Revista Facultad de Ingeniería

Title: Mechanical performance of asphalt mixtures modified with rubber granules and recycled concrete aggregates

Authors: Juan Gabriel Bastidas-Martínez, Cristian Andrés Cárdenas-Triviño, Laura Vanessa Casallas-Huertas, Diego Andrés Díaz-Cadena and Hugo Alexander Rondón-Quintana

DOI: **10.17533/udea.redin.20250366**

To appear in: *Revista Facultad de Ingeniería Universidad de Antioquia*

Received: July 08, 2024
Accepted: March 13, 2025
Available Online: March 14, 2025

Please cite this article as: J. G. Bastidas-Martínez, C. A. Cárdenas-Triviño, L. V. Casallas-Huertas, D. A. Díaz-Cadena and H. A. Rondón-Quintana. Mechanical performance of asphalt mixtures modified with rubber granules and recycled concrete aggregates, Revista Facultad de Ingeniería Universidad de Antioquia. [Online]. Available: https://www.doi.org/10.17533/udea.redin.20250366

Mechanical performance of asphalt mixtures modified with rubber granules and recycled concrete aggregates

Comportamiento mecánico de una mezcla asfáltica modificada con asfalto caucho y agregados reciclados

Juan Gabriel Bastidas-Martínez[1*] https://orcid.org/0000-0002-6818-0322, Cristian Andrés Cárdenas-Triviño[1] https://orcid.org/0009-0004-3610-7341, Laura Vanessa Casallas-Huertas[1] https://orcid.org/0009-0001-4434-672X, Diego Andrés Díaz-Cadena[1] https://orcid.org/0009-0006-7054-1349, Hugo Alexander Rondón-Quintana[2] https://orcid.org/0000-0003-2946-9411

[1] Programa de Ingeniería Civil, Facultad de Ingeniería, Universidad Piloto de Colombia. Carrera 9A 45A-44, 110231. Bogotá DC 110131, Colombia.
[2] Facultad del Medio Ambiente y Recursos Naturales, Universidad Distrital Francisco José de Caldas. Avenida Circunvalar sede Vivero UD. Bogotá D. C, Colombia.

Corresponding author: Juan Gabriel Bastidas-Martínez
E-mail: juan-bastidas@unipiloto.edu.co

KEYWORDS
Alternative aggregates; modified asphalt; Marshall test; resilient modulus; permanent deformation.
Agregados alternativos; asfalto modificado; ensayo Marshall; módulo resiliente; deformación permanente.

ABSTRACT: The use of recycled-concrete-aggregate (RCA) in asphalt mixtures is considered a viable technique from a technical standpoint to provide a solution to the environmental problem of final waste disposal. Likewise, the use of crumb-rubber-modified asphalts (CRMA) could contribute to this end. This article evaluated the physical-mechanical behaviour of a hot-mix asphalt (HMA) manufactured with CRMA and partially replacing the coarse fraction of the coarse aggregate of natural (NA) with RCA. For this purpose, four HMA mix designs were conducted by Marshall test, considering NA and RCA, and using as binders an asphalt cement AC 60-70 and CRMA. The mechanical performance was measured by performing Marshall, Indirect-Tensile-Strength (ITS), resilient modulus (RM), and permanent deformation. Resistance to moisture damage was also measured by calculating the Tensile Strength Ratio (TSR). The results show that mixtures with RCA require higher asphalt content. When replacing NA with RCA, HMA decreases its mechanical strength under monotonic and cyclic loading. Likewise, its resistance to moisture damage decreases. Contrary to the above, CRMA tends to increase the mechanical performance of the mixtures. However, the CRMA content used in this study was insufficient to adequately cover and adhere to the RCA, generating a mix that undergo the worst performance.

RESUMEN: La utilización de agregados reciclados de concreto (ARC) en la fabricación de mezclas asfálticas para pavimentos es una técnica viable para solucionar la problemática ambiental de disposición de residuos. Asimismo, el uso de asfalto modificado con grano de caucho reciclado (GCR) podría contribuir a este fin. Este artículo evaluó el comportamiento físico-mecánico de una mezcla asfáltica densa en caliente (MDC) fabricada con GCR y sustituyendo parcialmente la fracción gruesa del agregado grueso de origen natural (AN) por ARC. Para tal fin, fueron realizados ensayos de caracterización de los materiales. Posteriormente se realizaron cuatro diseños de MDC mediante el ensayo Marshall, considerando AN y ARC, y utilizando un cemento asfáltico CA 60-70 y modificado con GCR. El desempeño mecánico se midió realizando el ensayo Marshall, Resistencia a la Tracción Indirecta (RTI), módulo resiliente y deformación permanente. También se midió la resistencia al daño por humedad mediante el ensayo RTI en condiciones secas y húmedas. Los resultados demuestran que las mezclas con ARC requieren mayor contenido de asfalto. Al sustituir el AN por ARC, la MDC disminuye su resistencia bajo carga monotónica, cíclica y resistencia al daño por humedad. Contrario a lo anterior, el GCR tiende a aumentar el desempeño mecánico de las mezclas. Sin embargo, el contenido de GCR utilizado en el presente estudio fue insuficiente para cubrir y adherir adecuadamente los ARC, generando una mezcla que experimentó el peor desempeño.

Introduction

1.1.Recycled Concrete Aggregate (RCA) – Background

Construction and demolition waste (CDW) is waste obtained from construction, demolition, and civil works renovation activities. They are mainly composed of concrete, mortar, bricks, wood, ceramics, plaster, glass, plastics, and excavation soils, among other wastes [1] [2]. In China, approximately 2.36 billion tons of CDW were generated between 2003 and 2013 [3], accounting for 40% of the total municipal waste in mainland China [4]. In 2016, more than 322 million tons were produced, which accounted for 34% of all industrial waste in countries in Europe. On the other hand, in Australia and the United Kingdom, CDW constitutes approximately 44% and 50% of solid waste, respectively [5].

The lack of management and control of these wastes can produce environmental impacts due to i) reduction of the capacity of landfills and disposal sites; ii) contamination of water sources; iii) use of soil change, among others [6]. Therefore, appropriate management of CDW is essential to promote the reuse and recycling of materials to generate a circular economy [7]. Some countries have opted for the reuse of materials. In the United States, 583 million tons of waste were collected for recycling in 2014.[8], which represents 26% of total solid waste [4]. In Japan, approximately 98% of the concrete waste is processed to generate new recycled aggregates for construction [9].

Concrete is one of the most widely used materials in civil construction. Therefore, substantial amounts of waste are produced from the construction, demolition, and repair activities of civil works [9]. The treatment, crushing, and size reduction of these wastes lead to obtaining recycled aggregates, which are referred to as RCA [10] [11]. According to [12], RCA is composed of stone aggregate (between 65% to 70%) and overburden mortar (between 35% to 30%). RCA from CDW is considered a valuable source of construction material. In this sense, different studies have been conducted to generate the utilization of RCA in civil construction. One of the applications is the manufacture of HMA asphalt mixtures for pavement layers. This is because HMA requires large volumes of NA (between 90% and 95% by weight or between 80% and 90% by volume) [13] [14]. Details of these studies can be found in [15]. Most studies conclude that the volumetric and strength parameters of mixtures using RCA as aggregates meet the quality requirements demanded by asphalt mixtures (mainly on roads with low traffic volumes). However, given the great heterogeneity of RCA, it is not possible to find a clear trend in the performance of these materials as aggregates in asphalt mixtures.

Consequently, the results found in the literature differ and may be contradictory. However, in some studies there is consensus in [15]: i) Asphalt mixtures with RCA require higher asphalt contents concerning mixtures with NA due to the surface absorption and higher porosity of RCA aggregates. ii) It has not been possible to establish an optimum percentage of NA substitution for RCA in asphalt mixtures. [16] recommend a maximum of 30% of RCA in an HMA, since higher values notably increase the optimum asphalt content in the mix. iii) The fraction of NA to be substituted by RCA should be of particle sizes greater than or equal to 4.75 mm, which can represent 40% to 50% of the total mass of the mix. This is mainly because the particles of the fine fraction of the RCA generally have higher absorption and lower specific gravity than those of the coarse fraction, thus increasing the asphalt binder content. iv) RCA generally have lower mechanical strength than NA but have beneficial physical-chemical properties in terms of adhesion and compatibility with the binder (e.g., high calcium oxide content, high porosity, and surface texture), as well as optimum geometry (e.g., rounded particles with fractured faces and low content of elongated and flattened particles).

1.2.Crumb rubber modified asphalt – Background

In 1960, the first studies for the development of crumb rubber-modified asphalt - CRMA - were carried out [17] [18]. The above is to provide a solution to the final disposal of used tires and contribute to the preservation and conservation of the environment in terms of the final disposal of solid waste [19] [20] [21]. Two methods allow the incorporation of crumb rubber (CR) in asphalt mixtures [22][23][24]. The first process is "dry", where the CR particles replace the fine aggregate particles (smaller size between 0.4 to 10 mm) [25]. The second is "wet", where the CR particles are mixed with the asphalt cement at elevated temperatures (greater than 160 °C) for a time between 45 to 60 min [26][27][28][29]. Generally, the particle size of CR is less than 2.36 mm. According to ASTM D6114 specification, the minimum amount by mass of CR is 15%, but the percentage varies from 10 to 20% usually [30]. In this process, physicochemical processes occur between the original binder and the modifying material (CR particles), generating higher consistency of the asphalt [31]. Additionally, there are variations in the rheological characteristics, increasing the viscosity, stiffness, and resistance to fatigue and permanent deformation of the binder [32][33]. Additionally, other methods allow the incorporation of additives that improve some characteristics of the mixture (e.g., workability, adhesion, among others) [23] [24]. In general, the use of CRMA allows the improvement of technical and functional aspects of the mix and the pavement [34]. In technical terms, resistance to fatigue, permanent deformation, and aging is increased [35] [24] [36] [37] [38]. Concerning the environment, the use of CRM is considered a way of final and environmentally correct disposal of enormous quantities of used tires.

1.3.Objective

Multiple studies have been conducted to evaluate the performance of asphalt mixtures with RCA. However, few have evaluated the performance of these mixtures manufactured with CRMA. According to the literature consulted, only [39] and [40] studied the effect of incorporating RCA in HMAs manufactured with CRMA. [41] replaced 35 and 42% of NA with RCA, and the main objective of the study was to evaluate the influence of the use of rubberized asphalt on the resistance to moisture damage. [42], carried out a larger experimental phase (evaluating the performance under monotonic and cyclic loading), but they evaluated only a replacement (100% of the NA was replaced by RCA). The present study seeks to contribute to extending the discussion on the possible use of HMA mixtures manufactured with RCA and CRMA. Based on the literature review consulted and the research experience of the research group, it was opted to replace 21% of the NA by RCA (replacement of the particles retained in 1/2"+3/4" sieves) of an HMA-19 (maximum particle size of 19 mm; INVIAS, 2022). A higher substitution ratio was not chosen, since substituting the fine fraction of the NA by RCA does not generally achieve good performances in mixtures [15], [43]. Additionally, from a practical point of view, it is easier to substitute this fraction of aggregates in asphalt plants

2. **Materials and methods**

The methodological phase of the study was divided into three stages. The first included the physical characterization of the NA and RCA. Additionally, the characterization of conventional asphalt AC 60-70 and CRMA. The second stage considered the design of HMA asphalt mixtures with the incorporation of NA and RCA with conventional and modified asphalt, respectively. The third stage evaluated the mechanical performance of the asphalt mixtures through monotonic, dynamic, and static load tests.

2.1.Characterization of materials

The NA and RCA (Figure 1) used in this study correspond to aggregates obtained in the city of Bogotá D.C. (Colombia). These aggregates were supplied by companies authorized by the Urban Development Institute (IDU in Spanish). To characterize the aggregates, tests were conducted to evaluate hardness, resistance to sulfate attack, cleanliness, particle shape, and specific gravities. Additionally, NA and RCA particles (diameter of approximately 2 cm) were subjected to observation (between 50 and 1000 magnification) in a scanning electron microscope (SEM) type JEOL JSM 6700F (JEOL, Tokyo, Japan) with an accelerating voltage of 20 kV in high vacuum at a working distance of approximately 8 to 9 mm. Micrographs were taken with a backscattered electron detector (BSE).

Figure 1 NA and RCA particles.

The asphalts used were an AC 60-70 asphalt cement classified by penetration (dmm) and a CRMA type II [44]. These asphalts were supplied by the company Manufacturas y Procesos Industriales PMI of Colombia. Conventional physical characterization and viscosity tests were performed on both binders to determine the manufacturing and compaction temperatures of the asphalt mixtures.

2.2.Asphalt mix design

Four mix designs were performed using the Marshall test (AASHTO T 245) to determine the optimum asphalt content (OAC). The mixtures were denoted as i) HMA NA+AC 60-70 (control mix, manufactured with NA and unmodified AC 60-70); ii) HMA RCA + AC 60-70 (a mix that replaced 1/2"+3/8" particles of NA with RCA and used unmodified AC 60-70); iii) HMA NA+CRMA (mix manufactured with NA and CRMA-type modified binder); iv) HMA RCA+CRMA (mix that replaced 1/2"+3/8" particles of NA with RCA and used CRMA-type modified binder). In each mix design, four asphalt contents 5.0, 5.5, 6.0, and 6.5% of the total mix mass were tested. Each sample was manufactured by compacting it with 75 blows on both sides. The manufacturing and compaction temperature of the mixtures with AC 60-70 corresponds to 150 °C and 140°C, respectively. This was based on the asphalt Equiviscous method. For the CRMA mixtures, the manufacturing and compaction temperatures were 160°C and 170°C, respectively, based on the manufacturer's recommendations. For each mix design, 12 samples were manufactured (three samples for each asphalt content).

The particle size distribution of the mixtures is shown in Figure 2 (INVIAS, 2022). For the mixtures with the incorporation of RCA, the coarse fraction (1/2"+3/8" sieves) of the NA was partially substituted, which corresponds to 21% of the total mass of the aggregates. This substitution percentage was chosen based on the literature review consulted and on previous studies conducted by the research group [15], [45]. In addition to the OAC, the parameters of volumetric composition (voids with air - Va, voids in the mineral aggregate - VMA, voids filled with asphalts - VFA) and mechanical strength under monotonic loading (stability - S, flow - F and S/F ratio) were obtained.

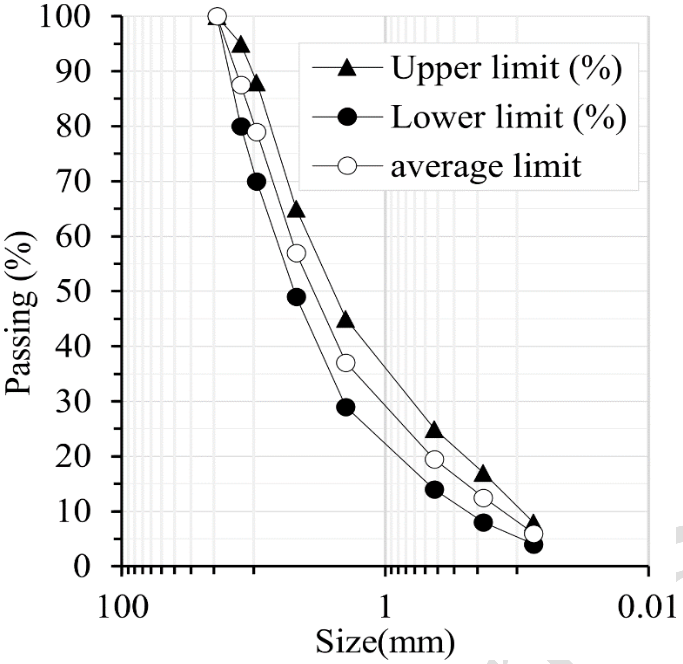

Figure 2. Particle size distribution of HMA

2.3.Mechanical resistance tests

2.3.1. Indirect Tensile Strenght – ITS

For the four asphalt mixtures, the ITS test was performed under dry and wet conditions. Each sample was subjected to a press under monotonic loading (at 50 mm/min) until the maximum breaking load was reached. The test temperature was 25°C. In the wet condition, the simples were subjected to 60°C and 25°C in a water bath for 24 and 2 hours, respectively. This procedure is mainly adopted in tropical countries where the freezing of pavements does not occur. The ITS values reported correspond to the average of three replicates. Additionally, the Tensile Strength Ratio - TSR (ITS in wet conditions/ITS in dry conditions) was determined as a percentage, to analyze the susceptibility to moisture damage.

2.3.2. Resilient modulus and permanent deformation tests

For all the study mixtures, resilient modulus (RM) tests by diametral compression (ASTM D 4123-82) and permanent deformation (AS 2891.12.1-1995) were performed in a Universal Testing Machine - UTM (Figure 3). To determine the RM, a cyclic load of 1200 N under load frequencies of 2.5, 5.0, and 10 Hz at a temperature of 20 °C was used. The frequencies correspond to loading periods of 0.4, 0.2, and 0.1 s, respectively. For the case of the permanent deformation test, an axial load producing a controlled stress of 100 kPa was applied for 7200 cycles. The loading frequency was 1 Hz (0.1 s corresponding to the load application time and 0.9 s to the unloading time) at a temperature of 20 °C, which corresponds to the laboratory temperature. As a result, the evolution curve of the permanent deformation with time was obtained. In all the tests described, the values reported correspond to the average of three repetitions.

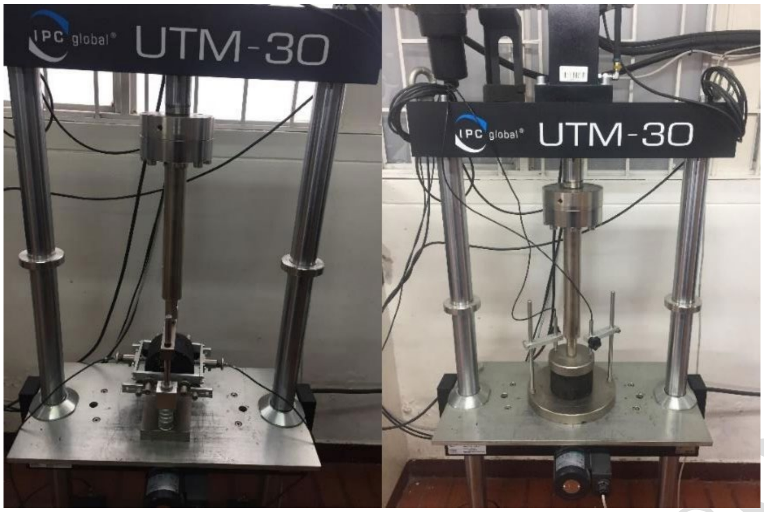

Figure 3. UTM for Resilient modulus (left) and permanent deformation tests (right).

2.3.3. ANOVA analysis

An analysis of variance (ANOVA) with a confidence level of 95% was performed to evaluate whether the variations in the results are statistically significant ($FT>f_{0.05}$). This made it possible to conclude whether the variations in the mechanical properties can be attributed to the presence of RCA or NA aggregates, as well as to the use of AC 60-70 or CRMA.

3. Results

3.1. Characterization of materials

Figures 4a and 4b show the surfaces of the NA and the mortar bonded to the RCA, respectively, observed in the SEM. It is observed that the RCA-bonded mortar shows higher porosity compared to the NA. Table 1 shows the elemental chemical composition of the NA and RCA bonded mortar determined in the SEM. It is observed that the bonded mortar has a similar chemical composition to cement and higher Ca/Si content concerning the NA, which may help to increase compatibility with the asphalt binder and improve bonding [46], [47].

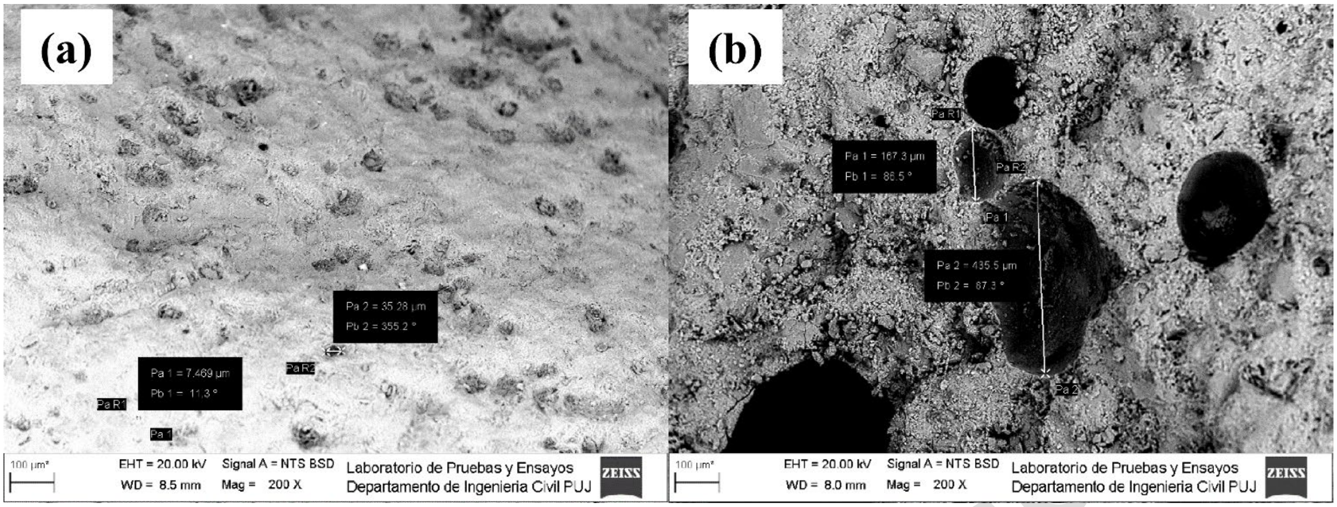

Figure 4. a) NA and b) RCA surface

Table 1. Elemental composition of particles based on SEM

Element	C	O	Ca	Mn	Si	Al	Fe	Mg	K	Ti
Adhered mortar	16.14	51.87	15.32	0.16	12.12	3.10	0.87	0.28	0.15	-
NA	-	48.30	0.33	-	41.26	2.82	6.32	0.38	0.32	0.27

Table 2 shows the results of the physical characterization of the NA and RCA. It is evident that: i) The RCA presented lower wear resistance in the Angels machine and Microdeval concerning the NA. This is mainly attributed to the high surface porosity and to the detachment of the coating mortar, which is fragile and brittle. Additionally, the bonded mortar can be detached by the cracks between the mortar and the NA of the RCA (Figure 5); ii) concerning wear in the soundness test, the RCA presented a higher value than the NA, which is attributed to the high detachment of the coating mortar during the test; iii) The values of elongation and flattening indexes can be considered relatively low, which can be deduced that there is a predominance of cubic-shaped particles. This may be the result of the crushing and size reduction process of the RCA during its recycling process, which is evidenced by the results of the fractured faces test; iv) the RCA reports a higher value of absorption percentage to the NA. This will generate a higher consumption of asphalt binder in the mix [48], and in conjunction with the presence of the mortar promote low specific gravity values [15].

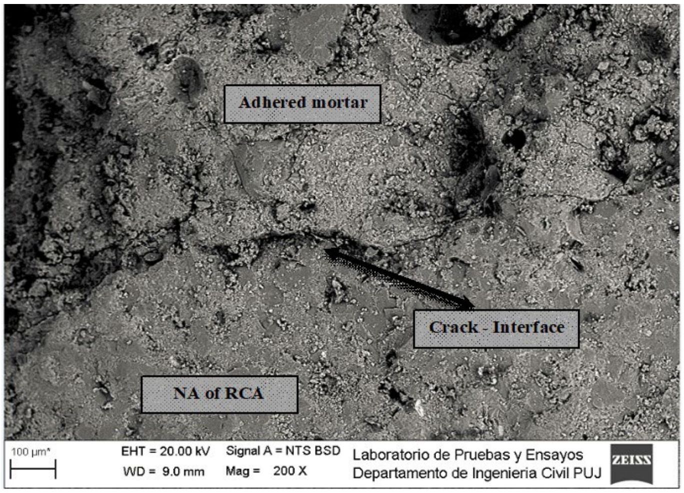

Figure 5. Cracking in the interface between the adhered mortar and the NA del RCA.

Table 2. Results of the aggregates NA y RCA

Characteristic	Test	NA	RCA	Specification
Abrasion loss (%)	AASHTO T96 2002	24.6	31.3	Max 25%
Micro-Deval (%)	AASHTO T327 2005	11.5	26.1	Max 20%
Soundness by magnesium sulfate (%)	AASHTO T 104 1999	8	29.5	Max 18%
Sand equivalent (%)	AASHTO T 176 2002	86	NA	Min50%
Methylene blue (ml/g)	ASSHTO T 330-2007	2	NA	Max 10
Flat and elongate particles (%)	NLT 354-1991	15/18	12/11	----
Fractured faces	ASTM D 5821-2001	86.9	94.1	Max 85
Specific gravity coarse (real/bulk)	AASHTO T 85 1991	2.65/2.60	2.41/2.15	----
Absorption coarse (%)	AASHTO T 85 1991	0.8	3.9	----
Specific gravity coarse fine (real/bulk)	AASHTO T 84 1991	2.64/2.58	NA	----
Specific gravity filler	AASHTO T 85 1991	2.71	NA	----

Table 3 shows the results of the asphalt binder characterization. Logically, the values reported in the tests show greater consistency and stiffness of the CRMA binder due to the incorporation of rubber particles into AC 60-70. Both binders meet the requirements for the manufacture of HMA mixtures.

Table 3. Results of physical characterization tests of the AC 6070 and CRMA Type II

Test	Method	Unit	AC 60-70		CRMA Type II	
			Result	Recommended	Result	Recommended
Tests on the original asphalt						
Penetration 25°C, 100 g, 5 s (0.1 mm)	ASTM D-5	0.1 mm	67	60-70	38	25-75
Penetration 4°C, 200 g, 60 s (0.1 mm)	ASTM D-5	-----	-----	-----	20	15 min
Softening point (°C)	ASTM D36-95	°C	48.9	48-54	77.6	54 min
Viscosity 60°C (Poises)	ASTM D-4402	Poises	2581	1500 min	-----	-----
Viscosity 175°C	ASTM D 6114	-----	-----	-----	4.6	1.5-5.0
Ductility 25°C, 5cm/min (cm)	ASTM D-113	cm	130	100 min	-----	-----
Flash and fire points (ºC)	ASTM D-92	°C	296	230 min	280	230 min

Test	Method	Unit	AC 60-70		CRMA Type II	
			Result	Recommended	Result	Recommended
Tests on the after RTFOT (Rolling Thin Film Oven Test)						
Mass loss (%)	ASTM D-2872	%	0.63	0.8 max	-----	-----
Penetration, in % of original penetration	ASTM D-5	%	53.8	50 min	80	75 min
Increase in the softening point (°C)	ASTM D36-95		8.8	0.8 max	-----	-----

3.2.Design of asphalt mixtures using the Marshall test

The results of the Marshall test are shown in Figures 6 to 11 and Table 5. The mixtures with RCA showed an increase in Va and a reduction in VMA, and VFA for the mixtures with NA. This is mainly attributed to the higher absorption and porosity of RCA (Table 1 and Figure 4), which generates a reduction of the asphalt coating layer on the aggregates. Likewise, the substitution by mass of NA for RCA results in a greater number of particles and consequently a larger surface area to cover with asphalt [49], [50], [51]. This is because RCA particles have lower specific gravity than NA. Similar results were also found in other studies [52], [53], [54], [55] [56] [55] [16] [57] [58] [41] [12][59] [60] [61][62][43][48] [45]. Additionally, the mixtures with CRMA presented higher Va values and lower VMA and VFA than the mixtures with AC 60-70. This is mainly due to the higher stiffness and viscosity of CRMA to AC 60-70, making the mixing and compaction process more difficult.

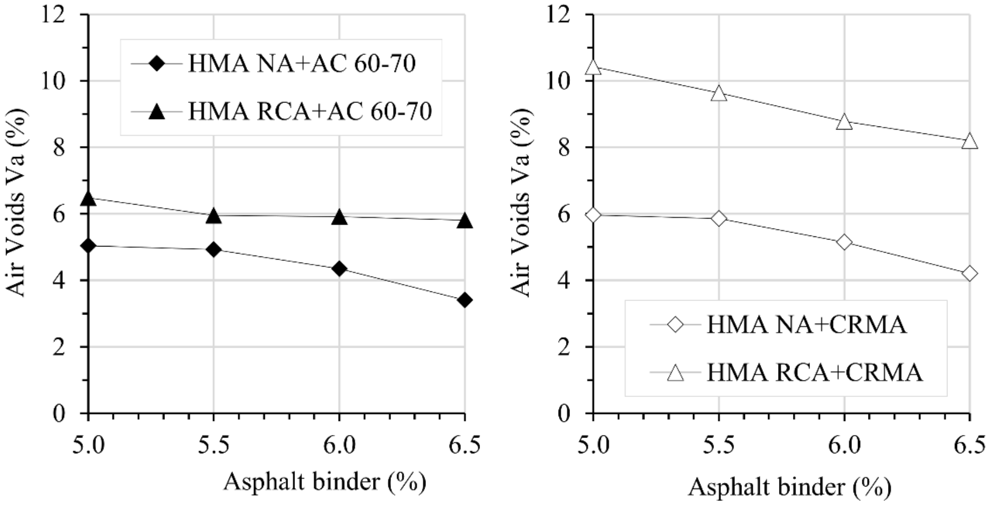

Figure 6. Variation of Va with the conventional and modified asphalt content for mixtures with NA and RCA.

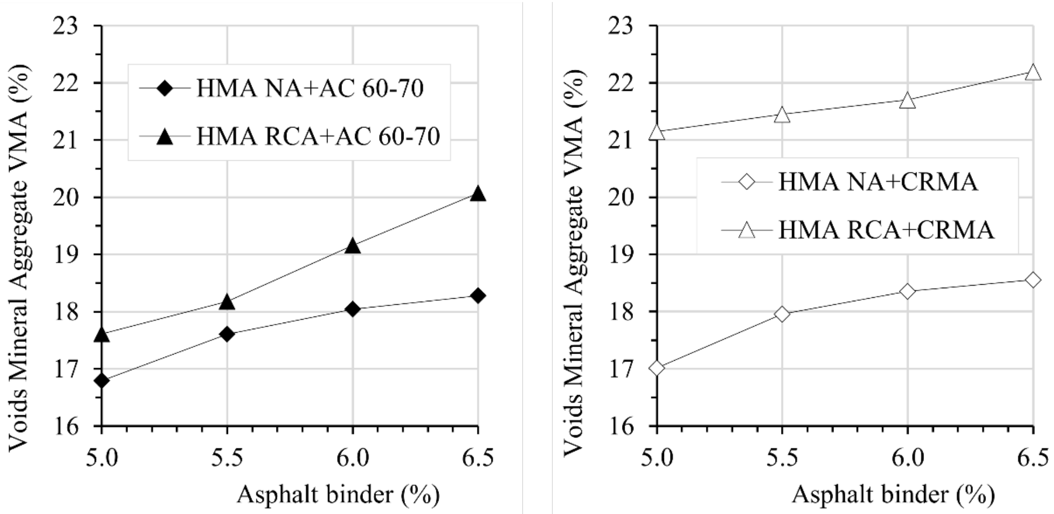

Figure 7. Variation of VMA with the conventional and modified asphalt content for mixtures with NA and RCA.

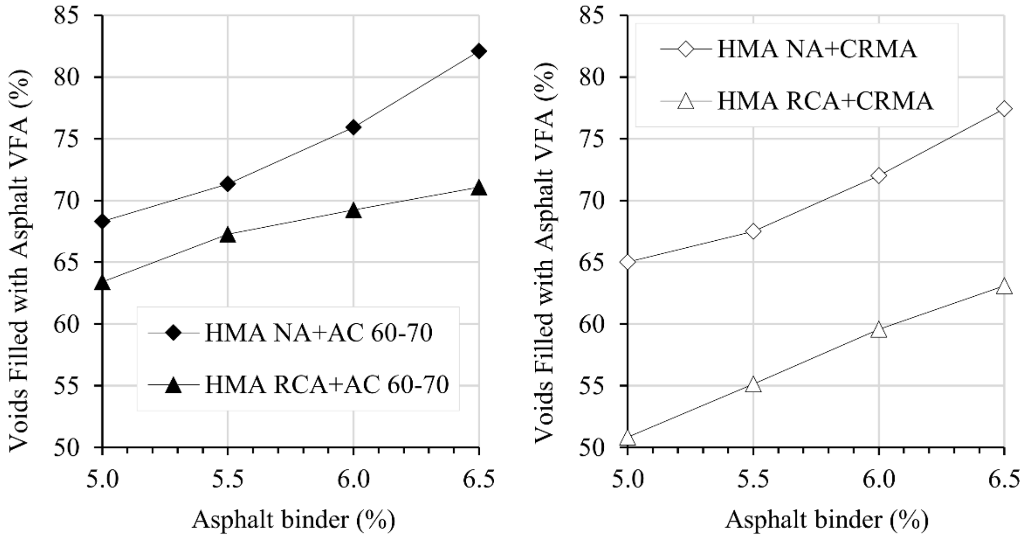

Figure 8. Variation of VFA with the conventional and modified asphalt content for mixtures with NA and RCA.

On the other hand, mixtures with RCA present lower S/F ratio values concerning mixtures with NA. With RCA, the mixtures tend to be more deformable (higher F), which can be attributed to the lower performance of RCA in the physical characterization tests (lower resistance to abrasive wear and particle fracture for NA), mainly due to the presence of the adhered mortar, which is fragile and brittle. With CRMA, even though these mixtures present higher porosity (higher Va), they undergo higher resistance under monotonic load (higher S/F), due to the increase in consistency, stiffness, and viscosity of the modified asphalt.

The FT results obtained from the ANOVA analysis are presented in Table 4. In general, when comparing the Marshall test parameters of the mixtures with NA and RCA using AC 60-70, it is evident that the general trend is not to show significant variations (FT < $f_{0.05}$ =7.708), except for: Va, VAM with 5.5% asphalt binder; VFA with 5.5% and 6.0% asphalt binder; F with 5.0% and 6.5% asphalt binder; and S/F with 6.0% asphalt binder. In other words, the general trend is that the studied RCAs do not result in significant changes compared to the NAs when using AC 60-70. In contrast, when using CRMA, the variations tend to be significant (FT > $f_{0.05}$ =7.708), except for the S/F ratio when using 5.0%, 5.5% and 6.5% of CRMA.

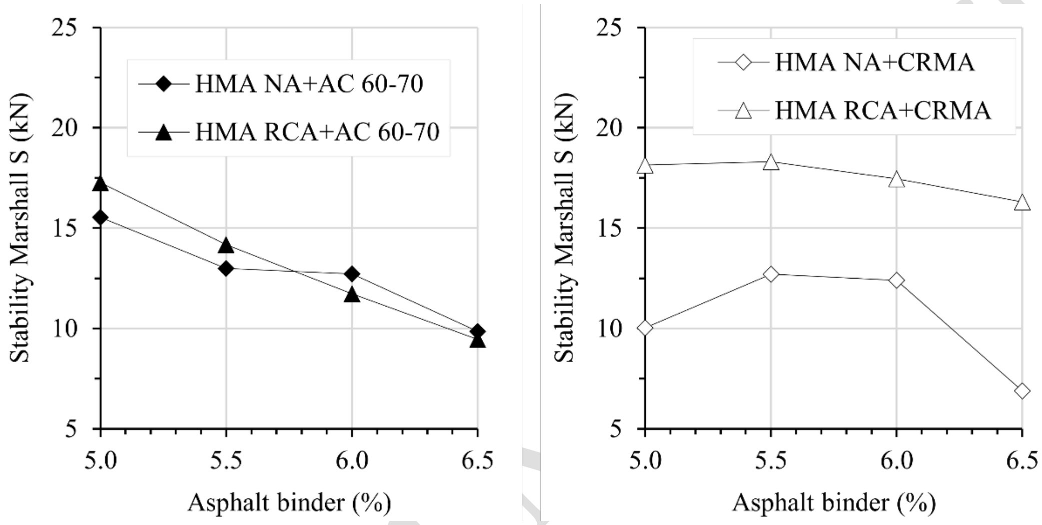

Figure 9. Variation of Marshall Stability with the conventional and modified asphalt content for mixtures with NA and RCA.

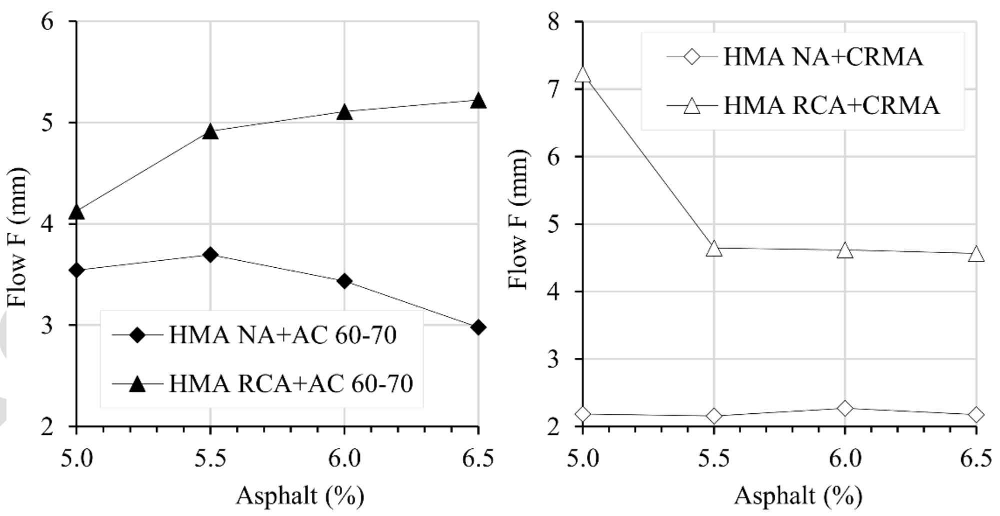

Figure 10. Variation of Marshall Flow with the conventional and modified asphalt content for mixtures with NA and RCA.

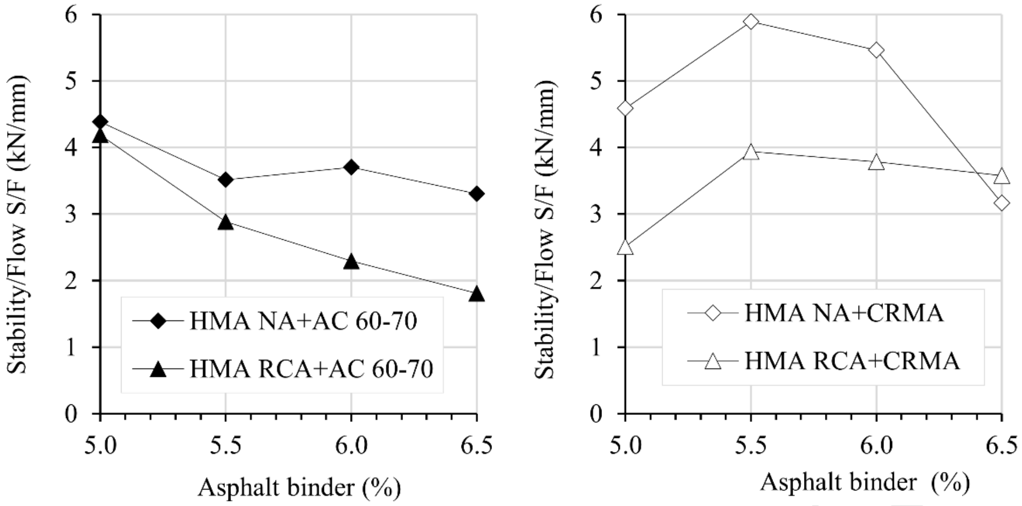

Figure 11. Variation of S/F with the conventional and modified asphalt content for mixtures with NA and RCA.

Table 4. FT value for ANOVA analysis para evaluar la influencia de los agregados.

Marshall Parameters	AC 60-70				CRMA			
Asphalt (%)	5.0	5.5	6.0	6.5	5.0	5.5	6.0	6.5
Va (%)	2.61	***94.12***	7.60	3.44	38.23	32.25	126.92	81.71
VAM (%)	1.69	***50.02***	5.22	2.67	42.22	36.50	145.92	93.99
VFA (%)	2.93	***112.97***	***9.31***	3.38	50.10	23.17	93.43	73.31
S (kN)	2.65	0.59	0.96	0.18	14.72	59.41	***7.68***	132.91
F (mm)	***11.71***	2.63	5.46	***29.18***	38.20	148.60	98.14	24.97
S/F (kN/mm)	0.18	1.08	2.92	***8.99***	***4.79***	14.86	***4.34***	***0.04***

Based on the Marshall test and the design criteria of the INVIAS specification (INVIAS 2022), the OAC of the HMA NA+AC 60-70 and HMA NA+CRMA mixtures is 5.0%. A higher content was not chosen in order not to increase the economic costs of pavement projects. For the mixtures with RCA (HMA RCA + AC 60-70 and HMA RCA+CRMA), it was found that the Va value is higher than that established in the specification and increases significantly in the mix with CRMA. Additionally, the HMA RCA+CRMA mixture does not comply with VFA. Therefore, the OAC of 5.5% for these mixtures was obtained based on the higher S and S/F. It is highlighted that the RCA mixtures require higher asphalt binder contents due to their high absorption, porosity, and surface area [63] [64] [55] [65][55] [61].

Table 5. Marshall test results

Marshall Parameters	HMA NA+ AC 60-70	HMA RCA + AC 60-70	HMA NA+CRMA	HMA RCA+CRMA	Specification
OAC (%)	5.0	5.5	5.0	5.5	-----
Va (%)	5.0	5.9	6.0	9.6	3 – 6
VMA (%)	16.8	18.2	17.0	21.4	15 min
VFA (%)	68.3	67.3	65.0	55.1	65 – 78
S (kN)	15.5	14.2	13.1	17.3	9 min
F (mm)	3.5	4.9	2.2	4.6	2.0 – 3.5

S/F (kN/mm)	4.4	2.9	6.0	3.7	3.0 – 6.0

3.3. ITS test results

The results of the ITS test in dry and wet conditions are shown in Figure 12. In wet conditions, the ranges of values obtained in the mixtures with NA and RCA presented similar values for the two asphalts studied. The ANOVA analysis reported no significant changes ($FT=2.330>f_{0.05}=7.708$). The HMA RCA+CRMA presented higher ITS reduction, which originated from high Va and the reduction of VFA. However, when AC 60-70 was used, they undergo less ITS loss, possibly due to the physical-chemical interactions between the residual cement and the RCA particles. Some researchers [5] [66] report that the presence of calcium (CaO), aluminum (Al_2O_3) and silicon (SiO_2) oxides promote pozzolan characteristics in concrete and may contribute to the adhesion in the asphalt mixture. Also, the contact of water with the bonded cement in RCAs could activate their self-cementing properties and favor adhesion with the asphalt binder [61]. That is, there is no clear behavior of the mixtures with RCA incorporation since the ITS decreased when using CRMA and increased when using AC 60-70, concerning the dry condition. These behaviors were also contrary to those of the mixtures with NA. Therefore, it is possible to show that the RCA produces different effects in the mixtures considering the two asphalts studied, which can be attributed to the high heterogeneity of the RCA.

In dry conditions, the mixture with RCA presented lower ITS values than the mixture with NA, which may be attributed to the increase in Va and decrease in VFA. However, when CRMA was used, the mixtures showed the opposite behavior, despite having a high Va (6.9%). This can be attributed to the fact that the mixtures with modified asphalts of higher consistency and viscosity provide high ITS values, which was also evidenced by the increase in Marshall resistance. Thus, the HMA RCA-CRMA presented ITS values similar to the control mix (HMA AN+AC 60-70).

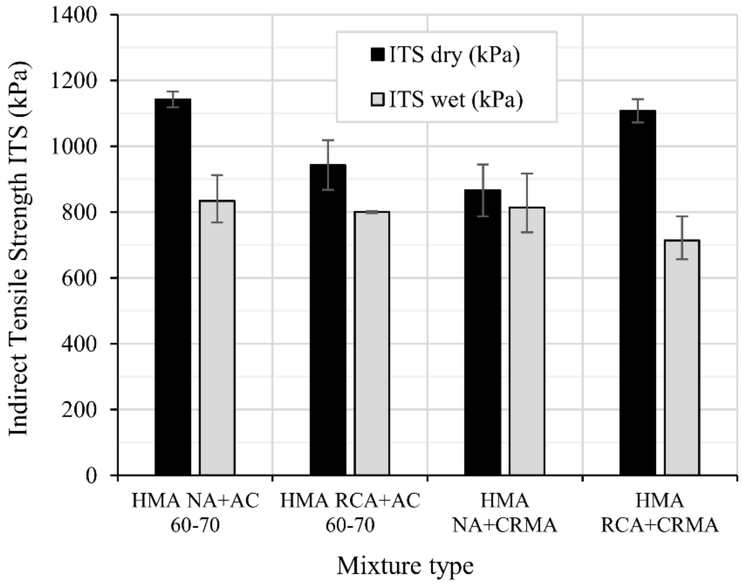

Figure 12. ITS test results

To analyze the water susceptibility of the asphalt mixtures, the TSR was determined (Figure 13). With conventional AC, the tendency of the mix with RCA (HMA RCA+AC 60-70) was to increase the resistance to moisture damage (increased TSR to the HMA NA+AC 60-70). This was mainly because the AC adhered better to the porous surface of the RCA compared to the NA. In addition, the mortar adhered to the RCA has a more compatible chemical composition than the NA in terms of adhesion (it has a higher Ca/Si ratio). Despite the above, when CRMA was used, the performance was different. It is observed that the HMA RCA+CRMA mixture presents the lowest resistance to moisture damage. In this case, the CRMA did not cover the RCA well enough. Perhaps this mixture needs a higher content of effective CRMA or AC (remember that in CRMA, 15% is CR and 85% AC). The above generated the development of higher Va and lower VFA content in the mix. The lack of an effective binder in this mix could have produced a reduction of adhesion and cohesion, as was also evidenced in the S/F Marshall results. Contrary to the above, the mix with NA and CRMA (HMA NA+CRMA) undergo the highest resistance to moisture damage. In this case, the effective binder of the CRMA was sufficient to adhere better to the NA particles, which had much lower porosity and surface absorption than the RCA.

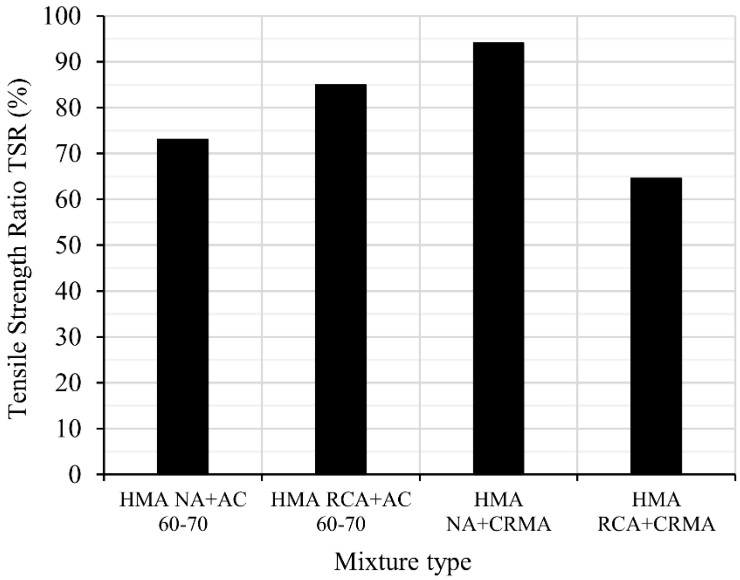

Figure 13. TSR results.

3.4.Resilient modulus

The results of the RM test are shown in Figure 14. Mixtures with RCA significantly decrease the RM concerning those made with NA. For the frequency range analyzed, the reductions correspond to approximately 1200 MPa and 2300 MPa with AC 60-70 and CRMA, respectively. This is consistent with the results obtained from the Marshall test. Additionally, the lower performance of the RCA compared to the NA in the characterization tests could have led to a decrease in the RM. Thus, it is possible to show that the HMA RCA+CRMA generated a greater reduction in RM, which is mainly associated with the higher Va. These results are also consistent with those found in the literature, which reports RM reductions of the blends with RCA [67] [68] [1], [61] [48].

On the other hand, mixtures with NA presented similar RM values, regardless of the asphalt used. The ANOVA results showed that there were no significant changes ($FT=0.003<f_{0.05}=7.708$). This behavior occurred although the HMA NA+CRMA presented higher Va for the control mix (HMA NA+AC 60-70). Perhaps the possible decrease in RM that would be expected from the mixture with CRMA as a result of its higher Va, was compensated by the increase in stiffness of the modified binder.

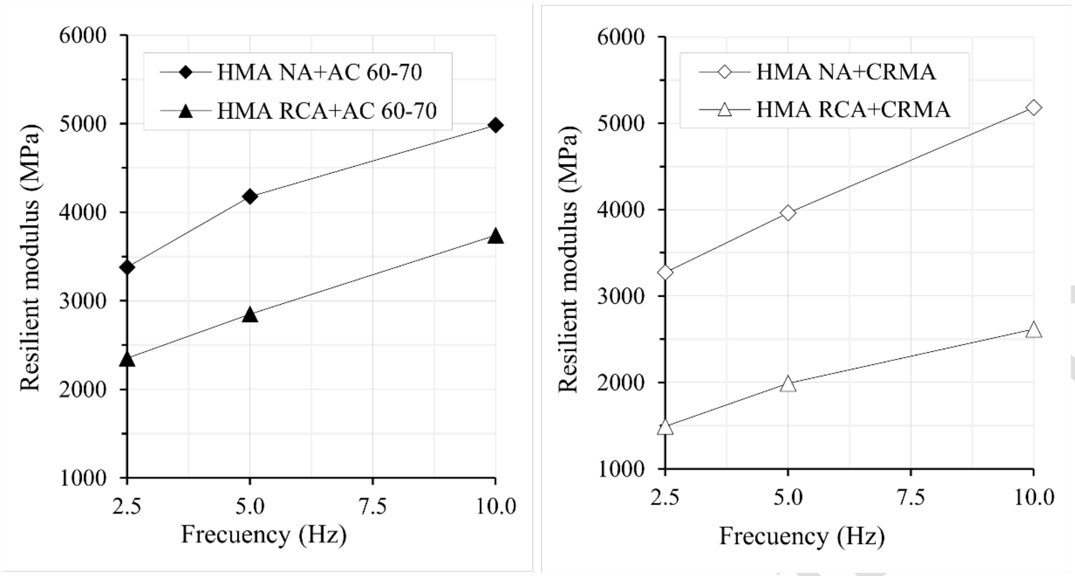

Figure 14. Resilient modulus at 20 ºC

3.5.Permanent deformation

The results of the permanent deformation test are presented in Figure 15. In general, the use of RCA in the mixtures decreased the resistance to permanent deformation. These results are consistent with the S/F ratio and RM and with the explanations given above.

Regarding the performance of the mixtures with NA, the mixtures with CRMA presented greater resistance to permanent deformation. This is attributed to the increased consistency and stiffness of CRMA, according to the tests obtained in the physical characterization stage of the binders. This behavior was also evidenced in the mixtures with RCA, which indicates that CRMA contributes significantly to the increase in the resistance to permanent deformation.

On the other hand, regardless of the type of asphalt, there is a clear difference in the trend of the deformation curves when using RCA and NA. That is, the mixtures with NA showed a stabilization of the permanent deformation value in the first 1000 load cycles. However, the mixtures with RCA did not show stabilization of the permanent deformation value during the applied cycles. This indicates that during the execution of the test, the degradation of the RCA coating mortar can be generated (Figure 5), despite the increase in the OAC. This is associated with the reduction of the abrasion resistance in the angel machine and the Micro-Deval apparatus of the RCAs. These results are also consistent with those evidenced in the literature, where the resistance to permanent deformation of the blends with RCA decreased about the blends with NA [48] [59], [69] [65] [16] [1]. Based on the final deformation results, the ANOVA statistical analysis indicates that the mixtures with RCA exhibit significant variations when using AC 60-70 ($FT = 1.40 \times 10^7 > f_{0.05} = 7.708$) and CRMA ($FT = 1.91 \times 10^7 < f_{0.05} = 7.708$)

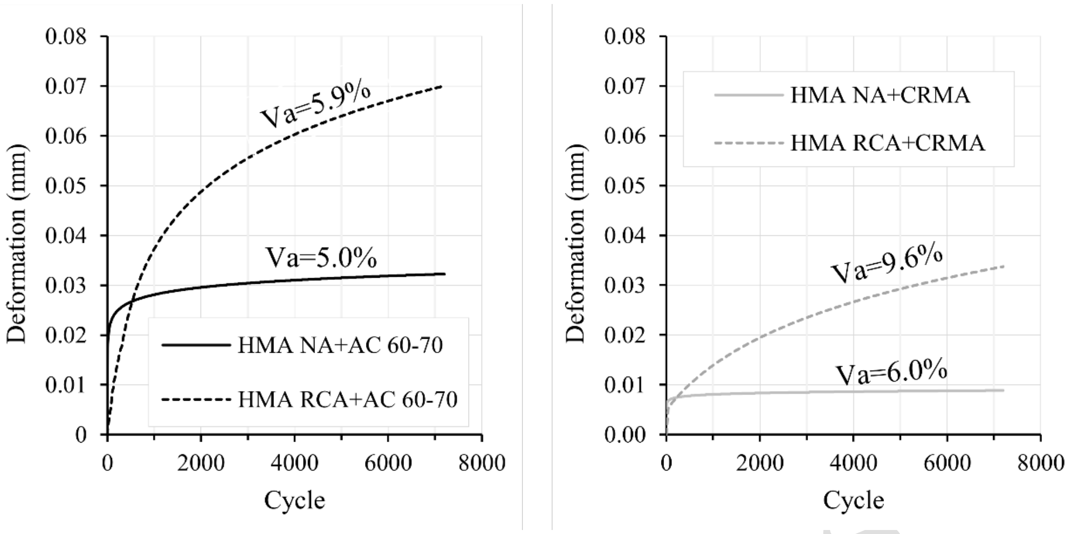

Figure 15. Permanent deformation test at 20 ºC

4. Conclusions

This study analyzed the physical-mechanical behavior of an asphalt mixture that partially replaced the coarse fraction of the NA with RCA (21% about the weight of aggregates). For this purpose, the mixtures were subjected to strength tests under monotonic and cyclic loading. Likewise, AC 60-70 and CRMA were used as binders. Based on the results obtained, it is concluded:

The RCA showed lower mechanical performance than the NA in the characterization tests (lower resistance in the Los Angeles machine, Micro-Deval, and resistance to sulfate attack). It also presents lower specific gravity, higher porosity, and absorption than the NA, mainly attributed to the bonded mortar.

The above increased OAC while decreasing the mechanical performance of the HMA mix in the tests evaluated.

The RCA decreased the S/F ratio, the resilient modulus, and the resistance to moisture damage and permanent deformation.

On the contrary, CRMA tends to increase the mechanical performance of the mixtures. However, the OAC used in the present study was insufficient to adequately cover and bond the RCA. It was also insufficient to cohesion the asphalt mix. For this reason, the mix manufactured with RCA and CRMA had higher Va content and lower VFA, showing the worst performance (low S/F ratio, lower resilient modulus, and resistance to moisture damage).

Therefore, it is recommended that in future studies: i) optimize the mix design by providing the adequate amount of CRMA to meet the volumetric parameters (Va, VMA, VFA); ii) Design a mix by substituting

NA with RCA on a volume basis (this method may be more appropriate for materials with different specific gravities, as in this case); iii) Perform surface treatments on the RCA to reduce its porosity, thereby decreasing the CRMA content.

From a practical standpoint, the use of RCA could be suitable for constructing asphalt layers in pavements subjected to low traffic volumes. As for CRMA, a more extensive experimental phase should be conducted (especially to optimize the mix design) to assess its performance under various traffic and climate conditions.

Additional tests should be conducted with the aim of analyzing the behavior of asphalt mixtures incorporating RCA using both conventional and modified asphalts. It is recommended to evaluate fatigue resistance and fracture tests to assess cracking resistance at low and intermediate temperatures, which should be validated with full-scale tests or trial sections to provide recommendations based on traffic levels. Furthermore, surface treatments with additives for the RCAs should be evaluated to analyze the aggregate-asphalt interface, with the goal of reducing the optimal asphalt content in the mix and improving the cohesion and adhesion of the mixture. Technical, economic, and environmental analyses considering the life cycle of pavements should be carried out to compare the performance of pavements with RCA-based asphalt mixtures against those with NA.

Declaration of competing interest

We declare that we have no significant competing interests including financial or non-financial, professional, or personal interests interfering with the full and objective presentation of the work described in this manuscript.

Acknowledgement

The authors thank the Central Research Directorate of the Pilot University of Colombia and the research seedbed of the HD+I research group: habitat, design, and infrastructure

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

Author contributions

Conceived and designed the analysis: J. G. Bastidas-Martínez; collected the data: C. A. Cárdenas-Triviño; contributed data or analysis tools: L.V. Casallas-Huertas; performed the analysis: D.A. Díaz; wrote the paper: H.A. Rondón-Quintana

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article [and/or] its supplementary materials.

References

[1] M. Arabani *et al*., "The effect of recycled concrete aggregate and steel slag on the dynamic properties of asphalt mixtures," Constr. Build. Mater., vol., 35, pp. 1–7, 2012.
[2] T. Afshar *et al*., "Impact of particle shape on breakage of recycled construction and demolition aggregates," Powder. Technol., vol. 308, pp. 1–12, 2017.
[3] L. Zheng *et al*., "Characterizing the generation and flows of construction and demolition waste in China," Constr. Build. Mater., vol. 136, pp. 405–413, 2017.
[4] R. Jin *et al*., "An empirical study of perceptions towards construction and demolition waste recycling and reuse in China," Resour Conserv Recycl, vol. 126, no. April, pp. 86–98, 2017.
[5] F. Rodrigues *et al*., "Physical-chemical and mineralogical characterization of fine aggregates from construction and demolition waste recycling plants," J Clean Prod, vol. 52, pp. 438–445, 2013.
[6] H. B. Le *et al*., "Recycled aggregate concretes – A state-of-the-art from the microstructure to the structural performance," Constr Build Mater, vol. 257, p. 119522, 2020.
[7] J. P. Giri *et al*., "Development and Evaluation of Some Bituminous Mixes Containing RCA," J Test Eval, vol. 49, no. 4, pp. 2579–2596, 2019
[8] CDRA, "Construction Demolition Recycling Association," 2021.
[9] V. W. Y. Tam, "Comparing the implementation of concrete recycling in the Australian and Japanese construction industries," J Clean Prod, vol. 17, no. 7, pp. 688–702, 2009.
[10] S. Ismail *et al*., "Engineering properties of treated recycled concrete aggregate (RCA) for structural applications," Constr Build Mater, vol. 44, pp. 464–476, 2013.
[11] R. Jin *et al*., "Investigation of Concrete Recycling in the U.S. Construction Industry," Procedia Eng, vol. 118, pp. 894–901, 2015.
[12] H. K. A. Al-Bayati, *et al*., "Influence of recycled concrete aggregate on volumetric properties of hot mix asphalt," Resour Conserv Recycl, vol. 130, 2017, pp. 200–214, 2018.
[13] M. A. Khasawneh *et al*., "Effect of nominal maximum aggregate size and aggregate gradation on the surface frictional properties of hot mix asphalt mixtures," Constr Build Mater, vol. 244, p. 118355, 2020.
[14] F. Tahmoorian *et al*., "Laboratory investigations on the utilization of RCA in asphalt mixtures," International Journal of Pavement Research and Technology, vol. 11, no. 6, pp. 627–638, 2018.
[15] J. G. Bastidas-Martínez *et al*., "Use of recycled concrete aggregates in asphalt mixtures for pavements: A review," Journal of Traffic and Transportation Engineering (English Edition), vol. 9, no. 5, pp. 725–741, 2022.
[16] A. R. Pasandín *et al*., "Laboratory evaluation of hot-mix asphalt containing construction and demolition waste," Constr Build Mater, vol. 43, pp. 497–505, 2013.
[17] G. R. Morris, *True cost effectiveness of bitumen-rubber paving systems,* Fred Waller ed., USA, 1993.
[18] G. B. Way, "Asphalt-Rubber 45 Years of Progress," *in Asphalt Rubber 2012 Conf.*, Portugal, 2012, p.
[19] A. F. De Almeida Júnior *et al*., "Use of scrap tire rubber in place of SBS in modified asphalt as an environmentally correct alternative for Brazil," J Clean Prod, vol. 33, pp. 236–238, 2012.

[20] J. W. Jang, *et al*., "Discarded tire recycling practices in the United States, Japan and Korea," Resour Conserv Recycl, vol. 22, no. 1–2, pp. 1–14, 1998.

[21] V. Torretta *et al*., "Treatment and disposal of tyres: Two EU approaches. A review," Waste Management, vol. 45, pp. 152–160, 2015.

[22] C. Wu *et al*., "Activated minerals as binder stabilizers in middle course's asphalt conctrete paving mixtures," *in 91 anual meeting of the Transportation Research Board conf*, 2012.

[23] J. B. Sousa, "Elastomeric Asphalt Extender – A New Frontier on Asphalt Rubber Mixes" 2012.

[24] I. Sousa *et al*., "Reacted and activated rubber - an elastomeric asphalt extender," vol 2012.

[25] J. L. Feiteira Dias *et al*., "Mechanical performance of dry process fine crumb rubber asphalt mixtures placed on the Portuguese road network," *Constr Build Mater*, vol. 73, pp. 247–254, 2014.

[26] J. Wang *et al*., "Chemical, thermal and rheological characteristics of composite polymerized asphalts," *Fuel*, vol. 227, pp. 289–299, 2018.

[27] I. M. Khan *et al*., Almansoor, "Asphalt Design Using Recycled Plastic and Crumb-rubber Waste for Sustainable Pavement Construction," *Procedia Eng*, vol. 145, pp. 1557–1564, 2016.

[28] M. A. Dalhat *et al*., "Performance of recycled plastic waste modified asphalt binder in Saudi Arabia," *International Journal of Pavement Engineering*, vol. 18, no. 4, pp. 349–357, 2015.

[29] P.-H. Yeh *et al*., "Evaluation of thermal and viscoelastic properties of asphalt binders by compounding with polymer modifiers," *Polym Compos*, vol. 31, no. 10, pp. 1738–1744, 2010.

[30] H. A. Rondón-Quintana *et al*., Pavimentos: Materiales, construcción y diseño, -2*nd* ed. Ecoediciones, Bogotá, 2022.

[31] A. Lozano *et al*., "Asphalts and modified dense bituminous mixtures with rubber of military boots," *Revista Dyna*, vol. 87, no. 212, pp. 120–128, 2020.

[32] L. Zhang *et al*., "Using DSR and MSCR tests to characterize high temperature performance of different rubber modified asphalt," *Constr Build Mater*, vol. 127, pp. 466–474, 2016.

[33] S. Wang *et al*., "Recent developments in the application of chemical approaches to rubberized asphalt," *Constr Build Mater*, vol. 131, pp. 101–113, 2017.

[34] F. F. Camargo *et al*., "Case history study: field monitoring and performance prediction of a field-blended rubber asphalt mixture in Brazil," *International Journal of Pavement Engineering*, vol. 20, no. 2, pp. 172–182, 2017.

[35] T. W. Hsu *et al*., "Performance Evaluation of Asphalt Rubber in Porous Asphalt-Concrete Mixtures," *Journal of Materials in Civil Engineering*, vol. 23, no. 3, pp. 342–349, 2011.

[36] C. Wang *et al*., "Development of paving performance index system for selection of modified asphalt binder," *Constr Build Mater*, vol. 153, pp. 695–703, 2017.

[37] Marais *et al*., "Shelf-Life and Performance properties of bitume rubber," *Asphalt Rubber*, vol. 1, pp. 429–441, 2012.

[38] M. Msallam *et al*., "Improvement of local asphalt concrete binders using crumb rubber," *Journal of Materials in Civil Engineering*, vol. 30, no. 4, pp. 1–7, 2018.

[39] I. Pérez *et al*., "Moisture damage resistance of hot-mix asphalt made with recycled concrete aggregates and crumb rubber," *J Clean Prod*, vol. 165, pp. 405–414, 2017.

[40] M. Muniz *et al*., “Influence of asphalt rubber on the crushing of recycled aggregates used in dense HMA,” *Proceedings of asphalt rubber*. Munich., 2012.

[41] A. R. Pasandín *et al*., “Fatigue performance of bituminous mixtures made with recycled concrete aggregates and waste tire rubber,” *Constr Build Mater*, vol. 157, pp. 26–33, 2017.

[42] M. Muniz de Farias, F. Quiñonez-Sinisterra, and H. A. Rondón-Quintana, “Behavior of a Hot-Mix Asphalt Made with Recycled Concrete Aggregate and Crumb Rubber,” Canadian Journal of Civil Engineering, vol. 70, pp. 1–39, 2019, doi: 10.1139/cjce-2018-0443.

[43] E. H. Sanchez-Cotte *et al*., “Influence of recycled concrete aggregates from different sources in hot mix asphalt design,” Constr Build Mater, vol. 259, pp. 120427, 2020, doi: 10.1016/j.conbuildmat.2020.120427.

[44] INVIAS, “Instituto Nacional de Vías - INVIAS. Especificaciones Generales para Construcción de Carreteras. Bogotá D.C., Colombia.,” 2022.

[45] J. G. Bastidas-martínez *et al*., “Evaluación de una mezcla de concreto asfáltico con incorporación de agregados reciclados de concreto” *Revista UIS*, vol. 20, no. 2, pp. 75–84, 2021.

[46] H. A. Rondón *et al*., “Blast Furnace Slag as a Substitute for the Fine Fraction of Aggregates in an Asphalt Mixture,” *Journal of Materials in Civil Engineering*, vol. 30, no. 10, 2018.

[47] H. A. Rondón-Quintana *et al*., “Mechanical resistance of hot-mix asphalt using phosphorite as filler,” *Journal of Materials in Civil Engineering*, vol. 35, no. 2023.

[48] C. M. Nwakaire *et al*., “Laboratory study on recycled concrete aggregate-based asphalt mixtures for sustainable flexible pavement surfacing,” *J Clean Prod*, vol. 262, p. 121462, 2020.

[49] H. A. Rondón-Quintana *et al*., “Behavior of Hot-Mix Asphalt Containing Blast Furnace Slag as Aggregate: Evaluation by Mass and Volume Substitution,” Journal of Materials in Civil Engineering, vol. 31, no. 2, 2019.

[50] H. A. Rondón-Quintana *et al*., “Substitution by Mass and Volume of a Natural Aggregate with Recycled Concrete Aggregate in an Asphalt Mixture.,” *International Journal of Advanced Science and Technology*, vol. 29, no. 4, pp. 10845–10850, 2020.

[51] D. A. Zuluaga-Astudillo *et al*., “Mechanical performance of gilsonite modified asphalt mixture containing recycled concrete aggregate,” Applied Sciences (Switzerland), vol. 11, no. 10, 2021.

[52] M. M. Rafi *et al*., “Experimental testing of hot mix asphalt mixture made of recycled aggregates,” *Waste Management and Research*, vol. 29, no. 12, pp. 1316–1326, 2011.

[53] M. Arabani *et al*., “Effect of glass cullet on the improvement of the dynamic behaviour of asphalt concrete,” Constr Build Mater, vol. 25, no. 3, pp. 1181–1185, 2011.

[54] M. Arabani *et al*., “Modeling the fatigue behaviors of glasphalt mixtures,” Sharif University of Techology Scientia Iranica, vol. 19, no. 3, pp. 341–345, 2012.

[55] S. Bhusal *et al*., “Evaluation of Effects of Recycled Concrete Aggregate on Volumetrics of Hot-Mix Asphalt,” *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2205, no. 1, pp. 36–39, 2011.

[56] J. Mills-Beale *et al*., “The mechanical properties of asphalt mixtures with Recycled Concrete Aggregates,” *Constr Build Mater*, vol. 24, no. 3, pp. 230–235, 2010.

[57] S. Ektas *et al*., “Use of recycled concrete in Hot Mix Asphalt and an ANN model for prediction of resilient modulus,” *Ekoloji*, vol. 60, no. 83, pp. 53–60, 2012.

[58] H. Qasrawi *et al*., “Effect of bitumen grade on hot asphalt mixes properties prepared using recycled coarse concrete aggregate,” *Constr Build Mater*, vol. 121, pp. 18–24, 2016.

[59] J. P. Giri *et al*., “Use of waste polyethylene for modification of bituminous paving mixes containing recycled concrete aggregates,” *Road Materials and Pavement Design*, vol. 21, no. 2, pp. 289–309, 2018.

[60] J. G. Bastidas-Martínez *et al*., “Study of hot mix asphalt containing recycled concrete aggregates that were mechanically treated with a Los Angeles machine,” *International Journal of Civil Engineering and Tecnology IJCIET*, vol. 10, no. 10, pp. 226–243, 2019.

[61] D. A. Álvarez *et al*., “Influence of partial coarse fraction substitution of natural aggregate by recycled concrete aggregate in hot asphalt mixtures,” Sustainability, vol. 12, no. 1, 2020.

[62] P. Mikhailenko *et al*., “Incorporation of recycled concrete aggregate (RCA) fractions in semi-dense asphalt (SDA) pavements: Volumetrics, durability and mechanical properties,” *Constr Build Mater*, vol. 264, p. 120166, 2020.

[63] D.-H. Shen *et al*., “Damage-Induced Modeling of Asphalt Mixtures through Computational Micromechanics and Cohesive Zone Fracture,” *Journal of Materials in Civil Engineering*, vol. 17, no. 5, pp. 477–484, 2005.

[64] A. Ossa *et al*., “Use of recycled construction and demolition waste (CDW) aggregates: A sustainable alternative for the pavement construction industry,” *J Clean Prod*, vol. 135, pp. 379–386, 2016.

[65] A. Radević *et al*., “Effects of recycled concrete aggregate on stiffness and rutting resistance of asphalt concrete,” *Constr Build Mater*, vol. 136, pp. 386–393, 2017.

[66] A. Zulkati *et al*., “Mechanistic Performance of Asphalt-Concrete Mixture Incorporating Coarse Recycled Concrete Aggregate,” *Journal of Materials in Civil Engineering*, vol. 25, no. 9, pp. 1299–1305, 2013.

[67] S. Paranavithana *et al*., “Effects of recycled concrete aggregates on properties of asphalt concrete,” *Resour Conserv Recycl*, vol. 48, no. 1, pp. 1–12, 2006.

[68] J. Mills-Beale *et al*., “The mechanical properties of asphalt mixtures with Recycled Concrete Aggregates,” *Constr Build Mater*, vol. 24, no. 3, pp. 230–235, 2010.

[69] J. P. Giri *et al*., “Performance of Bituminous Mixes Containing Treated Recycled Concrete Aggregates and Modified by Waste Polyethylene,” Journal of Materials in Civil Engineering, vol. 30, no. 8, p. 04018184, 2018.