and strain rates. The geometry used in this study is shown in Figure 1. The parallel plates are 40,0 mm in diameter and sample thickness was set to 0,8 mm.

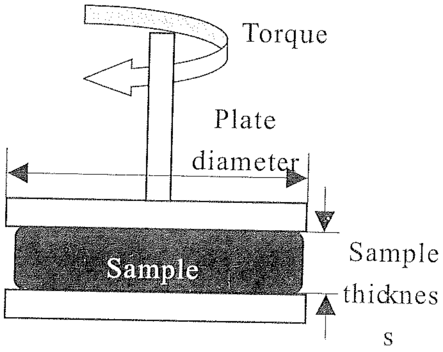

Figure 1. *Parallel plate geometry rheometer*

3. Materials characterization

3.1. *Crumb rubber*

Two types of crumb rubber from waste tires were used in this study: i) ambient grinding; ii) cryogenic process.

The crumb rubber gradation from ambient grinding (R1) and from cryogenic process (R2) is presented in Figure 2. The different appearance between the types of crumb rubber can be seen in Figure 3.

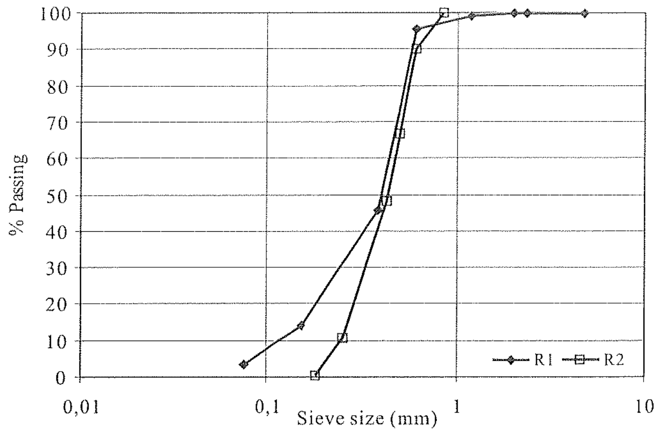

Figure 2. *Grain size distributions for rubber types*

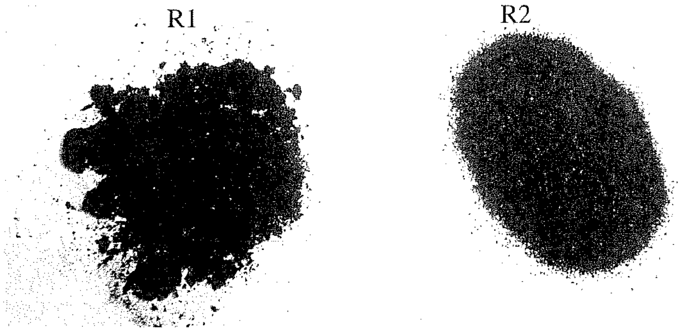

Figure 3. *Appearance of crumb rubbers R1 and R2*

3.2. *Asphalt binder*

Three asphalt binders from different sources were used in this study. The conventional asphalts used have been used in most pavements in Brazil and Portugal and have the following classifications:

- CAP-20, classified by viscosity, (A1);

- PEN 50/70, classified by penetration, (A2);

- PEN 35/50, classified by penetration, (A3).

Conventional asphalt binder tests were conducted to obtain material characteristics, which can be an indicator of the mixture properties such as fatigue cracking and permanent deformation. These results are presented in Table 2.

Table 2. *Conventional asphalt binder properties*

Test	Standard	A1	A2	A3
Penetration 0,1 mm (100 g, 25 °C, 5 s)	ASTM D 5	49,0	52,5	32,4
Softening point (°C)	ASTM D 36	51,5	48,0	52,7
Resilience (%)	ASTM D5329	0	0	9
Brookfield viscosity 175 °C (cP)	ASTM D 2196	200	112	175

The results of rheological tests are shown in Figures 4 to 6. Figure 4 display viscosity values against applied shear rate for all asphalts.

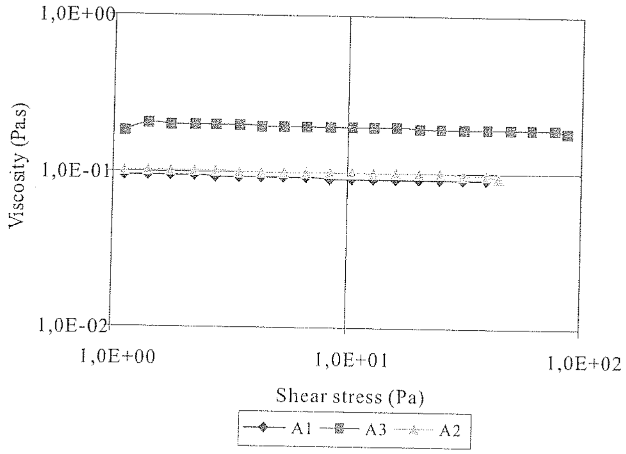

Figure 4. *Shear stress for asphaltic samples*

From Figure 4 it is clear that asphalts A1 and A2 have similar viscosities and these are lower than viscosity of asphalt A3. While the shear stress increases, the behaviour remains the same for all samples.

Figure 5 presents the storage modulus (G') and loss modulus (G") as a function of frequency for the asphalts A1, A2 and A3.

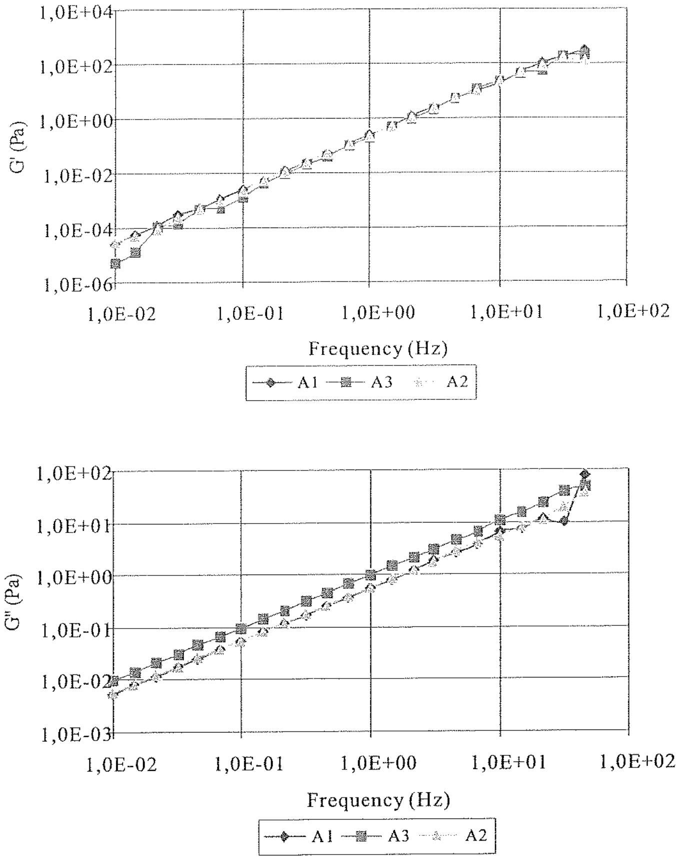

Figure 5. *Storage modulus (G') and loss modulus (G") for asphalts*

The analysis of the storage modulus (G') allows to conclude that all asphalts have the same behaviour. The loss modulus (G") of asphalt A3 is higher than the asphalts A1 and A2.

Figure 6 presents the phase angle and tangent of delta against the applied frequency. The results indicate that for low frequencies, less than 1 Hz, all asphalts have the same behaviour. Afterwards, for high frequencies, the phase angle of asphalt A1 is higher than the asphalts A2 and A3. The A2 and A3 have analogous phase angles for all range of frequency. The tangent of delta indicates that asphalt A3 reaches a greater elasticity, whereas the A2 and A1 presented an identical performance.

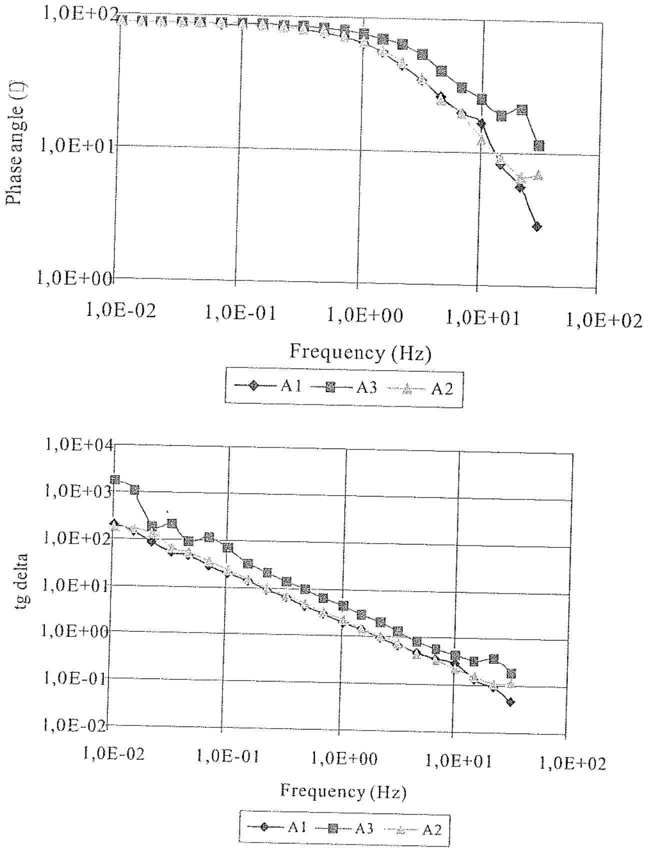

Figure 6. *Phase angle and tangent of delta*

3.3. *Asphalt rubber*

The intensity of mixing during the digestion time period can influence asphalt rubber properties. Differences in mixing and shearing intensity can vary from low speed agitation that gently keeps the rubber particles in suspension to high speed shearing that can mechanically break down the rubber particles. With low speed agitation, the asphalt contents are simply absorbed as the rubber particles swell with little dispersion of the rubber polymer into the asphalt. During high intensity mixing, the rubber particles swell and soften due to asphalt absorption, and the high energy mixing tends to shear off the softened rubber outer surfaces and produces a dispersed rubber component in the asphalt phase of the material (Hicks *et al.*, 2000).

The performance of the asphalt rubber binder depends on its elastomeric properties. The manufacturing process influences these properties. Therefore, it is important to achieve the required digestion through adequate dispersion to create a rubber network or matrix within the asphalt. The physical aspect of mixing creates a physic-chemical interaction between the asphalt and the rubber (Shatnawi *et al.*, 2000).

The reaction process of rubber particles in asphalt binder is both time and temperature dependent. Higher temperatures result in faster reaction and may result in greater amounts of swelling. In order to obtain the required properties of asphalt rubber produced with a continuous blend process, a previous study was conducted to choose the better blend conditions that resulted as follows:

- digestion time: 90 minutes;
- temperature of blend: 180 °C;
- rubber content: 21% by weight.

The matrix of this study resulted in six different configurations from crumb rubber and asphalts binders:

- R1A1: (rubber from ambient grinding + CAP-20);
- R1A2: (rubber from ambient grinding + PEN 50/70);
- R1A3: (rubber from ambient grinding + PEN 35/50);
- R2A1; (rubber from cryogenic process + CAP-20);
- R2A2: (rubber from cryogenic process + PEN 50/70);
- R2A3: (rubber from cryogenic process + PEN 35/50).

Table 3 and Table 4 summarize the asphalt rubber properties from combinations of crumb rubber and asphalt binders.

Table 3. *Properties of asphalt rubber with crumb rubber from ambient grinding*

Test	Standard	R1A1	R1A2	R1A3
Penetration 0,1 mm (100 g, 25 °C, 5 s)	ASTM D 5	26,0	31,8	19,7
Softening point (°C)	ASTM D 36	65,0	62,5	69,9
Resilience (%)	ASTM D5329	40	20	52
Viscosity (cP) (175°C)	ASTM D2196	3067	3088	4712

Table 4. *Properties of asphalt rubber with crumb rubber from cryogenic process*

Test	Standard	R2A1	R2A2	R2A3
Penetration 0,1 mm (100 g, 25 °C, 5 s)	ASTM D 5	36,7	26,7	16,8
Softening point (°C)	ASTM D 36	55,4	61,9	73,4
Resilience (%)	ASTM D5329	40	16	49
Viscosity (cP) (175 °C)	ASTM D2196	1288	1821	3075

For asphalt binders A1, A2 and A3 (Table 2) the addition of crumb rubber from both ambient grinding and cryogenic process improved significantly the properties.

The lower penetration found in asphalt rubber with asphalt binder A3 could be explained because this asphalt is harder than the others. As a consequence, the asphalt rubber R2A3 presented the best softening point. The elastic properties, traduced by the resilience test, presented better behaviour for this asphalt rubber.

3.4. *Mixtures*

The granite (100% crushed) aggregates used in this study are commonly used for asphalt concrete pavement construction in Portugal. The aggregate laboratory tests, confirmed that these aggregates have suitable properties for use in pavement mixtures.

The Caltrans ARHM-GG mix (asphalt rubber hot mix gap graded) complies with the Standard Special Provisions, SSP39-400 (Caltrans, 2003). Figure 7 shows the specified grading envelope and the mixture designed according to the aggregate composition.

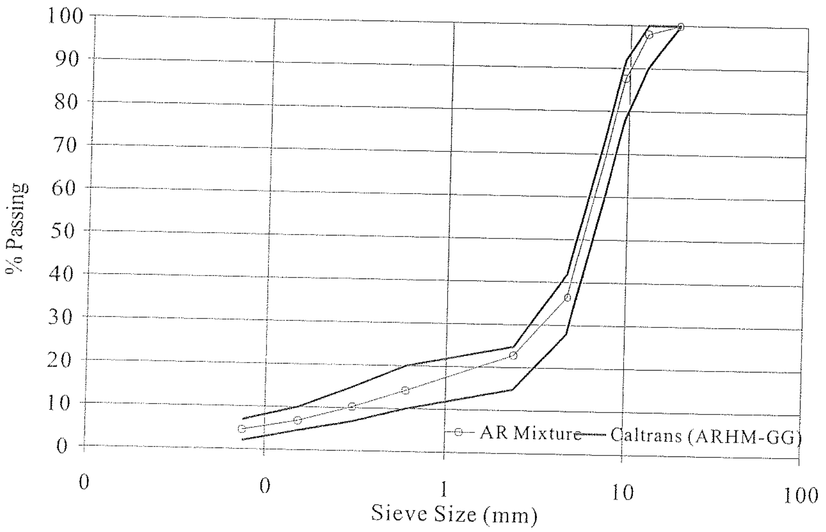

Figure 7. *Aggregate gradation of gap graded mix*

Mixture design was performed using the Marshall method by preparing and compacting samples with asphalt content varied in 0,5% increments (6,0% to 8,5%), using a Marshall Apparatus.

Taking into account that asphalt rubber mixtures in general have higher asphalt content, the draindown characteristics were evaluated for all mixtures. The Caltrans fixes 4 grams for maximum requirement for draindown test.

The draindown test (Figure 8) measures the potential for asphalt binder to drain from the coarse aggregate structure while the mix is held at high temperature and during transportation. The draindown test in this study was based on AASHTO T 305-97 using the standard 6,3 mm wire cloth.

To run this test, a sample is prepared in the laboratory (during mix design) or obtained from field production. The sample is placed in a wire basket that is put onto a suitable container of known mass. The sample, basket, and container are then placed into a forced draft oven for one hour at or above the anticipated production temperature. At the end of one hour, the mass of asphalt binder draining from the sample that is retained in the container is determined and the amount of draindown calculated (Cooley Jr. *et al.*, 2003).

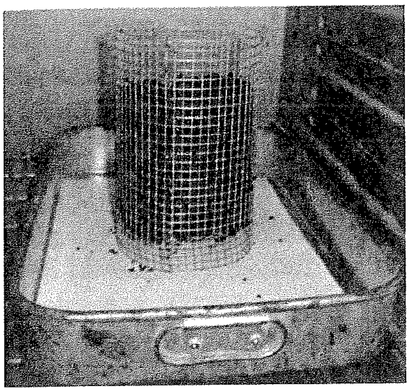

Figure 8. *The draindown test*

4. Tests results

The complex modulus and fatigue tests were carried out under controlled strain conditions in beam specimens with the dimensions 381 mm in length, 50,8 mm in height and 63,5 mm in width.

4.1. *Complex Modulus*

Stiffness properties of pavement materials are generally presented in terms of complex modulus and phase angle (Partl *et al.*, 1997).

The frequency sweep test measures the stiffness and the phase angle of a mixture when subjected to different loading frequencies. All the frequency sweep tests of this study were performed at 20 °C and at: 10; 5; 2; 1; 0,5; 0,2 and 0,1 Hz. The complex modulus tests are considered to be non-destructive, thus they were conducted before the fatigue testing. The complex modulus values for all mixtures at 20 °C and 10 Hz are presented in Table 5.

Table 5. *Complex modulus values for mixtures*

Mixture	Complex Modulus (MPa)
MR1A1	4592
MR1A2	3944
MR1A3	4783
MR2A1	4776
MR2A2	3356
MR2A3	5192

According with Table 5, the mixtures that used asphalt rubber with asphalt A2 presented a lower modulus than the other mixtures. The crumb rubber source had influence, once cryogenic rubber increases the modulus value for mixtures MR1A2 and MR2A2. On the other hand, the mixtures whose asphalt rubber was produced with asphalt A3, obtained the higher modulus. As stated before, the rubber from cryogenic process had a favourable effect in the modulus value, comparing MR1A3 and AR2A3. The same effect was confirmed for mixtures MR1A1 and MR2A1.

Figure 9 presents the complex modulus of all mixtures studied as a function of the applied frequency.

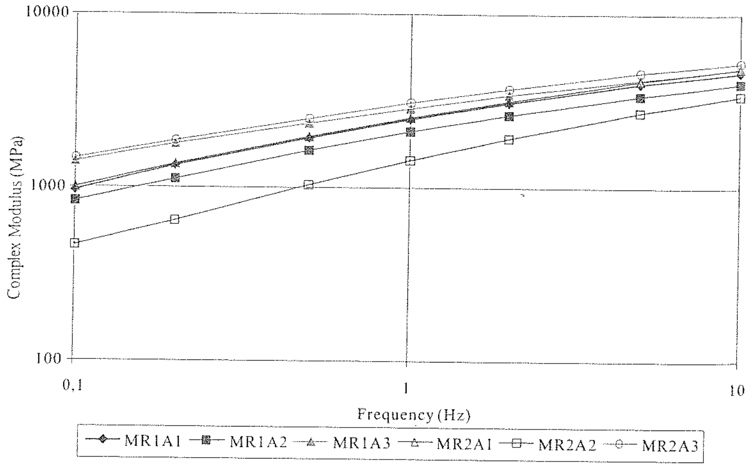

Figure 9. *Complex modulus*

The phase angle (φ) is one yield variables of the dynamic modulus test and is an indication of the elastic viscous properties of the materials. The value of $\varphi = 0^{\circ}$ is indicative that the material behave as a pure elastic material. A value of $\varphi = 90^{\circ}$ indicates a pure viscous (Newtonian) material (Harman, 2001).

Figure 10 presents the phase angle as a function of load frequency. The phase angle results show the visco-elastic behaviour of the six mixtures.

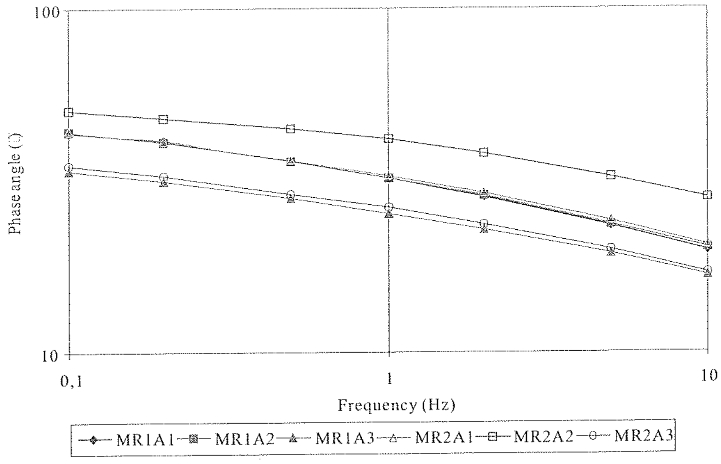

Figure 10. *Phase angle*

4.2. *Fatigue*

Fatigue is a fracture phenomenon caused by repeated application of tensile strains. In a fatigue process, microscopic flaws in a material under repeated loading grow in size, becoming more densely concentrated until visible flaws or cracks develop. The fatigue characteristics of asphalt mixes are usually determined by using repeated flexural tests. The fatigue behaviour of a specific mixture is generally characterized by the log-log slope of strain (or stress) relative to the number of load repetitions to failure. Fatigue tests can be done using constant load (stress) or constant displacement (strain) loading (Pellinen *et al.*, 2004).

Flexural fatigue tests (four point bending beam) 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. Fatigue life is defined as the number of cycles supported by the material when 50% decrease of the initial stiffness of the test beam is measured. Tests were undertaken at 20 °C and at 10 Hz frequency rate of loading.

A fatigue model has been established using a linear regression between fatigue life logarithm, log N, and the initial strain logarithm; log ε_t, for controlled strain tests. The fatigue model proposed by Monismith *et al.* (1971) is based on Equation 1 as follows:

$$N = a\left(\frac{1}{\varepsilon_t}\right)^b \qquad [1]$$

where:

N = number of repetitions to failure (cycles);
ε_t = strain;
a and b = coefficients determined experimentally.

Table 6 presents a summary of the application of Equation 1 at 20 °C for the tested mixtures. The high R^2 coefficient indicates the good relationship between the number of the cycles and the strain level. Figure 11 presents the fatigue life for all mixtures.

Table 6. *Coefficients a and b of Equation 1 for all mixtures*

Mixture	a	b	R^2
MR1A1	1,150E+15	3,898	0,983
MR1A2	4,876E+13	3,361	0,875
MR1A3	6,156E+16	4,409	0,981
MR2A1	3,140E+15	4,086	0,973
MR2A2	2,269E+17	4,707	0,992
MR2A3	9,809E+18	5,138	0,989

The analysis of the Figure 11, based in comparisons between the mixtures, allows the following conclusions:

– the addition of rubber from cryogenic process (R2) in asphalt binder A2 improves significantly the fatigue life when compared with the addition of R1 in asphalt binder A2;

– the same behaviour occurred in other mixtures. The addition of R2 improves the fatigue life of the mixtures, whatever the type of binder asphalt that was used;

– the mixture that presented the best fatigue life was MR2A3, whose the results demonstrated the good interaction between the rubber and the asphalt binder.

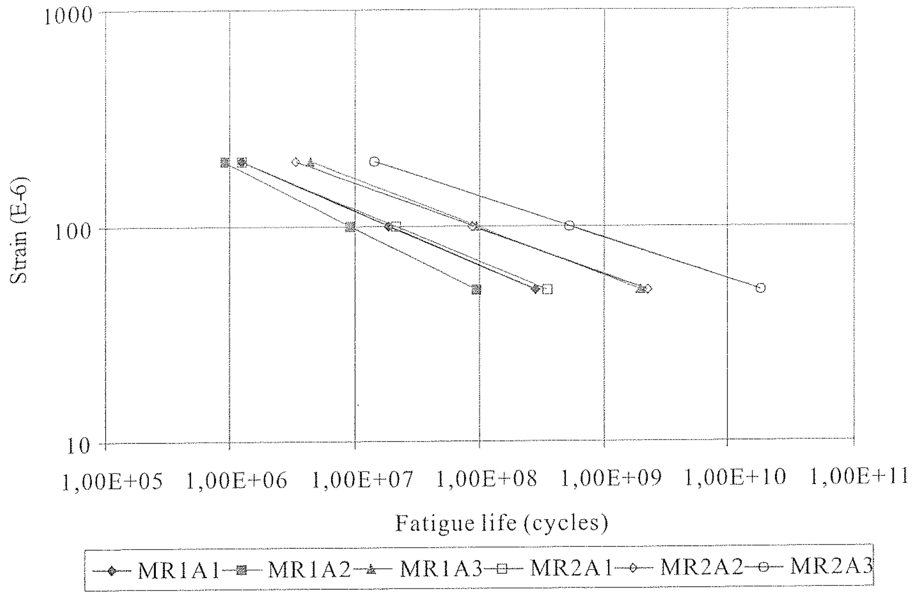

Figure 11. *Fatigue curves for all mixtures*

5. Conclusions

This study presented an evaluation of fatigue and stiffness performance of asphalt rubber mixtures with the same aggregate gradations (gap graded proposed by the Caltrans Specifications) in which different compositions were used among crumb rubber from ambient grinding and cryogenic process mix, with different grades of asphalt binders. Furthermore, the results of the interaction between asphalts binder and crumb rubber were also presented.

From the analysis of each test, the following conclusions can be drawn:

– there are several sources of asphalt binder and crumb rubber that can be used. However, the interaction between the asphalt binder and the rubber must be tested in order to reach the best performance;

– with different asphalt binder, varying the rubber source, it is possible to improve the fatigue life more than 1,5 times;

– in this study, the rubber from cryogenic process had better characteristics to be used as binder modifier;

– the conventional tests such as penetration, resilience and softening point for asphalt rubber were good indicators for the asphalt rubber behaviour;

– the rheological analysis of the asphalt binder proved to be a good tool since it can classify the material behaviour;

– despite the fact that the properties of the asphalt binder affect the final product (asphalt rubber), the main and relevant modifier agent of the asphalt rubber in this study was the crumb rubber.

ACKNOWLEDGEMENTS

The first author is supported by the Programme Alban, the European Union Programme of High Level Scholarships for Latin America, scholarship nº E04D040507BR.

The authors are thankful to Engineer Susana Arieira who done the rheological tests and also for her assistance on the analytical research.

6. References

Baker, T. E., Allen, T.M., Jenkins, D.V., Mooney, T., Pierce, L.M., Christie, R.A., Weston, J.T., "Evaluation of the Use of Scrap Tires in Transportation Related Applications in the State of Washington", Washington State Department of Transportation, Washington, D.C., 2003.

Barnes, H.A., "A Handbook of Elementary Rheology", Institute of Non-Newtonian Fluid Mechanics, University of Wales, 2000.

Caltrans, " Maintenance Technical Advisory Guide (TAG)", Caltrans, State of California Department of Transportation, Sacramento, California, 2003.

Caltrans, "Feasibility of Recycling Rubber Modified Paving Materials", Caltrans, State of California Department of Transportation, Sacramento, California, 2005.

Cooley Jr., L.A., Brown, E.R., "Potential of Using Stone Matrix Asphalt (SMA) for Thin Overlays", National Center of Asphalt Technology, NCAT Report 03-01, Auburn University, Auburn, 2003.

CWC, "Best Practices in Scrap Tires & Rubber Recycling: Ambient versus Cryogenic Grinding", Clean Washington Center, Seattle, 1998.

Heitzman, M., "Design and Construction of Asphalt Paving Materials with Crumb Rubber Modifier", Transportation Research Record 1339, TRB National Research Council, Washington D.C., 1992.

Hicks, R.G., Epps, J.A., "Quality Control for Asphalt Rubber Binders and Mixes", Rubber Pavements Association, Tempe, 2000.

Hicks, R.G.,"Asphalt Rubber Design and Construction Guidelines", Volume I – Design Guidelines, Northern California Rubberized Asphalt Concrete Technology Center (NCRACTC), Sacramento, 2002.

HPV Petroleum Testing Group, "High Production Volume (HPV) Chemical Challenge Program, Asphalt Category, Consortium Registration # 1100997, USA, 2003.

Jackson, G.J., Durairaj, R., Ekere, N.N., "Characterisation of Lead-Free Solder Pastes for Low Cost Flip-Chip Bumping", Electronics Manufacturing Engineering Research Group School of Aeronautical, Civil and Mechanical Engineering University of Salford, Greater Manchester, 2006.

Jorgenson, L., "Tires Make the Road – The Latest in Asphalt Rubber Pavements", University of California Berkeley, Institute of Transportation Studies, Technology Transfer Program, Berkeley, 2002.

Monismith, C.L., Epps, J.A., Kasianchuk, D.A., McLean,, D.B., "Asphalt Mixture Behaviour in Repeated Flexure", Report TE 70-5, University of California, Berkeley, 1971.

Partl. M.N., Francken, L., "RILEM Interlaboratory Tests on Stiffness Properties of Bituminous Mixtures", Proceedings of the Fifth International Rilem Symposium, Lyon, 1997.

Pellenin, T.K., Christensen, D.W., Rowe, G.M., Sharrock, M., "Fatigue Transfer Functions – How Do They Compare?", TRB 2004 Annual Meeting, Washington D.C., 2004.

Recycling Research Institute, "Rubber Recycling – Crumb Rubber", Scrap Tire News, Leesburg, 2005.

Shatnawi, S., Holleran G., "Asphalt Rubber Maintenance Treatments in California", Pavement Maintenance Specialists, Valley Slurry Seal Co., Sacramento, 2000.

Van Kirk, J., Holleran, G., "Reduced Thickness Asphalt Rubber Concrete Leads to Cost Effective Pavement Rehabilitation", 1st International Conference World of Pavements, Sydney, 2000.