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ENGLISH VERSION..

Effect of the grain size of recycled rubber on the behaviour of an asphalt mix

Efecto del tamaño del grano de caucho reciclado en el comportamiento de una mezcla asfáltica

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Abstract

The elimination of a large quantity of waste such as plastic, bottles, tyres, etc., that are generated in large quantities and produce an environmental impact and risk in the areas where they are produced and stored. The current study aims to use recycled rubber grain (GCR), originating from discarded tyres, in the manufacture of asphalt concrete. Seven mixtures were designed using the Marshall methodology, one mixture without the addition of the rubber grain, which will be the control mixture for comparison, and six mixtures with the addition of 1% of rubber grain of varying sizes, which oscillate between that passing through a sieve of 2.36 mm (No. 8) and that retained on a sieve of 0.075 mm (No. 200). Once the respective working formulas had been determined, performance tests were carried out such as: susceptibility to humidity damage, plastic deformation resistance, resilient modulus, fatigue resistance and skid resistance or each of the mixtures. The results show that the incorporation of rubber grain in some cases produces a slight decrease in the optimum content of asphalt cement, increase in Marshall stability, an improvement in plastic deformation, an increase in resistance, a longer fatigue life in comparison with a conventional mixture. The results of the laboratory tests indicate that in using recycled rubber grain, it is possible to obtain asphalt concretes with improved required technical characteristics whilst constructing a surface which is environmentally friendly.

Keywords*: Recycled rubber grain; plastic deformation; fatigue; resilient modulus; adherence*

Resumen

La eliminación de una gran cantidad de desechos como plástico, botellas, llantas, etc., que se generan en grandes cantidades y producen un impacto y riesgo ambiental en las zonas donde se producen y almacenan. El presente estudio pretende utilizar el grano de caucho reciclado (GCR), proveniente de las llantas desechadas, en la fabricación de concreto asfáltico. Se diseñaron siete mezclas utilizando la metodología Marshall, una mezcla sin la adición de grano de caucho que será la mezcla base de comparación y seis mezclas con adición de 1% de grano caucho de diferentes tamaños, los cuales oscilan entre pasa tamiz de 4.76 mm (No. 40) y retenido tamiz de 0.075 mm (No. 200). Una vez determinadas las respectivas fórmulas de trabajo se realizaron pruebas de desempeño como: susceptibilidad al daño por humedad, resistencia a la deformación plástica, módulo resiliente, resistencia a la fatiga y resistencia al deslizamiento a cada una de las mezclas. Los resultados demuestran que la incorporación de grano de caucho produce en algunos casos una leve disminución en el contenido óptimo de cemento asfáltico, incremento en la estabilidad Marshall, mejora de la deformación plástica, incremento en la resistencia, mejor vida a la fatiga en comparación con la mezcla convencional. Los resultados de las pruebas de laboratorio indican que, al utilizar grano de caucho reciclado, se pueden obtener concretos asfálticos con mejores características técnicas requeridas y se pueden construir un pavimento amigable con el medio ambiente.

Palabras clave: *Grano de caucho reciclado; deformación plástica; fatiga; módulo resiliente; adherencia*

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1. Introduction

Currently, interest in ecological and sustainable design and construction has intensified with the aim of guaranteeing a better-quality environment. The construction and maintenance of roadways is one of the sectors incurring the greatest consumption of natural resources (Horvath, 2003), something which can be reduced if recycled materials, residues or waste is used in the construction of new roadways or in refurbishments. In some countries, the most widely used recycled materials are slag, ash, concrete waste, recycled asphalt, bricks and tyre rubber (Chui et al., 2008)(Pettinari and Simone, 2015).

The discard and disposal of out-of-use tyres in Colombia has resulted in a worrying environmental situation during recent years, it being estimated that in the country around 100,000 tonnes of tyres are disposed of with only 18% being used in remoulding, 10% being used for artisanal ends, and the remaining 72% being left to burns, uncontrolled stacks and, in consequence, plagues, respiratory diseases and severe atmospheric damage (Ministerio de Ambiente y Desarrollo Sostenible, 2015). On a global scale, studies have demonstrated that more than 60% of discarded tyres are disposed of in an unknown way, causing environmental problems (Alamo-Nole et al., 2011). Studies realised in the year 2007 concluded that one billion tyres are disposed of each year and that for the year 2030, up to 5 billion tyres could be discarded (Colom et al., 2007)(Pacheco-Torgal et al., 2012). To deal with this situation, it has been proposed that recycled rubber grain (GCR) produced through the disused tyre grinding process be used as part of the composition of asphalt mixture.

Currently, at the time of developing any infrastructure construction, environmental conservation is a primordial consideration due to the fact that, according to the intergovernmental panel on climate change in Colombia, it is still possible to reduce the impact generated by these constructions through urgent actions in the sectors committed to sustainability and the mitigation of climate change (DNP, 2018). Actions such as the use of materials that take a long period of time to decompose, for example tyres, which are normally discarded to later be burnt in open-air incineration and thereby increase the levels of carbon dioxide and monoxide that, in turn, reduces the quality of life of the population. One alternative to mitigate this problem is the use of said material, which through a series of processes can yield recycled rubber grain (GCR), in the manufacture of asphalt mixtures for flexible road surfaces.

Investigations carried out in Colombia have found that the use of GCR as a component of the asphalt mixture improves the efficiency of the surface in aspects such as the diminishing of plastic deformation, an improvement in resistance to fatigue and a decrease in susceptibility to changes in temperature and related inherent damage, resulting in a direct reduction in the cost of construction and maintenance(Correa Lesmes, 2018)(Díaz and Castro, 2017).

This investigation includes the analysis of the effect of the grain size of GCR in the mechanical performance of a type MDC-19 hot mix asphalt. For this analysis, asphalt mixtures were designed using the Marshall methodology to evaluate and compare their posterior mechanical and volumetric response with and without the incorporation of GCR. Additionally, performance tests were carried out and the benefits of using GCR in asphalt mixtures was thereby determined.

The use of recycled rubber grain (GCR) in a road surface structure does not only generate environmental benefits but also allows for the improvement in some mechanical properties and increases the lifespan of the structure, reducing maintenance costs (Bansal et al., 2017).

2. Materials and methodology

2.1 Materials

The recycled rubber grain was provided by the company "Futuro Ambiental RandR" located in the city of Duitama, Boyacá. The rocky aggregate used in the investigation was sourced from the Company "Triturados Paz de Río S.A.S. The basic physical properties of the aggregate is shown in (Table 1). The tests were carried out in accordance with the relevant Colombian guidelines INVIAS-2013 (INVIAS, 2013b) and the international ASTM guidelines. The asphalt cement used was of penetration grade 80/100 and supplied by the Company "Manufacturas y Procesos Industriales MPI Ltda. The results of the characterization trials were found to be within the limits of the specification and are detailed in (Table 2). The asphalt concrete mix selected for the investigation was MDC-19 in accordance with the INV E-450-13 specifications for an NT2 level of transit ($5.0x10^5$ <ESAL< $5.0x10^6$) (Instituto Nacional de Vías INVIAS, 2013a).

***Table 1**. Basic physical properties of the aggregate used*

Properties	*Results*	*Specification*	*Standard*
Loss Angeles Abrasion (%)	*17.4*	*<25*	*ASTM C 131*
Degradation (Micro-Deval) (%)	*22.6*	*<25*	*ASTM D 6928*
Soundness test (%)	*1.2*	*<28*	*ASTM C 88*
Fractured faces (%)	*99.1*	*>60*	*ASTM D 5821*
Plasticity index (%)	*NP*	*NP*	*ASTM D 4318*
Sand equivalent (%)	*4.8*	*>50*	*ASTM D 2919*

***Table 2**. Basic properties of asphalt cement*

Properties	*Ieasured value*	*Specification*	*Standard*
Penetration at 25°C (0.1 mm)	*88.73*	*80 - 100*	*ASTM D 5-97*
Ductility, 5 cm/min, 25°C (cm)	*150*	*>100*	*ASTM D 113*
Softening point (°C)	*45.5*	*>45*	*ASTM D 36*
Flash point (°C)	*292*	*>230*	*ASTM D 92*
Viscosity at 60°C (P)	*2336*	*>1000*	*ASTM D 2171*

2.1 Methodology

2.1.1 Trials to characterize the recycled rubber grain

Chemical composition and Topographical information: The scanning electron microscope (SEM) was used to determine the chemical composition and morphology of the recycled rubber grain and of the asphalt cement. The digital topographical images were obtained from the samples.

2.1.2 Design of the mixture

The type of mixture designed corresponds with a dense hot asphalt mixture with continuous gradation and maximum nominal aggregate size of 19 millimetres (MDC-19). It was designed following the Marshall methodology (Bahia et al., 2009) and the incorporation of the recycled rubber grain was done by dry process. It was made up of the creation of seven asphalt mixtures: one conventional control mixture (without GCR) identified as mix M0, three with the addition of GCR with a wide grain size passing through a 2.36mm sieve and being retained by a 0.425mm sieve, and three with the addition of fine grain GCR passing through a 0.425mm sieve and being retained by a 0.075mm sieve. Mix M1, with GCR between 2.36mm and 2.0mm; mix M2 with GCR between 2.0mm and 0.425mm; mix M3 with GCR between 2.36mm and 0.425mm; mix M4 with GCR between 0.425 and 0.180mm; mix M5 with GCR between 0.180mm and 0.075mm; and mix M6 with GCR between 0.425mm and 0.075mm. The work gradation of all mixtures is shown in (Figure 1).

The indicators and parameters that were considered for the verification of each of the mixtures were: unit weight, stability, flow, gap percentage, voids in the mineral aggregate and voids filled by asphalt cement. The tests to verify the performance of each of the mixtures were: susceptibility to humidity damage, plastic deformation resistance, resilient modulus and fatigue resistance. To determine the operation of each mixture, skid resistance tests were also carried out.

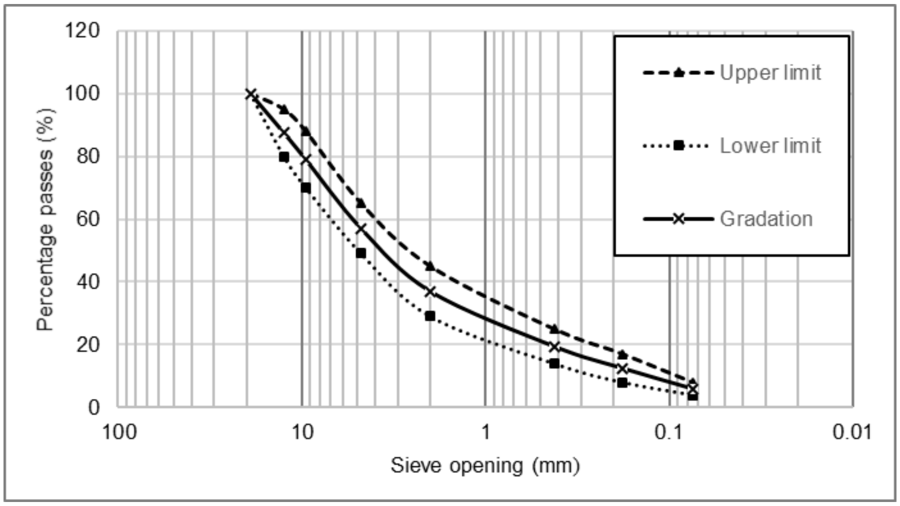

Figure 1. *Working gradation for mixtures type MCD-19 according to article 450-13 INVIAS*
Source: the authors

Susceptibility to humidity damage.
The water susceptibility trials using the indirect traction test evaluate the change in resistance to traction as a result of the effects of saturation and accelerated conditioning to water on laboratory-compacted asphalt mixtures. The trial was carried out flowing the procedure from the INV E-725-13 and ASTM D4867 guidelines; six samples were elaborated for each type of mix, three of which were tested in a dry process and three after partial saturation. The samples from the humid group were submerged in a water bath for 24 hours at a temperature of 60°C. After this time, both groups of samples were submerged in a bain-marie at 25°C for one hour. The resistance to indirect traction was determined using (Equation 1).

$$R_T = \frac{2000P}{\pi h D} \qquad (1)$$

Where R_T *is tensile strength (kPa); P is maximum load applied (N); h is thickness of the specimen (mm) and D is diameter of the specimen (mm).*

The relation of resistance to traction (TSR) was calculated as the relation between the average resistance to the tension of the water-conditioned subgroup (R_{TH}) *and the average resistance of the subgroup which was kept dry* (R_{TS})*, as expressed in (Equation 2).*

$$RRT = \left[\frac{R_{TH}}{R_{TS}}\right] * 100 \qquad (2)$$

Resistance to plastic deformation
The trial of resistance to plastic deformation was carried out to evaluate the resistance to permanent deformation or rutting. The trial was conducted in accordance with the Colombian INV E-756-13 guidelines and the European EN-12697-22 guidelines, using "Wheel Tracking Test" equipment. The trial was conducted at a constant temperature of 60°C, by passing a 20cm diameter metallic wheel equipped with a surrounding 5cm wide, 2cm thick solid rubber band, which exerted a contact pressure of 900KN/m^2 *on the surface of the sample.*

The total deformations after minutes 1, 3 and 5 from the start of the test were measured. After this period, every 5 further minutes until reaching 45 minutes from which measurements were taken every 15 minutes until finishing the trial at 120 minutes. From the deformations recorded corresponding to the different times, and taking into account *the previous deformations recorded, the median deformation velocity was calculated corresponding to the 105 to 120 minute time interval, using (Equation 3).*

$$V_{t2}/V_{t1} = \frac{d_{t2} - d_{t1}}{t_2 - t_1} \qquad (3)$$

Where: V_{t2}/V_{t1} *is average speed of deformation, in the time interval between* t_1 *y* t_2 *(µm/min);* d_{t1}, d_{t2} *is deformations to* t_1 *y* t_2 *respectively (µm) and* t_1, t_2 *is times in the established time (min).*

Resilient Modulus

To determine the resilient modulus of the asphalt mixtures being studied, three samples were prepared for each type of mix, which were then trialled through the procedure established in the guidelines found in prNE-12697-26-Anexo C, in the Nottingham Asphalt Tester (NAT) equipment. Considering that the trial is not destructive, the samples were tested at 5°C, 25°C and 40°C and at a frequency of 0.33Hz.

The resilient modulus depends on the temperature of the trial. Based on the values of the tests carried out and applying the technique of OLS regression, the modulus is adjusted to a mathematical function of the type given in (Equation 4), which represents the behaviour of the resilient modulus for each mix.

$$M_r = A * e^{B*T} \qquad (4)$$

Where: M_r *is temperature resilient module T; T is mix temperature and A y B = regression constants.*

Resistance to fatigue.

This test aimed to determine the number of cycles (of an undetermined load) necessary to produce the failure of a briquette and was carried out in accordance with the guidelines found in BS-EN 12697-24 Anexo E. The test was realized at a temperature of 20°C with a frequency of 2.5Hz and under controlled deformation using the NAT (Nottingham Asphalt Tester) equipment.

Eight briquettes were manufactured with the optimum obtained asphalt percentage and its corresponding granulometric composition. The briquettes manufactured were divided into four groups which were subjected to tests with distinct loads of 250kPa, 300kPa, 320kPa and 350kPa correspondingly. For each briquette subjected to this trial, the lifespan until fail was determined from the number of applications of load that caused the failure of the briquette. The force in the centre of the briquette was calculated using (Equation 5) and the maximum deformation from traction was calculated using (Equation 6).

$$\sigma_0 = \frac{2P}{\pi t \varphi} \qquad (5)$$

$$\varepsilon_o = \left(\frac{2\Delta H}{\varphi}\right) * \left[\frac{1 + 3\mu}{4 + \pi * \mu - \pi}\right] \qquad (6)$$

Where: σ_0 *is tensile stress in the center of the specimen (MPa); P is maximum load (N); t is specimen thickness (mm);* φ *is specimen diameter (mm);* ε_o *is tensile deformation in the center of the specimen (µε);* ΔH *is Horizontal deformation (mm) and* μ *is Poisson coefficient*

To obtain the fatigue laws for the prediction of the fatigue life, (Equation 7) (Wholer) was used (Pasandín and Pérez, 2017), as this trial was carried out with controlled force

$$\varepsilon_o = k(N_f)^{-n} \qquad (7)$$

Where: Nf is number of load cycles to fatigue failure; k y n = Material constants and ε_0 is the initial tensile horizontal strain at the sample center in $\mu\varepsilon$.

3. Results and discussions

3.1 Chemical elements of gcr and of the asphalt cement

The main elements in the GCR simple are shown in (Figure 2(a)). It can be observed that carbon is the principal element present. In (Figure 2(b)) it can be observed that the principal element present in the asphalt cement is also carbon. A good affinity between the GCR and the asphalt cement can be attributed to this similarity.

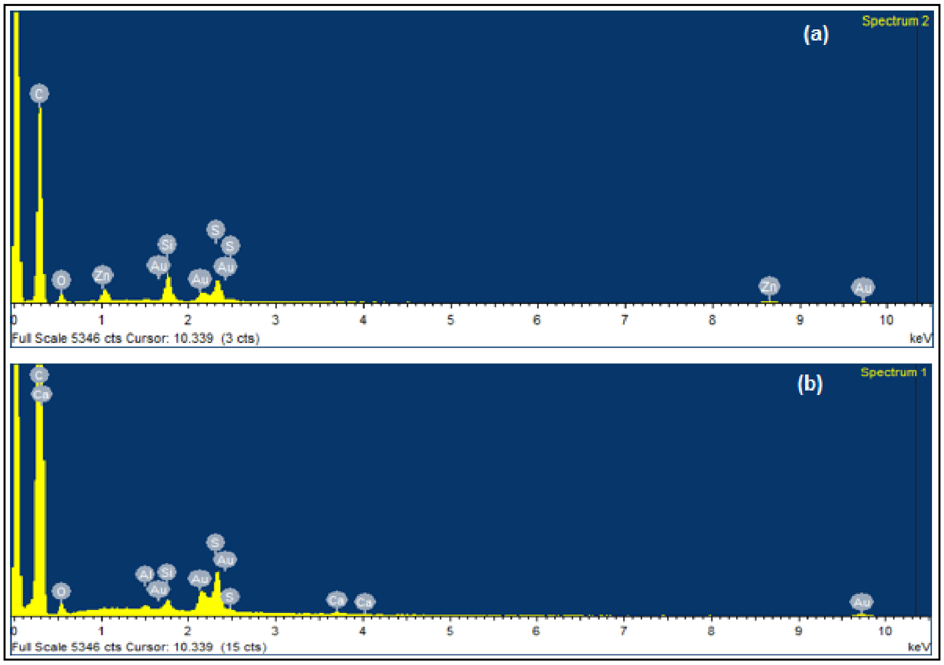

***Figure 2.** Concentration of elements (a) GCR, (b) asphalt cement*
Source: The authors, according to a SEM trial conducted at INCITEMA-Uptc, Tunja

3.2 Microscopic morphology

The microscopic morphology of the recycled rubber grain is represented in (Figure 3) at a scale of 1.00KX, which shows a coarse texture, corrugated, rough and with well-defined ridges; the edges are seen to be angled in form and subrounded.

3.3 Design of the mixtures

3.3.1 Preliminary design

The first step consisted of carrying out the granulometric dosing for each mix. Next, the optimum content of asphalt cement was determined using the Marshall methodology and taking into consideration the criteria established in article 450-13 of INVÍAS (INVIAS, 2013). Once determined, compliance with the requirements established in the specifications was verified. The results are shown in (Table 3). The optimum content of asphalt cement in the conventional mix (M0), corresponds to 5.7% and this value is equal in the asphalt mixtures with the incorporation of *the coarser grain rubber between 2.36mm and 0.425mm (M1, M2, M3) and was slightly reduced in the mixtures modified by the addition of finer grain rubber between 0.425mm and 0.075mm (M4, M5, M6).*

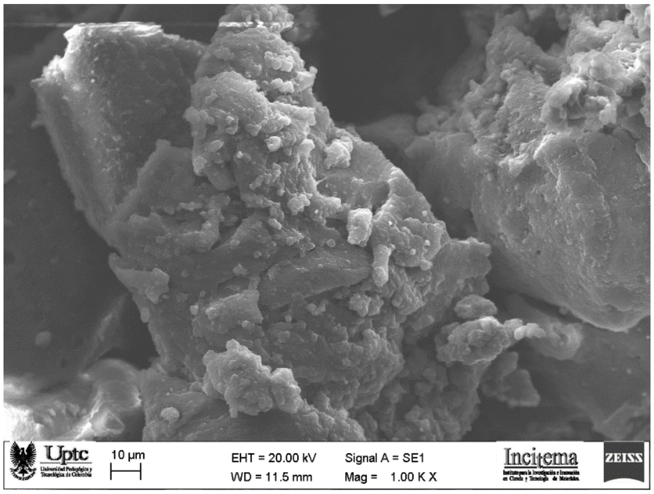

***Figure 3**. GCR microscopic morphology*
Source: The authors, according to tests carried out at INCITEMA-Uptc, Tunja

***Table 3.** Verification results and mechanical characteristics of the mixtures*

Parameter	*M0*	*M1*	*M2*	*M3*	*M4*	*M5*	*M6*	*Specification INV E 450-13*
% optimal asphalt	*5.7%*	*5.7%*	*5.7%*	*5.7%*	*5.5%*	*5.6%*	*5.5%*	*-*
Minimal stability (N)	*10076*	*10693*	*11108*	*9897*	*18085*	*15381*	*14352*	*7500*
Flow (mm)	*3.2*	*3.3*	*3.4*	*3.0*	*3.8*	*3.6*	*3.4*	*2.0 a 4.0*
Relation, Stabiliyt/Flow (kN/mm)	*3.2*	*3.2*	*3.3*	*3.3*	*4.8*	*4.2*	*4.2*	*3.0 a 5.0*
Va (%)	*3.9*	*4.3*	*4.2*	*3.9*	*4.0*	*3.7*	*4.9*	*3.0 a 5.0*
VAM (%)	*15.6*	*15.9*	*15.8*	*15.5*	*16.0*	*15.8*	*16.8*	*> 15.0*
VFA (%)	*75.3*	*73.1*	*73.4*	*74.8*	*75.4*	*76.6*	*75.5*	*65 a 78*
Relation Filler/Binder cash	*1.1*	*1.1*	*1.2*	*1.2*	*1.1*	*1.1*	*1.2*	*0.8 a 1.2*

The results obtained indicate that all of the mixtures comply with the requirements. With respect to stability, all of the mixtures satisfy the minimum requirement of 7500N, established in the specifications of INVIAS-2013. In the case of flow, all of the mixtures comply with the values given in the requirements. For the parameters of air voids (%Va) and voids in mineral aggregate (%VAM) for the mixtures with GCR, the majority tend to increase their values compared to the conventional mix. For the parameter of voids filled by asphalt (%VFA), a slight reduction was seen in the values in the mixtures with addition of coarse GCR, whilst in the mixtures with the addition of fine GCR, the variation is much less pronounced. In the case of the results referring to the filler/binder relation, no significant variation was evidenced.

3.3.2 Performance tests

Once the working formula was obtained for each of the mixes, trials were carried out to verify the design and determine the performance properties.

Susceptibility to humidity damage

The results of the TSR test are shown in (Figure 4). The values of resistance to traction of the samples trialled in a dry test behaved similarly across all of the mixtures. Equally in the conditioned samples, with the exception of mix M2 which returned higher values in resistance to traction in both the conditioned samples and those tested in a dry test. This increase, however, was not proportional in the conditioned samples and, due to this, the ratio of resistances to traction (TSR) is the lowest in comparison with the other mixtures studied. Notwithstanding, all of the mixes complied with the minimum required 80% as specified in the INV E 450-13 guidelines. The TSR values are very similar to those observed in a study carried out in Italy (Eskandarsefat et al., 2018), which utilized RAP and GCR. Moreover, the European guidelines require just 75% in the ration of the resistances to traction.

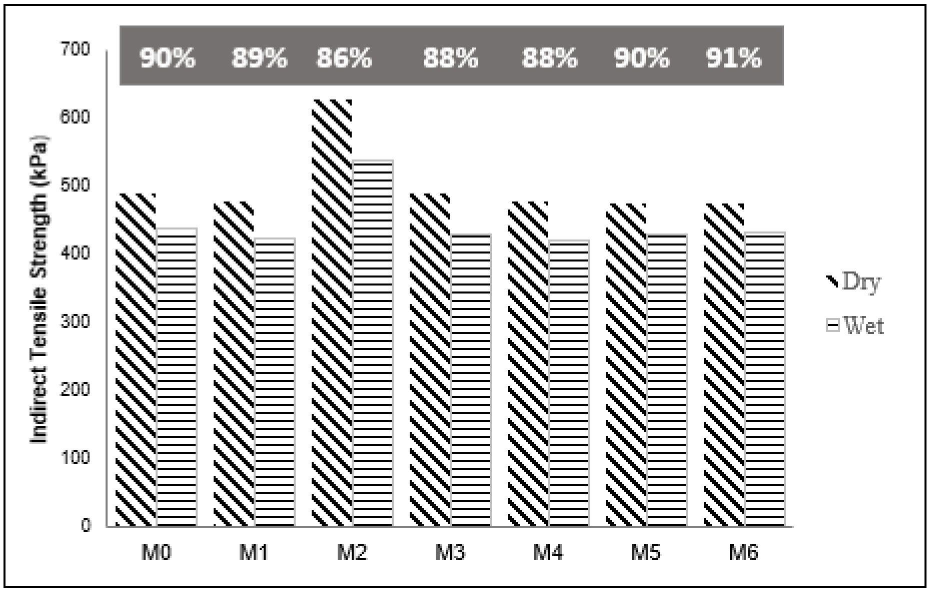

***Figure 4**. values of ITS y TSR*
Source: The authors

Resistance to plastic deformation

In (Figure 5), the results of the test using the Wheel Tracking Test equipment are shown. This relates the depth of the deformation and the time that the wheel passed in each simple of the mixtures analysed. The results of the maximum deformation at the conclusion of the test and the speed of the deformation in the 105-120 minute interval are summarised in (Table 4). The consistency of these test results can be seen for the two samples created of each type of mixture.

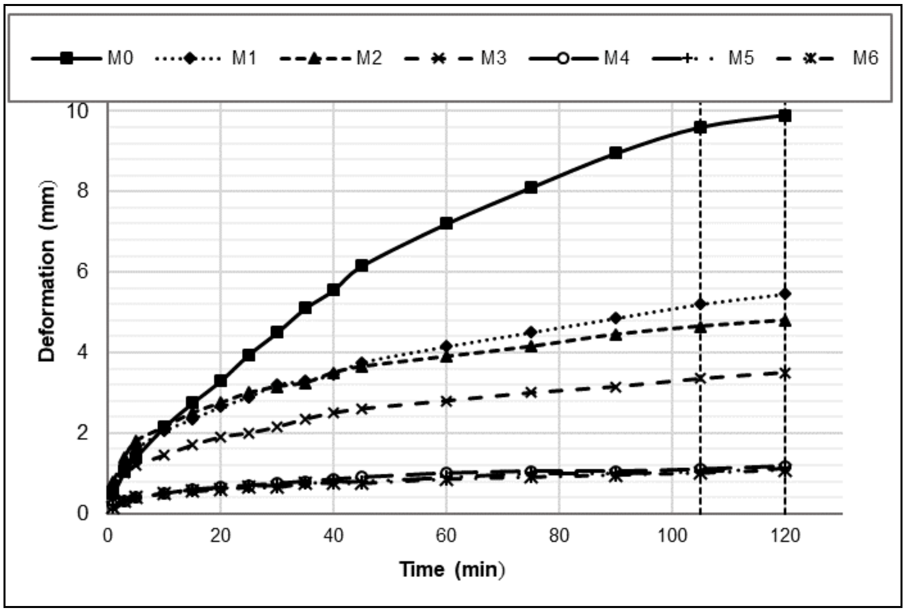

Figure 5. *Evolution of plastic deformation*
Source: The authors

Table 4. *Plastic deformation test results*

Id Mixture	*Deformation depth after test completion (mm)*			*Deformation speed 105 to 120 min (µm/ min)*		
	Specimen 1	*Specimen 2*	*average*	*Specimen 1*	*Specimen 2*	*average*
M0	*9.50*	*10.30*	*9.90*	*20.00*	*20.00*	*20.00*
M1	*5.60*	*5.30*	*5.45*	*20.00*	*13.33*	*16.67*
M2	*4.60*	*5.00*	*4.80*	*6.67*	*13.33*	*10.00*
M3	*3.70*	*3.30*	*3.50*	*13.33*	*6.67*	*10.00*
M4	*1.10*	*1.25*	*1.18*	*6.67*	*0.00*	*5.00*
M5	*1.10*	*1.15*	*1.13*	*6.67*	*3.33*	*5.00*
M6	*0.90*	*1.25*	*1.08*	*6.67*	*3.33*	*5.00*

The incorporation of GCR improved the resistance to plastic deformation with all mixtures presenting a decrease in the depth of the deformation. The mixes with GCR between 2.36mm and 0.425mm showed the following decreases in deformation when compared to the control mix (M0): Mix M1 of 44%, mix M2 of 51% and mix M3 of 69%. Meanwhile, the mixtures with finer grain GCR (between 0.425mm and 0.075mm) yielded better performance in relation to resistance to plastic deformation, showing a reduction of more than 80% in the depth of the deformation with respect to the control mix (M0). The same behaviour was seen with respect to the speed of the deformation. This can be attributed to the smaller size of the GCR particles which act with the asphalt cement and result in a lower susceptibility to plastic deformation. In an investigation in Thailand, similar results were obtained in that, in the mixtures with coarser grain GCR, significant differences were not seen, while mixtures with finer grain GCR, were shown to have excellent efficacy in terms of resistance to plastic deformation (Unsiwilai and Sangpetngam, 2018).

Resilient Modulus

As is natural, with an increase in temperature, the resilient modulus lessens. (Figure 6) shows the highest values determined in the mixtures with GCR at the three trial temperatures. The values with higher resilient modulus are found in the mixes created with the incorporation of finer grain GCR. This can be attributed, as in the previous case, to the better digestion of the GCR particles with the asphalt cement.

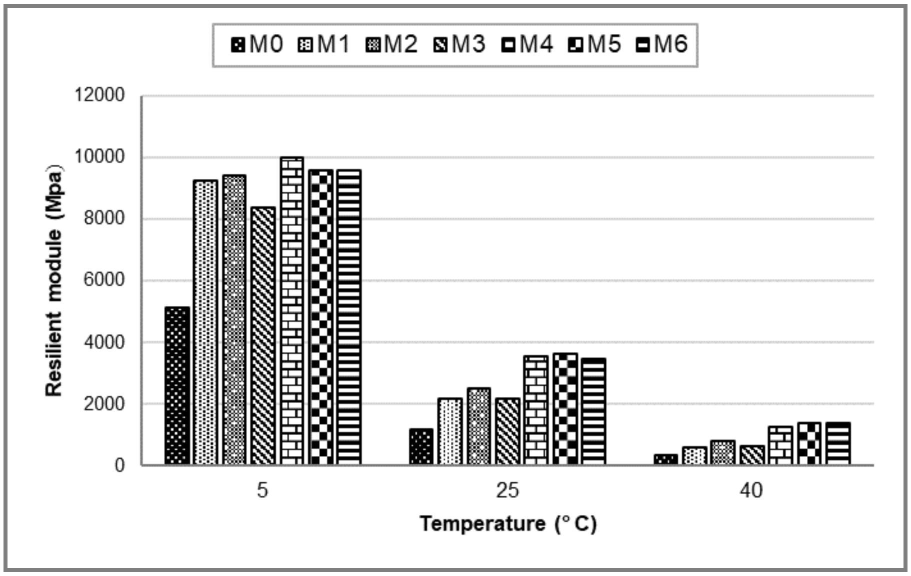

Figure 6. *Resilient module variation*
Source: The authors

Fatigue laws

The fatigue life is defined as the number of load cycles until failure occurs (Nf) and represents the capacity of the mixture to support cyclical transport loads (Li et al., 2013). (Figure 7) and (Figure 8) show the stress against the number of cycles for the mixtures studied. The figures also include the calculations of the fatigue law and the correlation coefficient (R^2), which indicates that there is a statistical correlation between the results obtained to determine each fatigue law, given that the R^2 coefficients are over 0.89.

As can be seen in (Figure 7), with the incorporation of GCR between 2.36mm and 0.428mm, the fatigue life of the mixtures is greater.

In (Figure 8), the fatigue laws in the mixtures with finer grain GCR between 0.425mm and 0.075mm are shown. These mixtures also yielded a greater fatigue life when compared to that of the control mix (M0). Of all of the mixtures analysed, mix M3 with GCR between 2.36mm and 0.428mm demonstrated the greatest fatigue life, presenting the lowest gradient. The result is that the addition of GCR can be affirmed to be beneficial to the fatigue life of asphalt mixtures.

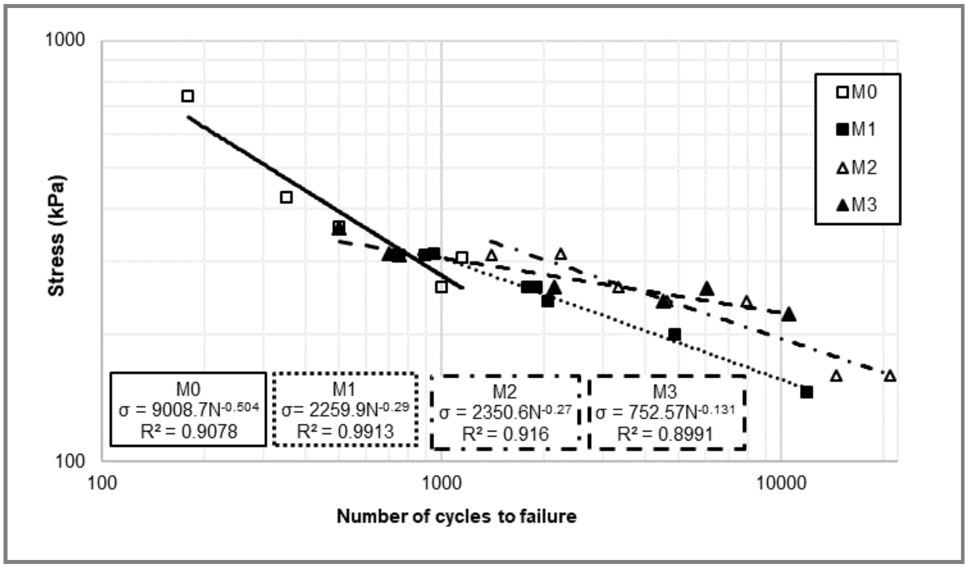

Figure 7. *Fatigue laws of mixtures M0, M1, M2 and M3*
Source: The authors

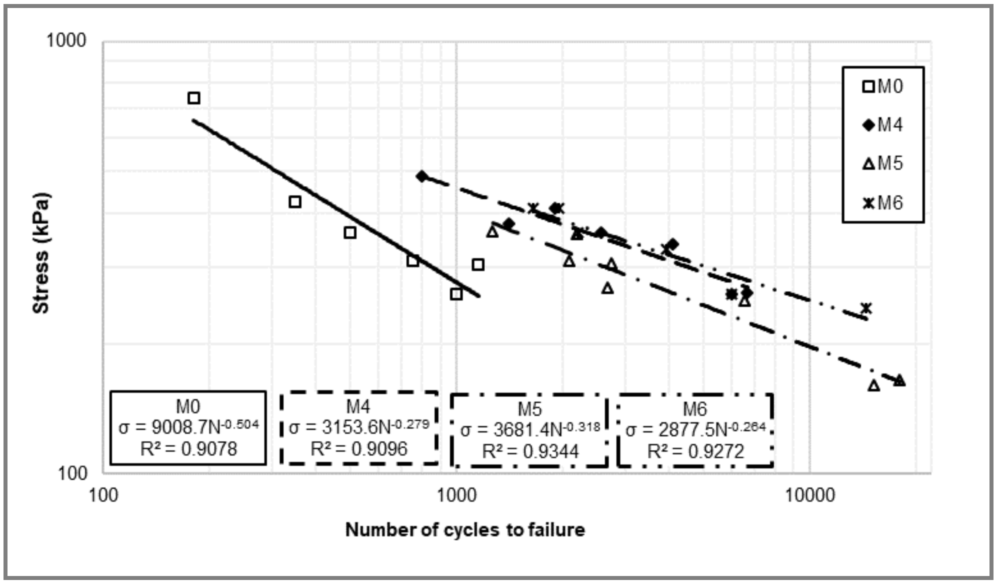

Figure 8. *Fatigue laws of mixtures M0, M4, M5 and M6*
Source: The authors

4. Conclusions

This document studies the effect of the size of GCR on the behaviour of asphalt mixtures. To achieve this aim, six types of mixture were evaluated in which GCR of different granulometry were incorporated. The granulometry of the GCR comprised of sizes passing through a 2.36mm sieve and being retained in a 0.075mm sieve. This granulometry was divided into two groups; one coarse, with particles between 2.36mm and 0.425mm in size and the *other fine, with particles between 0.425mm and 0.075mm in size. Based on the results of this study, the following conclusions are presented:*

- *With respect to the Marshall design of the asphalt mixtures, it was determined that the incorporation of finer grain GCR (passing through a 0.425mm sieve and retained by a 0.075mm sieve) slightly reduced the optimum percentage of the asphalt mix, increasing considerably the stability, flow, and stability-flow ratio values, reaching the greatest increase when using GCR with a granulometry of between 0.425mm and 0.180mm. Additionally, the mixtures with incorporation of GCR yielded a slight increase in the percentage of air voids and VAM percentage with a slight reduction in the VFA percentage, however, these variations could not be clearly associated according to the size of the GCR incorporated.*
- *The addition of GCR improves the conditions of the asphalt mix with relation to resistance to plastic deformation due to offering a more solid mineral skeleton which reduces the voids and yields a better response to the action of transit, however mix M6 is that in which plastic deformation reduced significantly in the final time interval.*
- *Fatigue resistance was shown to be best in mix M3 due to it having a lower gradient, something that indicates that as the number of load cycles increases, the amount of stress did not suffer significant changes and it would be this mix that offers the best response to distinct variations in transit loads.*
- *The mix with the best response to the use of GCR is mix M6 considering the results obtained from the performance tests, this due to finer grain GCR considerably improving the mechanical conditions of the asphalt mix.*
- *Finally, the effect that the incorporation of GCR produces in the asphalt mix shows good responses in all six mixtures, indicating that the addition of GCR improves the mechanical behaviour when compared to a conventional mix, extending its lifecycle. Moreover, the smaller the size of the grains, the more significant the improvements in the mechanical properties of the mixture.*

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