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Influence of unserviceable tires' rubber on the mechanical performance of hot mix asphalt

C. G. L. Nunes[1]*, P. H. S. Pereira[2], R. A. Melo[3], J. K. G. Rodrigues[4], L. C. F. L. Lucena[4]
*Contact author: camilagluznunes@gmail.com
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ABSTRACT
This work aimed to optimize the production of hot mix asphalt (HMA) from the use of asphalt-rubber. For that, the mechanical performance of asphalt mixtures produced with different binders was evaluated: commercial asphalt-rubber (AR08), asphalt crumb rubber 10% (AR10) and 15% (AR15), and conventional asphalt (PEN 50-70). For the composition of these mixtures, the optimum asphalt contents were defined by the Marshall design. To carry out the mechanical tests, specimens molded with Marshall and Superpave compactors were tested. From the results obtained, it was verified that AR08 and AR10 asphaltic mixtures, compacted with Superpave, carried out the best mechanical performance. However, the AR08 binder is already available on the market, which facilitates its usage in paving works.
Keywords: hot mix asphalt; asphalt-rubber; *Marshall; Superpave.*

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[1] Ph.D. student of the Graduate Program in Civil and Environmental Engineering, Federal University of Paraíba, João Pessoa, Brazil.
[2] Master's student of the Graduate Program in Civil and Environmental Engineering, Federal University of Paraíba, João Pessoa, Brazil.
[3] Department of Civil Engineering, Federal University of Paraíba, João Pessoa, Brazil.
[4] Department of Civil Engineering, Federal University of Campina Grande, Campina Grande, Brazil.

Contribution of each author
In this work, the 1st author contributed to the conceptualization (50%), experimentation (60%), analysis (100%) and writing of the original draft (100%). The 2nd author contributed to the experimentation activity by 40%. The 3rd author contributed to the conceptualization (50%), orientation (100%) and writing - review and editing (70%). The 4th author contributed resources for the experiments (50%). The 5th author contributed to the writing - review and editing (30%) and resources for the experiments (50%).

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Influencia del caucho de desecho de neumáticos en el rendimiento mecánico de mezclas asfálticas en caliente

RESUMEN

Este trabajo tuvo como objetivo optimizar la producción de mezclas asfálticas en caliente utilizando caucho asfáltico. Para ello, se evaluó el desempeño mecánico de mezclas asfálticas producidas con diferentes aglutinantes: asfalto caucho comercial (AC08), asfalto caucho 10% (AC10) y 15% (AC15) de residuos de caucho y asfalto convencional (PEN 50-70). Para la composición de estas mezclas, el contenido óptimo de asfalto fue definido por el método Marshall. Para la realización de las pruebas mecánicas se ensayaron probetas moldeadas con compactadores Marshall y Superpave. De los resultados obtenidos se encontró que las mezclas con AC08 y AC10, compactadas con Superpave, presentaron el mejor desempeño mecánico. Sin embargo, el ligante AC08 ya está disponible en el mercado, lo que facilita su uso en trabajos de pavimentación.

Palabras clave: mezcla asfáltica en caliente; asfalto de caucho; *Marshall; Superpave.*

Influência da borracha de pneus inservíveis no desempenho mecânico de misturas asfálticas a quente

RESUMO

Este trabalho teve como objetivo otimizar a produção de misturas asfálticas a quente a partir da utilização de asfalto-borracha. Para isso, avaliou-se o desempenho mecânico de misturas asfálticas produzidas com diferentes ligantes: asfalto-borracha comercial (AB08), asfalto-borracha 10% (AB10) e 15% (AB15) de resíduos de borracha e asfalto convencional (PEN 50-70). Para a composição dessas misturas, os teores ótimos de asfalto foram definidos pela dosagem Marshall. Já para a realização dos ensaios mecânicos, foram ensaiados corpos de prova moldados com compactadores Marshall e Superpave. Pelos resultados obtidos, constatou-se que as misturas com AB08 e AB10, compactadas com o Superpave, apresentaram o melhor desempenho mecânico. Porém, o ligante AB08 já está disponível no mercado, o que facilita seu uso em obras de pavimentação.

Palavras-chave: mistura asfáltica a quente; asfalto-borracha; *Marshall; Superpave.*

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1. INTRODUCTION

Unserviceable tires are used tires that cannot be reused after retread because they present irreparable structural damages. These tires are related to one of the biggest and most problematic sources of waste. A great volume of tires is produced every year and it takes tires a long time to decompose. In addition, unserviceable tires become threats to human health and the environment when they are inadequately disposed of (Lo Presti, 2013).

In Brazil, there is a high reliance on highways for transporting freight and people. It boosts the tire market and, consequently, the generation of tire waste. Furthermore, this dependency increases the operating costs of transportation, accelerates pavement wear and the need for preservation and maintenance. Based on this, the utilization of asphalt-rubber in paving is a practicable alternative not only to protect the environment but also to reduce the transportation operational costs in the country.

The asphalt-rubber presents numerous advantages in comparison to the standard asphalt, such as lower penetration index, flexibility and ductility under low temperatures, greater resistance to permanent deformation, greater resistance to the appearance of cracks under low temperatures, and greater resistance to fatigue (Yetkin, 2007; Palit et al., 2004; Xiang et al., 2009). Other advantages include greater lifespan, lower conservation and maintenance costs, reduction of the asphalt mixture aging, and reduction of traffic noise (Sol-Sánchez et al., 2020; Lee et al., 2008; Navarro et al., 2004; Chiu and Lu, 2007; Bueno et al., 2014; Ding et al., 2017).

Despite the benefits, asphalt-rubber is not widely accepted and used yet. This occurs due to two reasons. First, there is a lack of professional training in terms of mastering the various techniques and fully understanding some variables (e.g., rubber content, dimensions of the rubber particles, rubber surface and storage). Second, there are no local public policies that encourage the usage of asphalt-rubber (Lo Presti, 2013; Picado-Santos et al., 2020).

The use of asphalt-rubber is still low at Brazil. In the country, there is a lack of specialized labor (Thives, 2009) and public policies that encourage the use of this material. Thus, one of the objectives of this study was to evaluate the mechanical performance of hot mix asphalt (HMA). The mixtures were produced with four types of binder: (i) commercial asphalt-rubber (AR08), (ii) asphalt-rubber 10% (AR10), and (iii) 15% (AR15) both produced in a laboratory from crumb rubber, and (iv) conventional asphalt, i.e., asphalt binder penetration grade of 50-70 (PEN 50-70), which is usual for paving in Brazil. In addition, it was also aimed to analyze the effectiveness of the dominant aggregate size range (DASR), method for predicting permanent deformation on asphalt mixtures, as well as analyzing the influence of the compaction method (Marshall or Superpave) on the mechanical performance of the mixtures.

The Brazilian way to select the grain size of asphalt mixtures follows the standard guidelines from National Department of Transportation Infrastructure (DNIT, in Portuguese) that recommend a procedure to fit the aggregates in one of the granulometric ranges. This method consists of a trial-and-error procedure in which the proportions of the aggregates that make up the mixture are adjusted so that the limits are within these ranges. Therefore, this method does not take into account the effects of aggregate distribution on the mechanical behavior of asphalt mixtures. This may result in mixtures with lower stability and lower resistance to permanent deformation. Therefore, the concept of DASR porosity was used in this study to evaluate the permanent deformation of asphalt mixtures.

The DASR is a rational method to select the granulometric composition of the asphalt mixtures. The method is simple to apply and only uses a single parameter, the DASR porosity, which does not depend on the asphalt mixture's maximum nominal size. Under this method, mixtures with porosity greater than 50% do not provide good interaction between the aggregates, which would make these mixtures less resistant to permanent deformation. Previous studies show the efficiency

of applying this method to obtain proper dosage design with a lower propensity to developing permanent deformation (Greene et al., 2014; Kim et al., 2009). Therefore, the DASR method was used to verify the efficiency of choosing the composition of the aggregates' matrix.
In this work, the optimum asphalt content was determined using the Marshall design, since this method is still the most commonly used in Brazil. Later on, to carry out the mechanical tests, specimens were molded with Marshall and Superpave compactors. In previous studies with other materials, which also used these two compactions, it was found that specimens compacted with Superpave tend to present better results in mechanical tests. These better results are usually attributed to the greater efficiency of the crushing compaction used by the Superpave, than the impact compaction used in the Marshall (Assis et al., 2017). Thus, in this work, the results obtained with the two forms of compaction were compared.

2. PROCEDURE

2.1 Materials

This study followed an experimental procedure that began with the collection of materials: PEN 50-70, AR08, granite aggregate, and crumbled tire rubber. These materials were donated by companies in the Northeast and Southeast. The rubber had a density of 0.99 g/cm^3. A preliminary screening was performed to remove coarse particles that could affect the homogeneity of the mixture with the conventional binder. ASTM D6114/D6114M-19 recommends not using very coarse rubber particles. Therefore, in this study, the particle sizes varied between 0.15 and 0.59 mm.

2.2 Production of asphalt-rubber

In the production of the asphalt-rubber in a laboratory, 10% and 15% of the conventional asphalt content were replaced by rubber, so carried out AR10 and AR15 binders. For these binders, rubber was added to the conventional asphalt in a mechanical mixer at a constant rotation of 2,000 rpm and a temperature of 170 ºC for one hour. The AR10, AR15, PEN 50-70, and AR08 binders were tested to determine their physical properties. These tests included penetration, softening point, rotational viscosity, elastic recovery, and storage stability. In addition, aggregate properties tests were performed, including particle size, absorption, density, durability, Los Angeles abrasion, and sodium sulfate soundness. The tests were performed in accordance with DNIT standards.

2.3 Asphalt mixture design

2.3.1 Granulometric composition selection

To determine the granulometric composition of the aggregate, the experimental method was used to fit the mixture into the "C" range of DNIT. The DASR porosity was also calculated to estimate whether the selected aggregate size would give the mixture good resistance to permanent deformation. Before calculating the DASR porosity, the aggregates that make up the DASR mixture were selected. The DASR method suggests the use of an interaction diagram to select the aggregates. Two types of aggregates should be selected: (i) with a particle size greater than 1.18 mm and (ii) with a ratio of percent retained material between successive sieves of 0.43 and 2.33 mm. The porosity was calculated according to equation (1).

$$\eta_{DASR} = \frac{VICag + VMA}{VTM - V_{\mathrm{ag>DASR}}} \quad (1)$$

Where η_{DASR} is the DASR porosity (%), VIC_{ag} is the volume of aggregate below the DASR; VMA is the voids in the mineral aggregate; VTM is the total volume of the mixture; $V_{ag>DASR}$ is the volume of aggregate above the DASR.

2.3.2 Selection of the Optimum Asphalt Content

The Marshall mix design was used to determine the optimum asphalt content. Cylindrical specimens were shaped and compacted with 75 blows on each side (DNER ME-043/95 Brazilian standard). Three parameters were selected to determine the optimum asphalt content: volume of voids, maximum bulk density, and maximum stability. Four dosages (i.e., one for each binder) were performed in total.

To produce the asphalt mixture with PEN 50-70, the aggregates were heated at 165 °C for 24 hours and mixed with the binder at 155 ºC. To mix the three asphalt-rubber types, the aggregates were heated at 175 °C for 24 hours and mixed with the binder at 165 ºC. These temperatures were determined by the rotational viscosity Brookfield test, which were determined to four binder types.

2.3.3 Mechanical Tests

To evaluate the mechanical performance, the asphalt mixtures were tested by the indirect tensile strength test (ITS), the resilient modulus test (RM), the moisture susceptibility, and the flow number (FN). The tests were performed with specimens produced by Marshall and Superpave compactors. Each test was conducted three times to analyze the accuracy of the results. Table 1 shows the standards that were followed to perform the tests.

Table 1. Standards for the mechanical tests

Test	Standard
Indirect tensile strength test	DNIT ME 136/2010
Resilient modulus	DNIT 135/2018-ME
Moisture susceptibility	AASHTO T 283/2002
Flow number	NBR 16505/2016

3. RESULTS AND DISCUSSIONS

3.1 Physical Properties

Table 2 shows the results for the physical properties of the aggregates. The acceptance criteria are based on the DNIT ES 031/2006 standard for flexible pavements.

Table 2. Physical properties of natural aggregates.

Properties	Test values	Criteria
Los Angeles abrasion (%)	27.53	Max. 50
Sodium sulfate soundness (%)	1	Max. 12
Absorption (%)		-
3/4” crushed stone	0.51	
3/8” crushed stone	0.79	
Crushed dust Bulk specific gravity (g/cm³)		-
3/8” crushed stone	2.67	
3/4” crushed stone	2.63	
Crushed dust	2.64	

According with the Table 2, the physical properties of the granite aggregate meet the criteria of the Brazilian standards. Therefore, the aggregate can be used to construct flexible pavements.
Table 3 shows the physical properties of the binders. For the PEN 50-70, the DNIT standards were followed for each test, except for the viscosity test. For this test, the criteria established in ASTM D4402 were followed. For the asphalt-rubber binders, the specifications in DNIT ES 111/2009 were followed.

Table 3. Physical properties of asphalt binders.

Tests	**Asphalt Binders**				**Standard Conventional Asphalt**	**Standard Asphalt-Rubber**
	PEN 50-70	**AR10**	**AR15**	**AR08**		
Penetration (10^{-1} mm)	69	44	36	45	50 – 70	30-70
Softening point (°C)	51	62	64	62	Min. 46	Min. 55
Brookfield Viscosity 135GC-SP21 (cP)	395	2,106	3,667	2,085	Min. 274	-
Brookfield Viscosity 150GC-SP21 (cP)	203	1,132	1,735	1,096	Min. 112	-
Brookfield Viscosity 177GC-SP21 (cP)	79	578	819	562	57 – 285	-
Elastic Recovery (%)	0	57	39	61	-	Min. 50
Storage Stability (°C)	0.5	5.0	8.5	5.5	-	Max. 9

According with the Table 3, PEN 50-70, AR08 and AR10 binders meet the Brazilian standards. Then, the binders can be used in the production of hot mix asphalt. The AR15 binder cannot be used because it does not meet the minimum requirements for elastic recovery testing. However, in this study, the test procedure using AR15 was retained in order to evaluate the mechanical performance of asphalt mixtures produced with this binder.

3.2 Granulometric composition of the mixtures

Figure 1 shows the results of the granulometric composition of the asphalt mixture. The gradation curve is composed of: (1) 21% crushed stone 3/4'', (2) 30% crushed stone 3/8'', and 49% crushed dust. This composition was used for the four asphalt mixtures. A trial procedure was used so that the gradation curve could fit into the limits of the "C" range, which is specified at DNIT ES 031/2006.

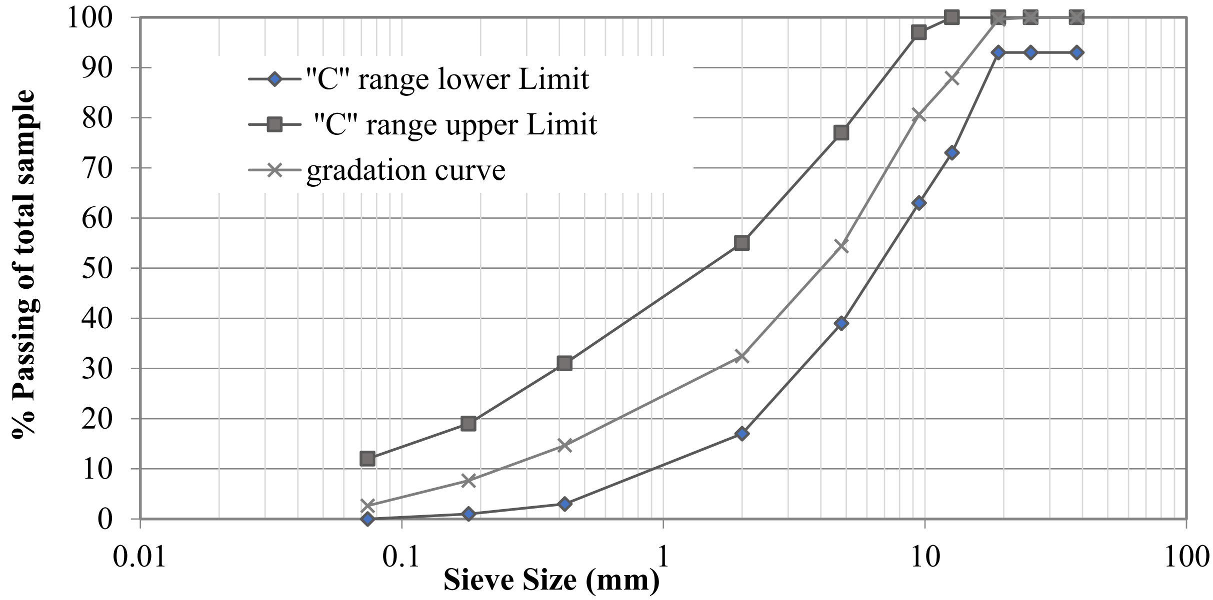

Figure 1. Gradation curve of mixtures.

The granulometric composition was tested by the DASR method to evaluate whether the asphalt mixtures had great resistance to permanent deformation. The interaction diagram was built to apply the DASR method, which is exhibited in Figure 2. This diagram enabled the definition of the coarse aggregate ranges that would compose the DASR.

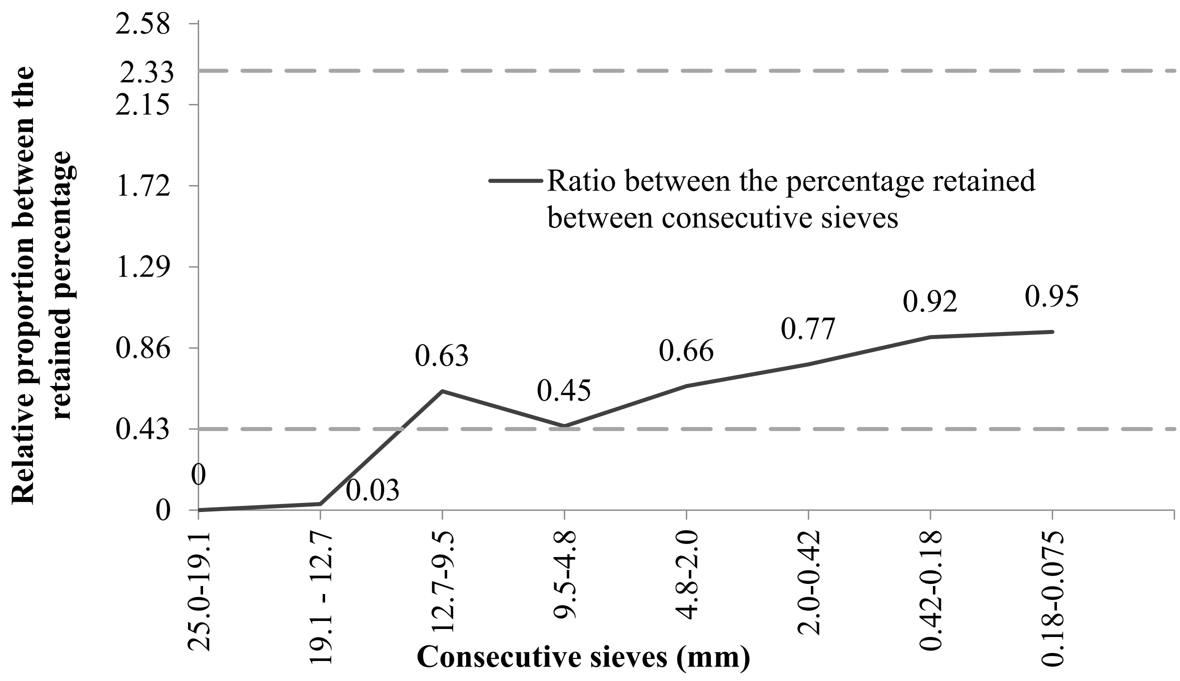

Figure 2. Diagram of interaction between aggregates

In accordance with the Figure 2, the 12.7-9.5, 9.5-4.8, and 4.8-2.0 mm ranges have aggregate with grain sizes greater than 1.18 mm. In addition, the ratio between the percent retained between consecutive sieves ranges from 0.43 to 2.33. The range of 9.5-4.8 mm had a ratio between the percent retained between consecutive sieves that was very close to the minimum estimated value

for good interaction between aggregates. Therefore, this value was not considered in the DASR selection. To select the ranges of 12.7-9.5 and 4.8-2.0 mm, the DASR porosity was calculated for each range using equation (1).
To calculate the VMA in Eq. (1), values for air voids (AV) and voids filled with asphalt (VFA) were assumed based on the limits required for these parameters in the standard DNIT ES 031/2006. According to this standard, asphalt mixtures to be used for wearing course must have an AV between 3 and 5% and a VFA between 75 and 82%. In this work, the average values of these limits (AV of 4% and VFA of 79%) were used to calculate the VMA. An approximate value VMA of 19% was obtained.
For the η_{DASR}, the following results were obtained: 53% for the range of 12.7-9.5 and 39% for the range of 4.8-2.0 mm. Therefore, only the range of 4.8-2.0 mm had a η_{DASR} of less than 50%. This is considered to be the minimum porosity for mixes that exhibit high resistance to permanent deformation. Therefore, this range was used to calculate the DASR. Since the particle size distribution curve provided by the DNIT methods showed a η_{DASR} value of less than 50%, the aggregate composition did not need to be adjusted.

3.3 Marshall Mix Design

Table 4 shows the results by Marshall mix design for the four binder types.

Table 4. Parameters obtained by the Marshal mix design.

Properties	Asphalt Binders				Standard Conventional Asphalt	Standard Asphalt Rubber
	PEN 50-70	AR10	AR15	AR08	DNIT ES 031/2006	DNIT ES 112/2009
Optimum asphalt content (%)	5.2	6.8	7.0	6.2	-	-
Marshall Stability (kgf)	1,163	1,374	806	1,351	> 500	> 800
Bulk Density (g/cm³)	2.31	2.27	2.21	2.26	-	-
AV (%)	3.86	4.99	4.87	4.92	3-5	3-5
VMA (%)	17	20	23	20	Min.16	Min.13
VFA (%)	77	74	78	75	75-82	65-78

Table 4 shows that the majority of mixtures with asphalt-rubber have higher Marshall stability than the conventional binder. According to Setyawan et al. (2017), rubber provides better interlocking and bonding between the aggregates and the asphalt binder, which increases the stability of the mixes. Therefore, it was expected that the asphalt-rubber mixtures would give better results. For the mixture with the AR15 binder, it was also expected that the mixtures with this type of binder would not have as good mechanical performance as the other asphalt-rubber mixtures. This binder does not meet all of the required physical criteria. The lower Marshall stability and density of the AR15 mix are related to the higher rubber content and lower homogeneity of this binder. These factors led to a volumetric expansion of the specimens. Consequently, they promoted the reduction of density and stability in this mixture.
Despite the reduction in stability with the AR15 binder, Table 4 shows that all the mixes met the standard Brazilian criteria in terms of Marshall mix design. The DASR porosity was calculated for each mixture after the volumetric parameters were determined. The results are exhibited in Table 5.

Table 5. η FAD after Marshal dosage.

Binder Designation	VMA (%)	η FAD (%)	Criteria
PEN 50-70	17	36	<50%
AR10	20	40	
AR15	23	44	
AR08	20	40	

Table 5 shows that the mixtures with AR10 and AR08 binders had η_{DASR} close to the estimated value of 39% (before dosage). The other mixtures showed greater variability for the estimated η_{DASR} value. This was due to greater variability between the post-dosage VMA values and the estimated VMA value of 19%. Despite the differences, the estimates were acceptable with respect to the DASR method, as all mixtures had a η_{DASR} value of less than 50%.

3.4 Mechanical Tests

3.4.1 Indirect Tensile Strength (ITS)

Figure 3 shows the results of the indirect tensile strength test for Marshall and Superpave methods.

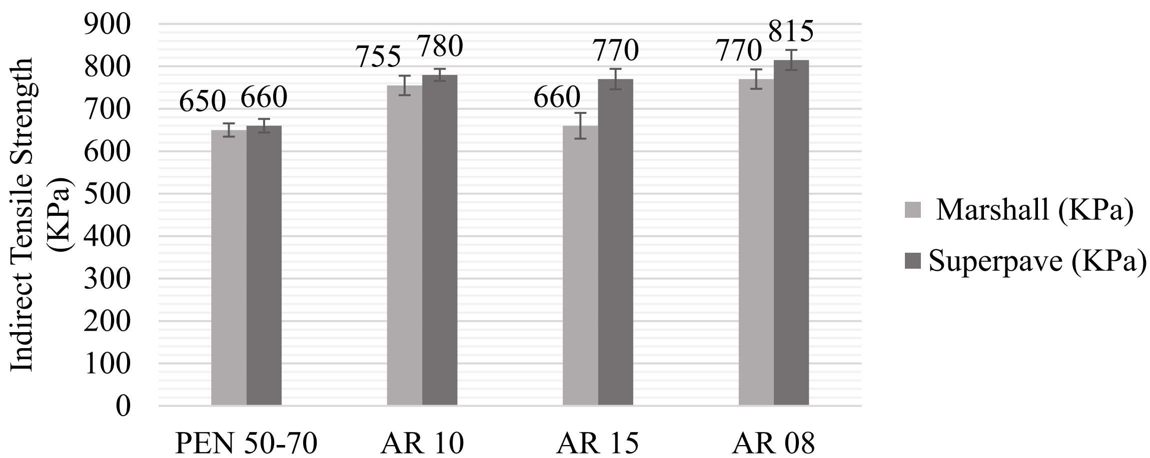

Figure 3. ITS results of mixtures.

Figure 3 shows that the mixtures exhibited greater ITS when compacted by the Superpave method. This result was expected since the Superpave method better replicates field conditions and has a lower risk of altering the granulometric composition of the aggregates.

The mixture with the PEN 50-70 binder met the minimum tensile strength of 650 kPa (i.e., according to the standard DNIT ES 031/2006), for both the Marshall and Superpave methods. For asphalt-rubber mixtures, DNIT ES 112/2009 requires a minimum tensile strength of 750 kPa. This limit was met by all mixes, except for the AR15 mix, which was compacted using the Marshall method.

For the AR15 mix, the results of the indirect tensile strength test and the Marshall stability may have been influenced by the higher rubber content. The storage stability gave a result close to the maximum value allowed by the standards. This indicates that the higher rubber content leads to lower adhesion between the rubber and the binder, which reduces the cohesion and homogeneity of the mixture (Navarro et al., 2004; Navarro et al., 2005; Shen et al., 2009; Dantas Neto et al., 2006; Navarro and Gámez, 2012). This leads to lower values in tensile strength and stability (Navarro and Gámez, 2012).

3.4.2 Resilient Modulus Test (RM)

Figure 4 shows the results for the Resilient Modulus Test using Marshall and Superpave methods.

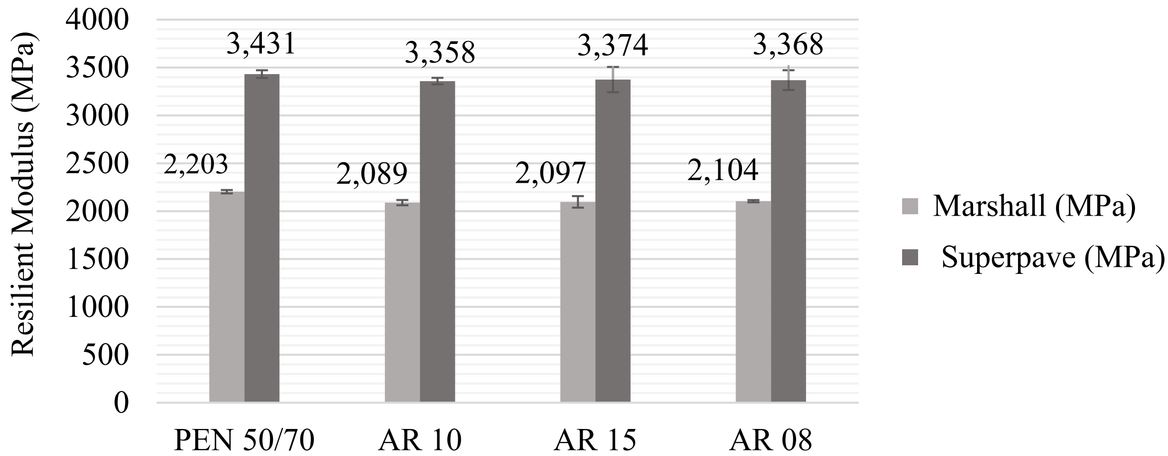

Figure 4. RM results of mixtures.

Figure 4 shows that the asphalt-rubber mixtures have lower RM values when both methods are considered. The reduction of RM is related to the greater elasticity of the asphalt-rubber mixtures. At low temperatures, these mixtures generally exhibit a decrease in resilient modulus than conventional mixtures. On the other hand, as the temperature increases, the value of the modulus tends to become higher. This results in the mixtures being less susceptible to brittle fracture and more flexible at low temperatures and exhibiting higher stiffness than conventional mixtures at higher temperatures (Palit et al., 2004). Therefore, the reduction in resilient modulus with asphalt-rubber does not mean that these mixtures have lower mechanical performance (than the mixture with PEN 50-70).

3.4.3 Moisture Susceptibility

Figure 5 shows the results of the moisture susceptibility test.

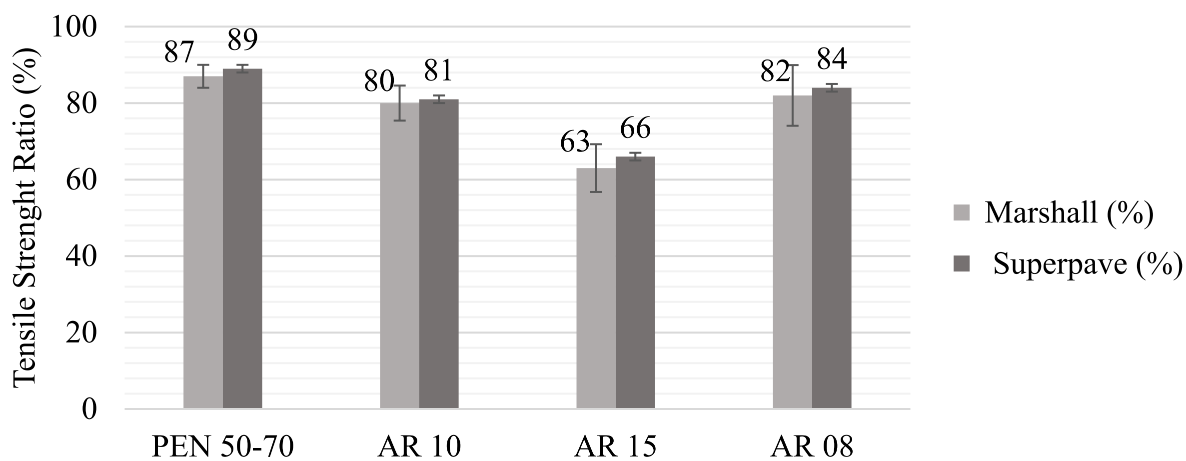

Figure 5. Moisture susceptibility results of mixtures.

Figure 5 shows that all of the mixtures, with the exception of the AR15 mixture, met the minimum TSR requirement of 80% as specified in AASHTO T 283/2002. Lower TSR values were obtained for the mixtures containing the asphalt-rubber binder. The California Department of Transportation

noted that dense mixtures with the asphalt-rubber binder are more susceptible to moisture effects than conventional mixtures. Therefore, the use of anti-stripping additives in these mixtures is recommended (Shatnawi, 2001).
In this study, an anti-stripping additive was used in all mixtures. The AR10 and AR08 mixtures were highly moisture susceptibility, although the results were lower than those of the PEN 50-70 mixture, and the use of the additive in the AR15 mixture was not sufficient to achieve the minimum 80% recommended by the standards. This indicates a greater susceptibility to moisture damage in this mixture.

3.4.4 Flow Number (FN)
Figure 6 shows the results of the FN tests for the mixtures using the Superpave method.

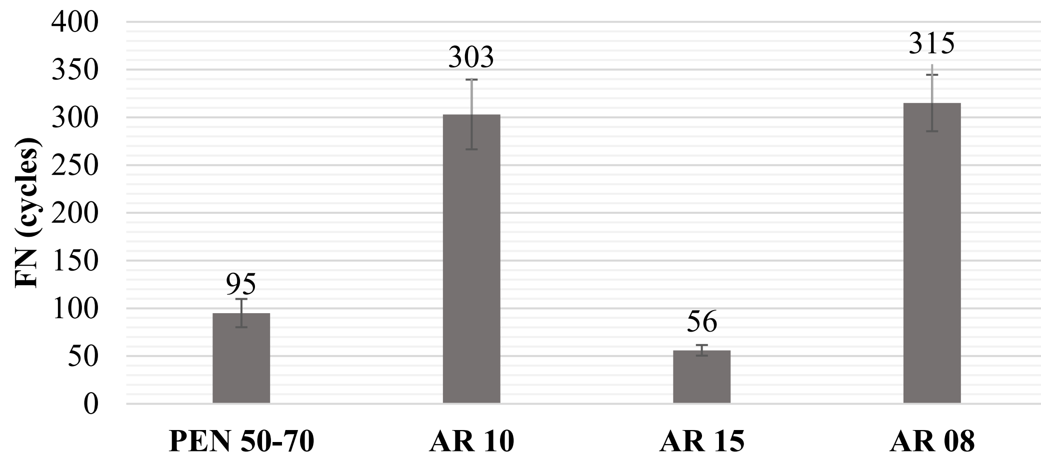

Figure 6. FN results of mixtures.

Figure 6 shows that the mixes with the AR10 and AR08 binders have better results than mix with the conventional binder. This indicates greater resistance to permanent deformation for these mixes. The lower values for the AR15 mix were to be expected given the results of the other tests. They showed that the higher rubber content and lower homogeneity negatively affected the mechanical performance of this mix.

4. STATISTICAL ANALYSIS

Analysis of variance (ANOVA) is a statistical method that allows comparisons between means of different populations. Therefore, it was used in this study to compare the performance of the different mixtures for each of the tests. For ANOVA, mixture type (or binder type in the case of the physical tests) was the explanatory variable. Four levels (treatments) were considered: PEN 50-70, AR08, AR10, and AR15. In addition, a significance level of 5% was assumed to test two hypotheses:
H_0: The mean values of the treatments are equal;
H_1: At least one of the mean values of the treatments is different from the others.
The null hypothesis is rejected if the p-value is less than or equal to the significance level. After this test, Tukey's test was applied to determine whether the pairs of treatments were significantly different or not. The results of the Tukey test are shown in Tables 6, 7, and 8 for the physical tests, the mechanical tests using the Marshall method, and the mechanical tests using the Superpave method, respectively.

Table 6. Tukey test results for physical tests.

Treatment		p-value - comparing pairs of means (ij)				
(i)	(j)	Penetration	Softening Point	Brookfield Viscosity	Elastic Recovery	Storage Stability
PEN 50-70	AR08	0.00000	0.00033	0.00000	0.00000	0.00171
	AR10	0.00000	0.00033	0.00000	0.00000	0.00336
	AR15	0.00000	0.00000	0.00000	0.00000	0.00006
AR08	AR10	0.91770	1.00000	0.28040	0.39200	0.93380
	AR15	0.00010	0.55530	0.00000	0.00000	0.03246
AR10	AR15	0.00018	0.55530	0.00000	0.00030	0.01464

* The mean difference is significant at the .05 level.

Table 7. Tukey test results for mechanical tests with the Marshall method

Treatment		p-value - comparing pairs of means (ij)		
(i)	(j)	ITS	RM	Moisture Susceptibility
PEN 50-70	AR08	0.00114	0.03360	0.71820
	AR10	0.00272	0.01633	0.48400
	AR15	0.95610	0.02392	0.00401
AR08	AR10	0.86120	0.94980	0.97230
	AR15	0.00198	0.99430	0.01556
AR10	AR15	0.00495	0.99160	0.02776

* The mean difference is significant at the .05 level.

Table 8. Tukey test results for mechanical tests with the Superpave method

Treatment		p-value - comparing pairs of means (ij)			
(i)	(j)	ITS	RM	Moisture Susceptibility	FN
PEN 50-70	AR08	0.00006	0.81640	0.42600	0.00002
	AR10	0.00036	0.74480	0.12140	0.00003
	AR15	0.00066	0.85530	0.00035	0.28970
AR08	AR10	0.21800	0.99900	0.77230	0.93140
	AR15	0.09347	0.99980	0.00184	0.00000
AR10	AR15	0.92500	0.99580	0.00539	0.00000

* The mean difference is significant at the .05 level.

Tables 6, 7, and 8 show that the null hypothesis was rejected for all tests, except the Resilient Modulus using the Superpave method (i.e., there were significant differences between the means of the treatments). Also, the AR08 and the AR10 binders, as well as the mixtures with these binders did not have significantly different mean values (i.e., p-values greater than 0.05). This indicates that there are no statistically significant differences between the physical and mechanical properties of the two binders.

Table 6 shows that there were significant differences between the conventional binder (i.e., PEN 50-70) and the asphalt-rubber binders in all tests. This indicates that the asphalt-rubber binders have different physical properties than PEN 50-70, and it shows that the rubber changes the physical properties of the mixtures. No significant difference was expected in the performance of AR08, AR10, and AR15 binders. The AR15 binder did not meet the minimum requirements in the physical tests.

For the mechanical tests using the Marshall method, the results in Table 7 show that there were no significant differences in the tensile strength capacities for the mixes with the binders PEN 50-70 and AR15. Similarly, no differences were found between the results for moisture susceptibility of mixes with PEN 50-70, AR08, and AR10. Therefore, it can be said that the reduction of TSR in mixtures with AR08 and AR10 did not affect the moisture susceptibility of these mixtures. The opposite effect was observed in the resilient modulus test. In this test, the reduction in RM of asphalt-rubber mixtures than the PEN 50-70 mixture can be considered significant.
Table 8 shows that the results obtained with the Superpave method do not show significant differences in the RM test. Since this method simulates field conditions more efficiently than the Marshall method, it is assumed that asphalt-rubber mixtures at RM do not show large variations than the PEN 50-70 mixture. In the ITS and FN tests, it was found that there were significant differences between the PEN 50-70, AR08, and AR10 mixtures. Thus, it can be said that the increase in ITS and FN observed in the AR08 and AR10 mixes, was indeed relevant than the PEN 50-70 mix. When moisture susceptibility was tested, significant differences were only observed with the AR15 mixture. This was to be expected as this blend showed a greater reduction in moisture susceptibility.

5. CONCLUSIONS

The main objective of this study was to evaluate the mechanical performance of asphalt-rubber mixtures through laboratory tests used for the construction of flexible pavements. In this sense, after the statistical analysis carried out, it can be said that asphalt-rubber mixtures have better performances than the mixture PEN 50-70, which makes their use practicable. A greater elastic recovery, a lower thermal susceptibility, a greater tensile strength and the occurrence of permanent deformations can be cited mentioned as advantages of the mixtures AR08 and AR10 than the mixture PEN 50-70.
The AR15 binder could not be used in asphalt mixtures because it did not meet the elastic recovery requirements. However, in some tests, it performed similarly to conventional asphalt (i.e., PEN 50-70). Similar results were also obtained when testing the resilient modulus than the other asphalt-rubber types. Therefore, the performance of this mixture in all tests could be acceptable if an additive were used. An agent compatible with the AR15 binder could increase its homogeneity.
In all the tests, the AR10 and AR08 mixtures showed no significant differences. This means that no significant differences in the mechanical performance of these mixtures were found in this study. However, the AR08 is already produced on large scale, which makes it more attractive than the AR10 binder. The AR10 was produced in the laboratory for this study. Therefore, the use of the AR08 binder would be more suitable for road construction.
For granulometric selection, the DASR method estimates good mechanical performance for porosity values below 50%, but this estimate was not valid for the AR15 mix. However, the lower performance of this mix is most likely due to the lower quality of the AR15 binder (than the granulometric selection). Therefore, the use of the DASR method to predict the mechanical performance of mixtures in this study cannot be considered unacceptable. For the compaction method, the trend of previous studies was confirmed (Jitsangiam et al., 2013; Swami et al., 2004; Asi, 2007): the results for the Superpave method were better than the results for the Marshall method in all tests. Therefore, the Superpave method should be preferred for the compaction of asphalt mixtures.

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