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Mechanical strength of an hot-mix asphalt using recycled concrete aggregate: mass and volume proportioning

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ABSTRACT

The generation of solid waste produced by the construction sector is considered a major problem worldwide. Several studies have been conducted to evaluate the use of construction and demolition wastes (CDW) in pavements. Within CDW, one material with great potential for use is recycled concrete aggregate (RCA). The present study evaluated the mechanical performance of a hot-mix asphalt (HMA) that used RCA as a partial substitute for the coarse fraction of the natural aggregate – Nag (particle size retained on 1/2″ and 1/2"+3/8″ sieves). The substitution was performed in a conventional way by mass and also by volume. To evaluate the performance under monotonic loading, the stability/flow ratio (*S/F*) of the Marshall test and the Indirect Tensile Strength (ITS) were measured on dry (*ITSd*) and conditioned (immersed in water, *ITSw*) samples. The tensile strength ratio (TSR) was calculated to evaluate the resistance to moisture damage. Under cyclic loading, tests of resilient modulus – RM (three temperatures and three loading frequencies), permanent deformation, and fatigue resistance under controlled-stress were performed. Cantabro tests were performed to measure the resistance to abrasive wear. Conventional characterization tests and imaging processing in a scanning electron microscope (SEM) were carried out on particles of RCA and Nag. A Life Cycle Cost Analysis (LCCA) was performed with the results obtained. The general conclusions were as follows: (i) RCA increases the asphalt content in the mixes, however, volume substitution could help to decrease it; (ii) the mixes with RCA met the volumetric and strength parameters established by the Colombian specification (especially for roads with low traffic volumes); (iii) mixes with RCA undergo better mechanical performance in all tests performed, however, resistance to moisture damage may be compromised when dosing by volume and asphalt content decreases; (iv) substitution by mass or volume did not generate clear trends in the results, but better overall performance is reported in mixes dosed by volume. It is recommended to carry out more studies where Nag is replaced by RCA in volume.

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KEYWORDS
Asphalt; hot-mix asphalt; mass substitution; volume substitution; recycled concrete aggregate

Introduction

Problem statement and background

The economic development of a country is largely influenced by the transportation sector. Therefore, the construction and maintenance of the quality of roadways in all categories and classifications are

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imperative. Emissions from the road infrastructure (material extraction, production and transportation, road construction, maintenance, and recycling of roads) make up 5-25% of total CO_2 emissions from transport (Liu et al., 2017). During the construction process of road projects, large quantities of aggregates of natural origin (Nag) are consumed, negatively impacting the environment. In the case of hot-mix asphalt (HMA), aggregate makes up about 90–95% of the mass (Khasawneh & Alsheyab, 2020). The use of recycled aggregates is strategic for the sustainability of the construction sector and the preservation of natural resources (Balaguera et al., 2018; Tefa et al., 2022). The overall potential of CO_2 emissions reduction of materials replacement and using recycled materials can be up to 70% (Liu et al., 2022). The exploitation of aggregates in Colombia for 2019 was 30.22 million m^3 of construction materials (UPME, n.d.). According to the above, the implementation of new technologies that are more environmentally friendly and the use of recyclable alternative materials is indispensable in Colombian engineering with the aim of mitigating the exploitation of Nag and reducing the impact on the environment.

The global construction industry has grown in recent years, increasing the production of construction and demolition wastes (CDW) (Gabr & Cameron, 2012; Jitsangiam et al., 2021). Soltanabadi and Behfarnia (2022) report that in the United States and European countries around 317 and 510 million tons of RCD are being produced per year, respectively. According to Pacheco-Bustos et al. (2017), the impacts produced by CDWs directly affect the air, soil, and water bodies, directly impacting public health. In the world, recycling CDWs as aggregates is a widespread practice in developed countries to prevent environmental pollution and reduce the impact of virgin aggregate extraction (Agrela et al., 2021; Castaño et al., 2013). On the other hand, recycled concrete aggregates (RCA) are from the demolition of civil constructions and are contained within CDWs (RCAs make up between 50 and 70% by weight of the total CDW; Jin & Chen, 2019). One way to reduce the impacts generated by these wastes (reduction of the carbon footprint in the construction industry, conservation of natural resources, and reduction of hazardous emissions, among others) is by replacing Nag with RCA (Jitsangiam et al., 2021; Kar et al., 2021; Purohit et al., 2021). Additionally, RCA is chemically stable and is not a hazardous material (Zulkati et al., 2013). RCA is considered as a potential substitute material for Nag in HMAs, while at the same time, it could offer environmental, economic and social benefits (Xu et al., 2022).

RCAs are characterized by being highly heterogeneous, possessing lower density, higher absorption capacity, and lower mechanical and abrasion resistance in the Los Angeles machine than Nag (Al-Bayati & Tighe, 2019; Kar et al., 2021; Kareem et al., 2019; Monu et al., 2020; Motter et al., 2015; Purohit et al., 2021; Zulkati et al., 2013). However, these residues present particles with ideal shapes (fractured faces with low flattening and elongation indices) that can help generate a compact granular skeleton with good intergranular friction. Their higher porosity compared to Nag could improve adhesion with asphalt binders (Motter et al., 2015; Tahmoorian et al., 2022; Zuluaga-Astudillo et al., 2021). Additionally, their properties depend in part on the compressive strength of the original concrete, its provenance, the environmental effects to which the concrete was exposed, and the materials used for its production (Sanchez-Cotte et al., 2020). Numerous investigations have been conducted worldwide regarding the use of RCA as a substitute for Nag in asphalt mixtures. The literature is ambiguous in reporting the performance of mixtures using RCA as aggregate. While some studies report that mechanical performance improves, others conclude the opposite (Sanchez-Cotte et al., 2020; Tahmoorian & Samali, 2018; Zuluaga-Astudillo et al., 2021). In addition, there is a large disparity in recommendations regarding the replacement levels of Nag by RCA in asphalt mixtures (Nwakaire et al., 2020). Despite the above, most studies have indicated that RCA produced from conventional concretes are generally suitable for use in HMA mixtures used in flexible pavement construction (Pasandín & Pérez, 2015), mainly in roads with low traffic volumes (Motter et al., 2015; Zuluaga-Astudillo et al., 2021). As a main limitation of use in asphalt mixtures, RCAs consume a greater amount of asphalt binder (Mikhailenko et al., 2020; Naser et al., 2022) mainly due to the mortar adhered to their surface, which is highly porous and brittle. This has encouraged studies that seek to remove this mortar through mechanical, thermal and chemical treatments (Al-Bayati & Tighe, 2019; Jitsangiam et al., 2021;

Kar et al., 2021; Kareem et al., 2019; Raman & Ramasamy, 2021; Tang et al., 2021; Upshaw & Cai, 2020; Xu et al., 2022).

In reference to mechanical behavior, some authors report increases in resistance to monotonic load action when using RCA (Bastidas-Martínez et al., 2022; Martinho et al., 2018; Paranavithana & Mohajerani, 2006). However, there is a trend in the reduction of tensile strength and susceptibility to water (Bastidas-Martínez et al., 2022; Mikhailenko et al., 2020; Sanchez-Cotte et al., 2020). In terms of stiffness and permanent deformation resistance, there is no clarity on the effects produced by RCA. Some studies report increases, while in others it decreases (Arabani, 2011; Arabani & Azarhoosh, 2012; Radević et al., 2017). Fatigue resistance has been less studied. However, most studies report similar or even higher values when using RCA. Few studies report a decrease in fatigue resistance (e.g. Arabani, 2011; Arabani & Azarhoosh, 2012). The differences in behavior can be attributed to the origin, mineralogy, source, chemical composition, particle size, and physical characteristics of the RCA. As well as the characteristics of the mixture (type and content of asphalt, gradation, RCA content, type of natural aggregates, mix design methodology, among others). State of the art on the subject can be found in Bastidas-Martínez et al. (2022).

Another alternative that could help reduce the asphalt content in mixes using RCA is to dose the substitution of Nag by volume. This is due to the fact that substitution by mass increases the number of RCA particles to be coated with asphalt (due to the lower density of this material concerning Nag; Mikhailenko et al., 2020; Rondón-Quintana et al., 2019). Additionally, by volume, the analysis is simplified, since in theory the number of particles is similar, decreasing the number of variables to evaluate. Most applications of RCA in HMAs are as substitutes for the coarse fraction of Nag and such replacement must be performed by volume in order to evaluate its effect on the resulting behavior of HMA mixture. However, this replacement is usually performed in mass since it is simpler and more practical. For this reason, in contrast to previous studies both evaluations were performed: replacing a Nag by RCA in mass and volume. The natural aggregate used is a limestone (LS) with low absorption, smooth surface texture and low porosity. These properties may have some disadvantages in terms of adhesion, asphalt bleeding and skid resistance. For this reason, this type of materials could be combined with others with opposite properties (rough superficial texture and high porosity as RCA) in order to improve the response of the resulting HMA.

Research significance and objective

In the literature consulted, no studies were found that specifically evaluated the influence of replacing Nag by RCA in volume. Rondón-Quintana et al. (2020) carried out a study, but only the influence that the substitution of Nag for RCA had on the design, the volumetric composition of the mix, and the mechanical strength under monotonic loading measured through the Marshall test were evaluated. In other words, the experimental phase was limited. Zuluaga-Astudillo et al. (2021) replaced Nag with RCA by mass and volume in two types of asphalt mixtures, but the main objective of the study was to evaluate the influence of a gilsonite on the mechanical properties of both mixtures. The present research provides a more extensive and complete experimental phase to evaluate the performance of asphalt mixtures using RCA. Due to the above, and given the need to reduce the use of Nag used in construction and cooperate with the preservation of the environment, in the present study, the behavior of an HMA type HMA-19 ('Instituto de Desarrollo Urbano' – IDU, 2018; 'Instituto Nacional de Vias' – INVIAS, 2022) was evaluated when the coarse fraction of the Nag is partially replaced (by mass and by volume) by RCA. To measure the performance of the mixes (without and with replacement of Nag by RCA), tests were performed under monotonic (Marshall, Indirect Tensile Strength) and cyclic loading (resilient modulus – RM, permanent deformation and fatigue resistance under controlled-stress). Additionally, resistance to moisture damage (Tensile Strength Ratio – TSR) and abrasion wear (Cantabro test) were measured. Nag and RCA particles were observed in a scanning electron microscope (SEM). On the other hand, a Life Cycle Cost Analysis (LCCA) was performed with the results obtained.

Table 1. Asphalt cement AC 24 (AC 50-70) properties.

Test	Specification	Unit	Recommended	Result
Tests on the original asphalt				
Specific gravity	AASHTO T 228	–	–	1.014
Penetration (25°C, 100 g, 5 s)	ASTM D5	0.1 mm	50–70	51.0
Viscosity (60°C)	ASTM D4402	Pa-s	240–360	314
Viscosity (135°C)	ASTM D4402	Pa-s	0.35 minimum	0.38
Softening point	ASTM D36	°C	50–58	50.4
Ductility (25°C, 5 cm/minute)	ASTM D113	cm	100 minimum	135
Flash and fire points	ASTM D3143	°C	232 minimum	322
Tests on the residue after RTFOT (Rolling Thin Film Oven Test)				
Mass loss	ASTM D2872	%	0.8 maximum	0.06
Penetration (25°C, 100 g, 5 s)	ASTM D5	%	58 minimum	58.1
Softening point Increase	ASTM D36	°C	9 maximum	5.95
Ductility at residue	ASTM D113	cm	40 minimum	98
Viscosity at residue	ASTM D4402	Pa-s	1500 maximum	833.3

Table 2. Aggregate properties.

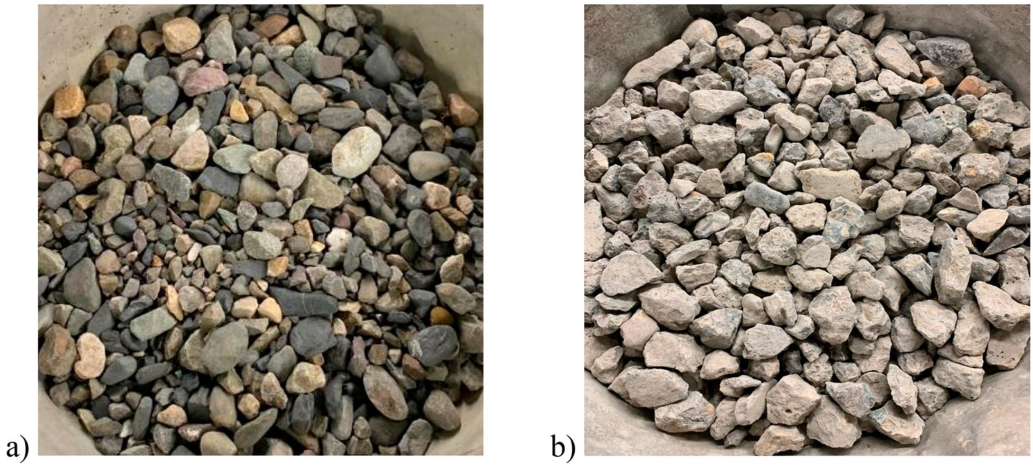
Test	Specification	Recommended	Nag	RCA
Specific gravity of fine aggregate	AASHTO T 84	–	2.61	2.19
Fine aggregate absorption	AASHTO T 84	–	1.13%	6.54%
Specific gravity of coarse aggregate	AASHTO T 85	–	2.38	2.06
Coarse aggregate absorption	AASHTO T 85	–	2.17%	9.64%
Fractured particles (1 side)	ASTM D5821	85% minimum	85.7%	100%
Plasticity Index	ASTM D4318	Not plastic	Not plastic	Not plastic
10% of fines (dry resistance)	DNER-ME 096	100 kN minimum	180.5 kN	141.5 kN
10% of fines (wet/dry ratio)	DNER-ME 096	75% minimum	88.8	60.0
Micro-Deval	AASHTO T 327	20% maximum	16.3%	17.3%
Abrasion in Los Angeles machine	AASHTO T 96	25% maximum	19.2%	28.58%

Materials and methods

Materials

The binder used was asphalt cement (AC) AC 24 (minimum absolute viscosity measured at 60 °C of 240 Pa-s) from the city of Bogotá D.C. (Colombia). Rated by penetration in 0.1 mm (ASTM D5) is AC 50-70 type. The properties of AC 24 are shown in Table 1. This AC meets the requirements established by IDU (2018) for its use as a binder in HMAs type HMA-19.

The Nag (Figure 1(a)) come from a quarry located in Bogotá DC. This material is a limestone (LS) with low absorption, smooth surface texture and low porosity. The RCAs (Figure 1(b)) come from the demolition of buildings in Bogotá DC. The properties of both materials are shown in Table 2. It is observed that the Nag meets the quality requirements demanded by IDU (2018) and INVIAS (2022) for HMA-19 mixes. The RCA display higher abrasion wear measured in the Los Angeles machine and in the Micro-Deval compared to the Nag. Also, Nag undergo higher resistance to particle fracture measured in the 10% fines test. This is mainly due to the mortar bonded on the surface of the RCA (Bastidas-Martínez et al., 2022; Kareem et al., 2019; Sánchez de Juan & Alaejos-Gutiérrez, 2009). Additionally, the RCA does not meet the requirement established by IDU (2018) and INVIAS (2022) for asphalt-wearing surfaces subjected to high traffic volumes (T3). However, this material could be used for asphalt intermediate and base layers for T3 transits, and asphalt wearing surfaces subjected to medium (T2) and low (T1) traffic volumes. It is also observed that Nag contains particles with fewer fractured faces and with flatter and more elongated geometric shapes than RCA. This is mainly due to the greater crushing process that RCA undergoes to obtain its different particle sizes. On the other hand, RCA has a lower specific gravity than Nag due to the higher surface porosity of the bonded mortar (Bastidas-Martínez et al., 2021; Martinez-Arguelles et al., 2019; Pasandín & Pérez, 2013; Sanchez-Cotte et al., 2020).



a) b)

Figure 1. (a) Nag; and (b) RCA.

Table 3. Elemental composition of particles based on SEM.

Element	C	O	*Ca*	Mn	Si	Al	Fe	Mg	K	Ti
Aggregate particle of the RCA	–	55.73	5.50	–	34.00	3.29	0.53	–	0.57	0.17
Adhered mortar	16.14	51.87	15.32	0.16	12.12	3.10	0.87	0.28	0.15	–
Nag	–	48.30	0.33	–	41.26	2.82	6.32	0.38	0.32	0.27

Table 4. HMA-19 – Particle size distribution.

Sieve	3/4″	1/2″	3/8″	4	10	40	80	200
Sieve (mm)	19.0	12.5	9.5	4.75	2.0	0.43	0.18	0.075
Passing (%)	100	87.5	79.0	57.0	37.0	19.5	12.5	6.0

Nag and RCA particles (diameter of approximately 2 cm) were also subject to observation (between 50 and 1000× magnification) in the SEM JEOL JSM 6700F (JEOL, Tokyo, Japan) with an acceleration voltage of 20 kV in high vacuum at a working distance of approximately 8–9 mm. The micrographs were taken with a backscattered electron detector (BSE). Observations were carried out on the adhered mortar of the RCA (Figure 2(a)), the aggregate particle (without adherer mortar) of the RCA (Figure 2(b)), and on the Nag (Figure 2(c)). Elemental chemical composition (Table 3) and average maximum pore diameter were measured and evaluated at five points on three samples of each material. As expected, the adhered mortar shows greater porosity than the Nag. The information from the SEM will be used further below to analyze the results.

Asphalt mixes design

For the design of HMA-19 mixes, the central aggregate grain size range recommended by IDU (2018) and INVIAS (2022) was used (Table 4).

The design of the HMA-19 Control mix (using Nag as aggregate) and the mixes that used RCA as a partial substitute (by mass and volume) for the coarse fraction of the Nag was performed using the Marshall method (AASHTO T 245), taking into account the criteria established by IDU (2018) and INVIAS (2022). For each mix, three samples were prepared for each asphalt binder percentage of 4.5, 5.0, 5.5, 5.5, 6.0, 6.5 and 7.0%. In the mixes using RCA, the coarse fractions of the Nag whose particle sizes were retained on the 1/2″ and 1/2"+3/8″ sieves were replaced (both by mass and by volume). Smaller

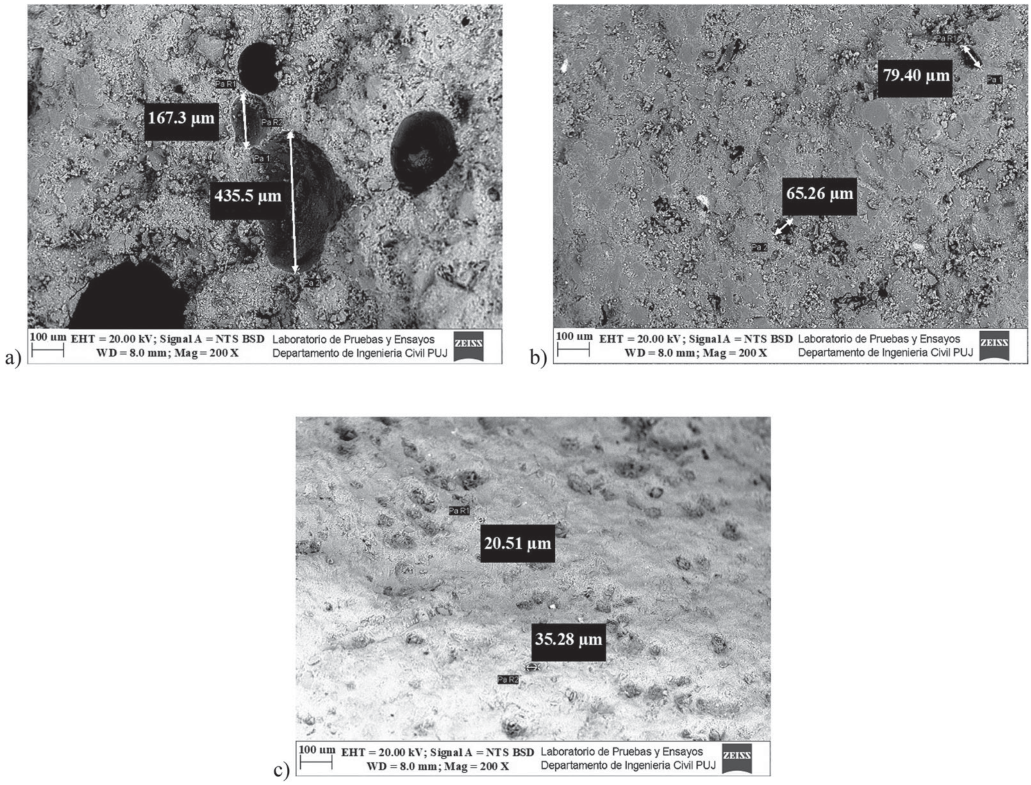


Figure 2. SEM observations in: (a) adhered mortar, (b) aggregate particle (without adherer mortar) of the RCA, (c) Nag particle.

particles were not replaced as recommended by the reference literature (Bastidas-Martínez et al., 2021; Bui et al., 2018; Sanchez-Cotte, 2021). Additionally, in the RCA production plants predominantly coarse particles are generated. By mass method, the replacement of 1/2″ particles equal 12.5% replacement of Nag, while 1/2"+3/8″ equals 21%. To perform the replacement by volume, the specific gravity values of Nag and RCA were considered. The required mass of Nag in each sieve was multiplied by the specific gravity ratio between RCA and Nag to obtain the new mass of RCA that would replace the Nag by volume. In total, five types of asphalt mixes were studied: (1) the Control mix (100% of Nag as aggregate); (2) mass replacement of the 1/2″ Nag aggregate fraction (HMA19-1/2-m); (3) volume replacement of the 1/2″ Nag aggregate fraction (HMA19-1/2-v); (4) mass replacement of the 1/2″ and 3/8″ Nag aggregate fraction (HMA19-1/2 + 3/8-m), and (5) volume replacement of the 1/2″ and 3/8″ Nag aggregate fraction (HMA19-1/2 + 3/8-v). A total of 105 Marshall-type samples were produced to make the corresponding designs for the five established mixes. The mixing (148-154°C) and compaction (140-144°C) temperatures were chosen following the guidelines established by the ASTM D 6925 specification (the laboratory viscosity required to obtain the mix and compaction temperatures of dense type asphalt mixtures is 150–190 cP and 250–310 cP, respectively; Rondón-Quintana & Reyes-Lizcano, 2022).

To establish the optimum asphalt binder content (OAC) for each type of mix, the volumetric composition of the mixes was determined: air voids content (*Va*), voids in the mineral aggregate (*VMA*), and voids filled with asphalt (*VFA*). Also, the resistance under monotonic loading was determined: Stability (*S*), Flow (*F*), and *S/F* ratio. This resistance was measured at a temperature of 60°C, under the application of a monotonic load at 50 mm/minute until rupture in the Marshall apparatus.

Mechanical strength tests

The mechanical performance of each mixture was measured through the following tests: Indirect Tensile Strength (ITS) test (AASHTO T 283; dry and wet conditions), indirect tension test to determine the RM (UNE-EN 12697-26), permanent deformation (UNE-EN 12697-25), indirect tension test on cylindrical samples to measure fatigue resistance under controlled-stress (UNE-EN 12697-24) and Cantabro test for HMA type mixtures (Tex-245-F).

For the ITS tests, six Marshall-type samples were made (three for dry condition and three for wet condition) per type of mix. This test consisted of measuring the ITS in dry (*ITSd*) and wet (*ITSw*) conditions of the samples, in order to calculate the TSR ratio (*ITSw/ITSd*), in percentage. The samples were made with the OAC obtained from the Marshall test and with the same volumetric composition. That is, they were not made with $Va = 7 \pm 0.5\%$ as recommended by the AASHTO T 283 specification, since it was desired to evaluate the resistance on the samples as they were obtained according to their design. Initially, the specific gravity of the mixtures (AASHTO T 209) and the height of each sample (ASTM D 3549) was determined, to later determine the Bulk specific gravity (AASHTO T 166). The wet condition of the samples was achieved with a target degree of saturation of 75-80%. After verifying saturation, the partially saturated samples were reconditioned by immersing them in a distilled water bath at 60 ± 1.0°C for 24 h. Subsequently, the temperature of the wet-conditioned samples was adjusted by placing them in a water bath at 25 ± 1.0°C for 1 h. Finally, for the development of the test, each sample was subjected to the application of monotonic load at 50 mm/minute until rupture.

The stiffness under cyclic loading of the mixtures was evaluated by means of the RM test (UNE-EN 12697-26), using a Nottingham Asphalt Tester (NAT). The RM was measured on three samples for each type of mix, applying the Haversian wave load at temperatures of 10, 20 and 30°C, and frequencies of 2.5, 5 and 10 Hz.

The permanent deformation (UNE-EN 201 UNE-EN 12697-25) was also evaluated in the NAT equipment. The test was performed on two Marshall-type specimens for each type of mix. The load applied for the test was 724 ± 14 N at a temperature of 50 °C. Likewise, the samples were subjected to quadratic loading cycles without lateral confinement, with loading and rest periods of 1 ± 0.05 s, at a frequency of 0.5 Hz, until reaching the application of 3600 cycles.

Fatigue resistance was performed using the indirect tension test on cylindrical Marshall-specimens in NAT equipment (UNE-EN 12697-24). The test was performed on nine Marshall-type specimens for each type of mixture, for a total of 45 samples. In the case of the HMA19-1/2 + 3/8-v mix, fatigue testing was only performed on mixes made with 6.0% OAC. Initially, the samples were placed in the thermostatic chamber conditioned at an ambient temperature of 20 °C for at least 4 h before the test. The test consisted of applying different cyclic loads under the controlled-stress loading mode to each of the Marshall samples. The load application frequency was 10 Hz, and material rupture was established as the failure criterion. The magnitude of the stress (σ) applied varied between 200 to 550 kPa (every 50 kPa). Based on the results obtained, a regression equation type σ-N curve (Eq. 1; Wöhler, 1858) was calculated. k_1 and b (slope of the fatigue law) are parameters obtained by regression and N is the number of failure cycles.

$$\sigma = k_1(N)^b \tag{1}$$

The Cantabro test for HMA-type mixtures allows evaluating the durability and cohesion properties through the wear loss of the mixture (Cox et al., 2017; Doyle & Howard, 2016). This test was performed with the specimens at a temperature of 19 °C without abrasive load inside the Los Angeles machine (300 revolutions at 33 revolutions per minute). Four Marshall-type specimens per mix type were used for this test. The wear loss in percent (a) for each of the specimens tested is calculated using Eq. (2).

$$a = \left[\frac{Mi - Mf}{Mi}\right] * 100 \tag{2}$$

Table 5. Design parameters.

ESALs (W_{18})	5×10^6
Initial Serviceability Index (Po)	4.2
Final Serviceability Index (Pt)	2.5
Reliability R (%)	90
Standard normal deviate (Zr)	1.282
Combined standard error of the traffic (So)	0.49

Mi is the mass of the dry specimen before the test (g), and *Mf* is the mass of the dry specimen after the test (g).

Finally, from the results of each of the above tests, an ANOVA analysis of variance with F test and 95% reliability level was performed to evaluate whether the mixtures dosed by volume (with RCA replacements by Nag in its coarse fraction) have statistically significant changes and effects with respect to the control mixture and the mixtures with RCA replacements dosed by mass.

Life cycle cost analysis (LCCA)

For the LCCA, the costs associated with the exploitation and production of materials, construction, and maintenance of asphalt pavement structures simulated for 30 years were calculated. Initially, pavement thicknesses were determined using the AASHTO (1993) methodology, which is applied in Colombia. A structure was utilized whose subgrade had a Californian Bearing Ratio (CBR) of 5% (RM = 7,500 psi according to AASHTO, 1993). Typical resilient modulus values for subbase (15,000 psi) and granular base (30,000 psi) materials were adopted according to IDU (2018) for the city of Bogotá. Two asphalt layers were used: asphalt surface and asphalt base. For the asphalt surface, the 5 cm thick Control mixture was employed. The asphalt base used the mixtures analyzed in this study (Control, HMA19-1/2- m, HMA19-1/2-v, HMA19-1/2 + 3/8-m, HMA19-1/2 + 3/8-v). The RM of the mixtures was obtained from tests performed at 20°C and a loading frequency of 10 Hz. For the design, a period of 10 years, equivalent single axle loads – ESALs of 5×10^6 and an annual growth rate of 3% were used. The general design parameters are shown in Table 5.

For the simulation and estimation of costs during the construction and maintenance of the designed pavements, the unit price analysis of the IDU (2023) for the City of Bogota at present value was used. Activities related to earthwork associated with the geometric design of the roadway were not considered. Subgrade shaping was considered, assuming that the construction would be carried out on flat ground. Likewise, this study did not consider activities related to infrastructure elements (e.g. slope stabilization, signaling, drainage works, among others). Only activities for the construction of granular layers (subbase, base), asphalt mixtures (asphalt surface and asphalt base), and bonding and priming irrigation were considered. For 30-year maintenance, restoration activities such as crack sealing and application of asphalt slurry every two years were contemplated. Furthermore, milling of the existing asphalt layer and construction of an overlay every 10 years were considered.

Results

Asphalt mix design – marshall test

The results of the Marshall test are shown in Figures 3(a)–(f). Following the design criteria established by IDU (2018) and INVIAS (2022), the OACs of each mix are as follows: Control = 5.5%; HMA19-1/2-m = 6.0%; HMA19-1/2-v = 5.5%; HMA19-1/2 + 3/8-m = 6.5% and HMA19-1/2 + 3/8-v = 6.5% (however, for this last mix, the percentage of 6.0% was also taken because of the results obtained). In general terms, the volumetric composition results agree with what is widely evidenced in the reference literature: the RCA generated more porous mixtures (higher *Va*, *VMA*, and lower *VFA*) with respect to the Control mixture (except for the HMA19-1/2-v mixture), as more substitution was performed.

Table 6. ITS test results.

Mixture	OAC (%)	*Va* (%)	*ITSd* (kPa)	*ITSw* (kPa)	TSR (%)
Control	5.5	5.3 ± 0.6	952.1	829.3	87.1
HMA19-1/2-m	6.0	5.8 ± 0.5	1273.4	1098.8	86.3
HMA19-1/2 + 3/8-m	6.5	4.6 ± 0.5	1370.9	1156.9	84.4
HMA19-1/2-v	5.5	5.1 ± 0.3	1390.3	943.4	67.9
HMA19-1/2 + 3/8-v	6.0	6.3 ± 0.4	1290.1	936.4	72.6
HMA19-1/2 + 3/8-v	6.5	5.3 ± 0.2	1536.2	1317.8	85.8

This is mainly due to the higher absorption of RCA and bonded mortar (Sanchez-Cotte, 2021; Sanchez-Cotte et al., 2020; Tahmoorian et al., 2022). This generated an increase in the OAC of the mixes with RCA (except for the HMA19-1/2-v mix). The best performance with RCA was obtained with the HMA19-1/2-v mix. The tendency of this mix in most of the asphalt contents was to undergo similar porosity and higher resistance under monotonic loading (higher *S* and *S/F*) compared to the Control mix. Additionally, the OAC of HMA19-1/2-v mix was the same (5.5%). At this asphalt content, the response of the HMA19-1/2-v mix was like that of the Control. There is no clear explanation for the observed phenomenon. However, dosing by volume tends to decrease the number of particles to be coated with asphalt binder (Martinez-Arguelles et al., 2019; Sanchez-Cotte, 2021).

On the other hand, the general tendency of the RCA mixes, in most of the asphalt binder contents, was to undergo higher resistance under monotonic loading (*S/F*) compared to the Control mix. This was despite the higher porosity of the RCA mixes and the lower resistance of these particles to abrasive wear and fracturing compared to the Nag. However, the good geometry (larger fractured faces and smaller flat and elongated particles), the higher absorption, and the rough texture of the RCA particles could generate an intergranular skeleton that helped to increase the internal cohesion of the mix and better resist monotonic loading.

There is also no clear trend in the results concerning the method of substitution (mass and volume). In general, when 1/2″ particles were substituted by mass, the mixtures undergo higher porosity. However, when 1/2"+3/8″ particles were substituted, the volumetric composition was similar concerning the dosage by volume. Concerning strength under monotonic loading, performance varied depending on the asphalt content. However, most of the time, the strength was higher in the mixes proportioned by volume. The lack of a clear trend in the results can be attributed mainly to the heterogeneity of the RCA (Bastidas-Martínez et al., 2022; Sanchez-Cotte et al., 2020).

ITS test

The results of the ITS test are shown in Table 6. An increase in the ITS (higher *ITSd* e *ITSw*) of the mixtures that used RCA is observed. These increases were greater when the content of Nag substituted by RCA increased. This is mainly due to the possible increase in adhesion generated by the combination of a higher porosity (Figure 2) and absorption material (RCA) and the increase in asphalt binder content. Additionally, materials with a greater CaO/SiO_2 ratio display a stronger bond with asphalt binders and the interfacial energy and adhesion work of the asphalt components with mineral aggregates is greater (Rondón-Quintana et al., 2023; Xie et al., 2012). The above could explain the greater ITS obtained in the HMA mix with RCA (adhered mortar has higher Ca/Si content respect to Nag; see Table 3).

Based on ANOVA analysis, these increases are statistically significant ($F > F_{0.05} = 7.71$; see Table 7). For the dry condition, it was determined that the HMA19-1/2-m and HMA19-1/2 + 3/8-m mixes have statistically significant effects concerning the Control mix. However, there were no statistical effects when analyzing the mixes dosed by mass concerning those by volume ($F < F_{0.05}$). For the wet condition, there were statistically significant effects for the mixtures dosed in volume and mass.

With the OAC determined from the Marshall test, the RCA mixes proportioned by a mass undergo similar TSR regarding the control mix (similar resistance to moisture damage). As in the Marshall test,

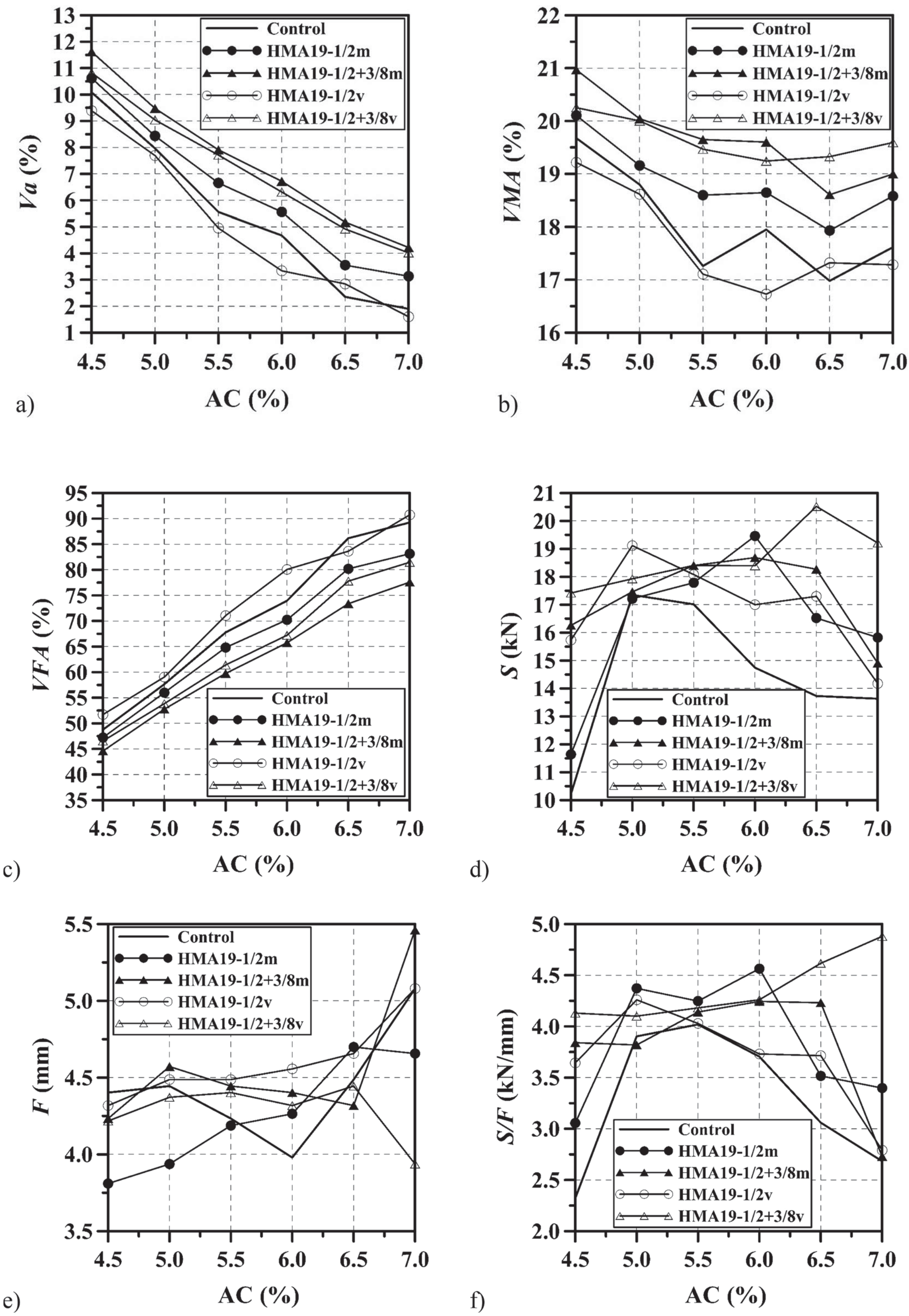


Figure 3. Evolution of (a) *Va*, (b) *VMA*, (c) *VFA*, (d) *S*, (e) *F*, (f) *S/F* with AC content.

Table 7. ANOVA data – F values (ITS test).

Mixture		F (*ITSd*) 1	2	3	4	5	6	F (*ITSw*) 1	2	3	4	5	6
Control	1	–	12.7	9.2	15.1	18.7	45.5	–	22.7	20.3	25.7	24.6	55.2
HMA19-1/2-m	2	12.7	–	8.4	6.5	3.7	20.6	22.7	–	10.2	21.6	22.6	33.3
HMA19-1/2 + 3/8-m	3	9.2	8.4	–	1.7	6.6	7.6	20.3	10.2	–	13.4	15.2	28.8
HMA19-1/2-v	4	15.1	6.5	1.7	–	7	22.5	25.7	21.6	13.4	–	2.2	43.8
HMA19-1/2 + 3/8-v (6.0%)	5	18.7	3.7	6.6	7	–	32.1	24.6	22.6	15.2	2.2	–	45.9
HMA19-1/2 + 3/8-v (6.5%)	6	45.5	20.6	7.6	22.5	32.1	–	55.2	33.3	28.8	43.8	45.9	–

the HMA19-1/2-v mix undergo higher *ITSd* and *ITSw* considering the control mix, while maintaining the same OAC. However, a noticeable decay of the TSR is observed, indicating a possible decrease in resistance to moisture damage, which could be improved by adding more asphalt binder. This same behavior is observed in the HMA19-1/2 + 3/8- mix when it was made with 6.0% asphalt. The best performance in the test (higher *ITSd*, *ITSw* and similar TSR respecting control mix) is observed when HMA19-1/2 + 3/8-v is made with the OAC obtained from the Marshall test (6.5%). Regarding the dosage form, the ITS tends to be higher when the Nag is replaced by RCA by volume, except for the case of the *ITSw* of the HMA19-1/2-v, perhaps due to an insufficiency in the asphalt content as mentioned above.

Resilient modulus and permanent deformation

RM and permanent deformation are tests used to measure rutting resistance under cyclic loading (Pasandín & Pérez, 2014; Rondón-Quintana & Reyes-Lizcano, 2022). Figures 4(a)–(c) show the RM test results. The general trend of the asphalt mixes was to undergo higher RM (under any temperature) when Nag was substituted for RCA. Additionally, these increases were greater with increasing substitution content. On the other hand, the highest stiffness under cyclic loading is obtained when Nag is substituted for RCA by volume. Even the highest stiffness was obtained when 1/2″+3/8″ particles were substituted in volume and an asphalt binder content of 6.0% was used (approximate increases of 10.8 ± 3.1%, 16.6 ± 3.8% and 28.4 ± 5.6% for temperatures of 10, 20 and 30°C, respectively). By adding higher asphalt content (6.5%) to the same HMA19-1/2 + 3/8v mix, the modulus decreases due to the increase in the asphalt binder. The results obtained are consistent with the *S/F* ratio obtained from the Marshall test and are explained based on the results of that test. Additionally, these increases in modulus may be due to the lower specific gravity of the RCA, since higher particle content is required when replacing the Nag, increasing the number of contacts and interlocking in the mineral skeleton (Martinez-Arguelles et al., 2019), and thus, the internal cohesion of the mixture.

Based on ANOVA analysis (Table 8), the increases denoted in the modulus of the mixtures with RCA are significant concerning the Control mixture ($F > F_{0.05}$) for temperature of 30°C and any frequency (except HMA19-1/2 m). At 10 and 20°C, changes are generally significant when replacing by volume (HMA19-1/2v and HMA19-1/2 + 3/8-v 6.5%). When comparing mass and volume replacement methods, no statistically significant changes in modulus are observed.

The results of the permanent deformation test are shown in Figure 5. Mixtures with RCA tend to be more resistant to rutting in high-temperature climates (except for the HMA-19-1/2 + 3/8-v 6.5% mixture). These results are consistent with those obtained from the Marshall test and RM (usually higher resistance to permanent deformation is obtained when RM and *S/F* ratio are higher) (Martinez-Arguelles et al., 2019). Additionally, higher friction and the number of intergranular contacts could help to decrease the displacement undergo by the mixtures under cyclic loading. Regarding the type of substitution, there is no clear trend. When 1/2″ particles are substituted by volume, the mix undergo higher resistance to permanent deformation compared to when substituted by mass. However, when 1/2″ and 3/8″ particles are substituted, the test performance is similar. The highest resistance to rutting

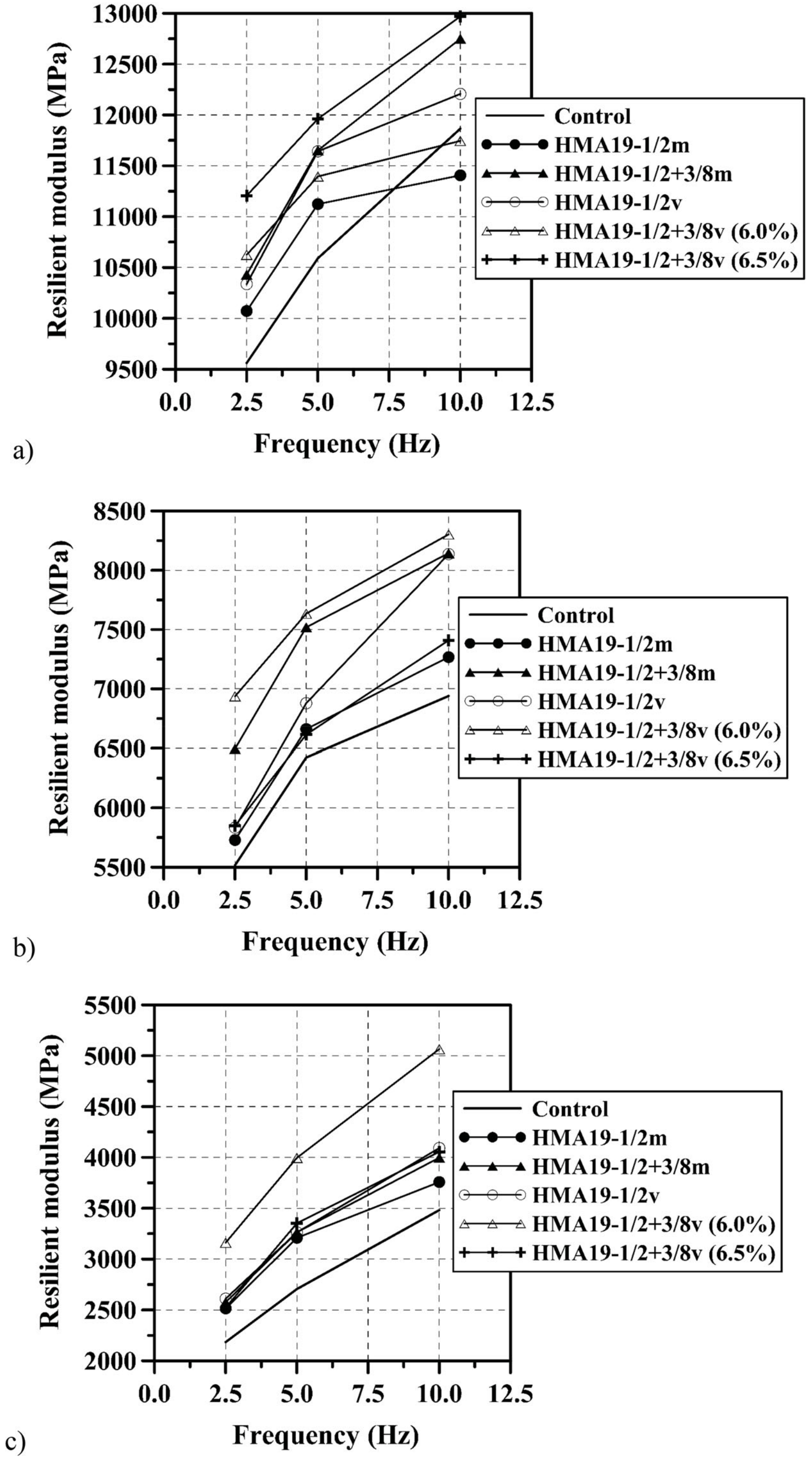


Figure 4. Resilient modulus at (a) 10°C, (b) 20°C, (c) 30°C.

Table 8. ANOVA data – F values (resilient modulus).

Mixture		F					
	1	2	3	4	5	6	
		T = 10 °C, F = 2.5 Hz					
Control	1	–	2.4	3.0	11.0	0.9	7.2
HMA19-1/2-m	2	2.4	–	0.4	0.5	0.2	2.8
HMA19-1/2 + 3/8-m	3	3.0	0.4	–	0.03	0.02	1.0
HMA19-1/2-v	4	11.0	0.5	0.03	–	0.06	1.9
HMA19-1/2 + 3/8-v (6.0%)	5	0.9	0.2	0.02	0.06	–	0.2
HMA19-1/2 + 3/8-v (6.5%)	6	7.2	2.8	1.0	1.9	0.2	–
		T = 10 °C, F = 5.0 Hz					
Control	1	–	1.8	2.7	26.5	0.8	15.4
HMA19-1/2-m	2	1.8	–	0.5	1.8	0.8	3.0
HMA19-1/2 + 3/8-m	3	2.7	0.5	–	0.01	0.05	0.2
HMA19-1/2-v	4	26.5	1.8	0.01	–	0.07	0.9
HMA19-1/2 + 3/8-v (6.0%)	5	0.8	0.8	0.05	0.07	–	0.3
HMA19-1/2 + 3/8-v (6.5%)	6	15.4	3.0	0.2	0.9	0.3	–
		T = 10 °C, F = 10.0 Hz					
Control	1	–	0.6	1.8	3.9	0.02	13.1
HMA19-1/2-m	2	0.6	–	2.3	1.7	0.9	5.5
HMA19-1/2 + 3/8-m	3	1.8	2.3	–	0.7	0.7	0.1
HMA19-1/2-v	4	3.9	1.7	0.7	–	0.2	5.4
HMA19-1/2 + 3/8-v (6.0%)	5	0.02	0.9	0.7	0.2	–	1.4
HMA19-1/2 + 3/8-v (6.5%)	6	13.1	5.5	0.1	5.4	1.4	–
		T = 20 °C, F = 2.5 Hz					
Control	1	–	0.2	3.4	0.6	3.0	0.6
HMA19-1/2-m	2	1.6	–	4.0	0.3	2.7	0.35
HMA19-1/2 + 3/8-m	3	7.9	4.0	–	3.3	0.3	3.1
HMA19-1/2-v	4	7.2	0.3	3.3	–	2.3	0.01
HMA19-1/2 + 3/8-v (6.0%)	5	3.8	2.7	0.3	2.3	–	2.2
HMA19-1/2 + 3/8-v (6.5%)	6	6.5	0.35	3.1	0.01	2.2	–
		T = 20 °C, F = 5.0 Hz					
Control	1	–	1.0	10.2	9.0	2.1	4.4
HMA19-1/2-m	2	1.0	–	4.3	0.6	1.3	0.03
HMA19-1/2 + 3/8-m	3	10.2	4.3	–	3.0	0.02	6.8
HMA19-1/2-v	4	9.0	0.6	3.0	–	0.8	2.6
HMA19-1/2 + 3/8-v (6.0%)	5	2.1	1.3	0.02	0.8	–	1.5
HMA19-1/2 + 3/8-v (6.5%)	6	4.4	0.03	6.8	2.6	1.5	–
		T = 20 °C, F = 10.0 Hz					
Control	1	–	2.4	17.0	792.2	2.8	65.8
HMA19-1/2-m	2	2.4	–	6.0	16.6	1.6	0.4
HMA19-1/2 + 3/8-m	3	17.0	6.0	–	0.01	0.03	6.1
HMA19-1/2-v	4	792.2	16.6	0.01	–	0.04	115.8
HMA19-1/2 + 3/8-v (6.0%)	5	2.8	1.6	0.03	0.04	–	1.2
HMA19-1/2 + 3/8-v (6.5%)	6	65.8	0.4	6.1	115.8	1.2	–
		T = 30 °C, F = 2.5 Hz					
Control	1	–	2.3	5.7	7.0	11.3	4.4
HMA19-1/2-m	2	4.8	–	0.2	0.4	5.2	0.01
HMA19-1/2 + 3/8-m	3	69.6	0.2	–	0.7	5.7	1.7
HMA19-1/2-v	4	156.6	0.4	0.7	–	5.1	11.8
HMA19-1/2 + 3/8-v (6.0%)	5	16.0	5.2	5.7	5.1	–	6.9
HMA19-1/2 + 3/8-v (6.5%)	6	109.4	0.01	1.7	11.8	6.9	–

(continued).

Table 8. Continued.

T = 30 °C, F = 5.0 Hz							
Control	1	–	4.7	84.4	9.0	10.9	163.4
HMA19-1/2-m	2	4.7	–	0.06	0.03	3.0	0.4
HMA19-1/2 + 3/8-m	3	84.4	0.06	–	0.01	3.5	2.1
HMA19-1/2-v	4	9.0	0.03	0.01	–	2.9	0.2
HMA19-1/2 + 3/8-v (6.0%)	5	10.9	3.0	3.5	2.9	–	2.7
HMA19-1/2 + 3/8-v (6.5%)	6	163.4	0.4	2.1	0.2	2.7	–
T = 30 °C, F = 10.0 Hz							
Control	1	–	0.9	43.3	75.1	15.7	124.4
HMA19-1/2-m	2	0.9	–	0.7	1.3	7.1	1.1
HMA19-1/2 + 3/8-m	3	43.3	0.7	–	1.2	7.0	0.6
HMA19-1/2-v	4	75.1	1.3	1.2	–	5.9	0.3
HMA19-1/2 + 3/8-v (6.0%)	5	15.7	7.1	7.0	5.9	–	6.4
HMA19-1/2 + 3/8-v (6.5%)	6	124.4	1.1	0.6	0.3	6.4	–

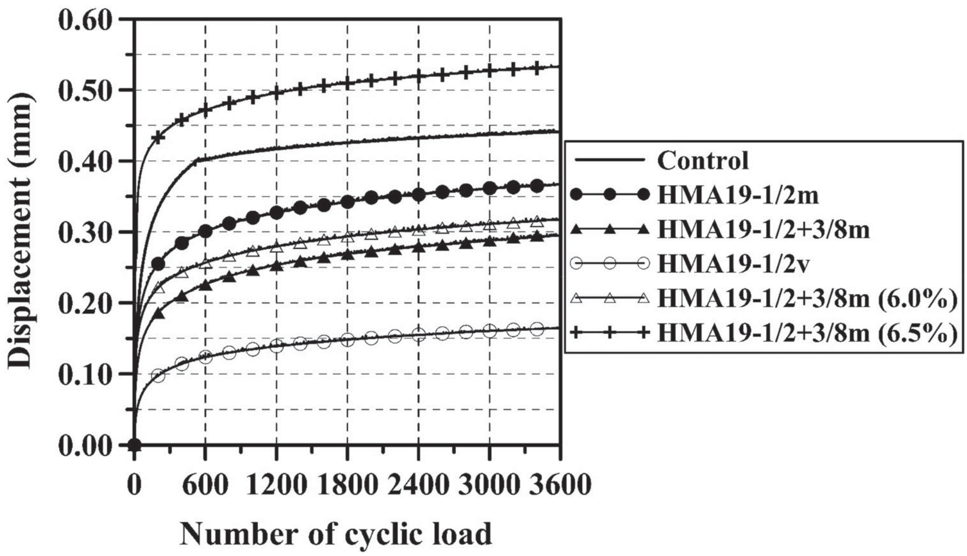


Figure 5. Evolution of permanent displacement.

is observed when 1/2″ particles are substituted by volume. The mix that shows the greatest accumulated axial deformation is the HMA19-1/2 + 3/8-v mix with 6.5% asphalt binder. This is mainly because this mix contains higher asphalt content (Pasandín & Pérez, 2014).

Cantabro test

The results of the Cantabro test are shown in Table 9. According to the Tex-245-F standard, the test allows empirical evaluation of the mix's resistance to disintegration before the abrasive effects caused by traffic. The RCA mixes show higher resistance to abrasive wear compared to the Control mix. This is even though the RCA has lower resistance than the Nag in the Los Angeles machine, Micro-Deval, and 10% fines tests. However, the mixes with RCA have higher asphalt content, which could help improve the response in terms of cohesion and adhesion. The mixes that presented the greatest wear were the Control mix and those where the Nag was replaced by RCA by mass. In general terms, the best performance in the test is observed in the mixes that are substituted by volume the Nag for RCA (except for the HMA19-1/2-v mix in which high wear is observed, perhaps due to the lack of asphalt binder).

Table 9. Cantabro test results.

Mixture	OAC (%)	*a* (%)
Control	5.5	37.4 ± 4.86
HMA19-1/2-m	6.0	21.8 ± 1.91
HMA19-1/2 + 3/8-m	6.5	16.52 ± 1.08
HMA19-1/2-v	5.5	27.87 ± 1.80
HMA19-1/2 + 3/8-v	6.0	15.41 ± 0.08
HMA19-1/2 + 3/8-v	6.5	11.24 ± 0.45

Table 10. ANOVA data – F values (Cantabro test).

		F					
Mixture		1	2	3	4	5	6
Control	1	–	26.9	53.0	10.3	61.7	86.5
HMA19-1/2-m	2	26.9	–	17.4	15.9	33.5	86.9
HMA19-1/2 + 3/8-m	3	53.0	17.4	–	87.3	3.1	60.8
HMA19-1/2-v	4	10.3	15.9	87.3	–	142.7	240.0
HMA19-1/2 + 3/8-v	5	61.7	33.5	3.10	142.7	–	249.5
HMA19-1/2 + 3/8-v	6	86.5	86.9	60.8	240.0	249.5	–

This is mainly since when replacing by volume the RCA particles in the mix decrease and therefore the adhered mortar (material more prone to wear by abrasion).

The greater resistance of the RCA mixtures compared to the Control is statistically significant according to the ANOVA analysis ($F > F_{0.05} = 5.99$; see Table 10). When comparing the mass and volume replacement methods, significant changes in the parameter *a* are also observed.

Fatigue resistance

The results of the fatigue tests under controlled-stress are shown in Figure 6. Eq. (1) was used to extrapolate the results and extend them in order to present the trend over a wider range of stresses. The R-squared (r^2) of the test results, the slope of the fatigue law (*b*), and the amplitude of the stress required for the material to fail at 10^6 and 10^7 cycles load (σ_6 and σ_7, respectively) are presented in Table 11. It is observed that the mixtures with RCA undergo higher fatigue resistance (higher σ_6 and σ_7; Bastidas-Martínez & Rondón-Quintana, 2020), and increases when the substitution content increases. Similar conclusions have been obtained by other researchers (Nejad et al., 2013; Pérez & Pasandín, 2017). The higher strength is mainly attributed to the higher asphalt binder content (Nwakaire et al., 2020), and to the more angular geometry of the RCA particles, as well as their higher surface texture and porosity (Figure 2). Additionally, Ca/Si ratio is higher in the adhered mortar of RCA (Table 3) compared to Nag, improving aspects associated with the cohesion and adhesion of the asphalt mix (Bastidas-Martínez et al., 2022a; Rondón-Quintana et al., 2023). On the other hand, under the controlled-stress loading mode, stiffer mixtures with higher ITS tend to undergo higher fatigue strength (Bastidas-Martínez et al., 2022; Bharath et al., 2021; Muniz de Farias et al., 2018a). Regarding the way of substitution, the results are not clear, since under 10^6 cycles of loading, the highest fatigue strength was obtained when Nag particles were substituted by RCA by mass (higher σ_6), but under 10^7 cycles the behavior changes (σ_7 is higher when the substitution is performed by volume).

Summary of the results

To observe the results qualitatively and conclude, Table 12 was prepared. The numbers in the Table mean 1: higher value, and 6: lower value. The best performances are obtained when *S/F*, *ITSd*, *ITSw*, *RM*, TSR, σ_6, σ_7, tend to 1, and when Displacement and *a* tend to 6. NA means 'not applicable' because the test was not performed. The highest strength values under monotonic loading in Marshall test (S/F), indirect tension (ITSd and ITSw) test, and abrasive wear in Cantabro test are observed in the

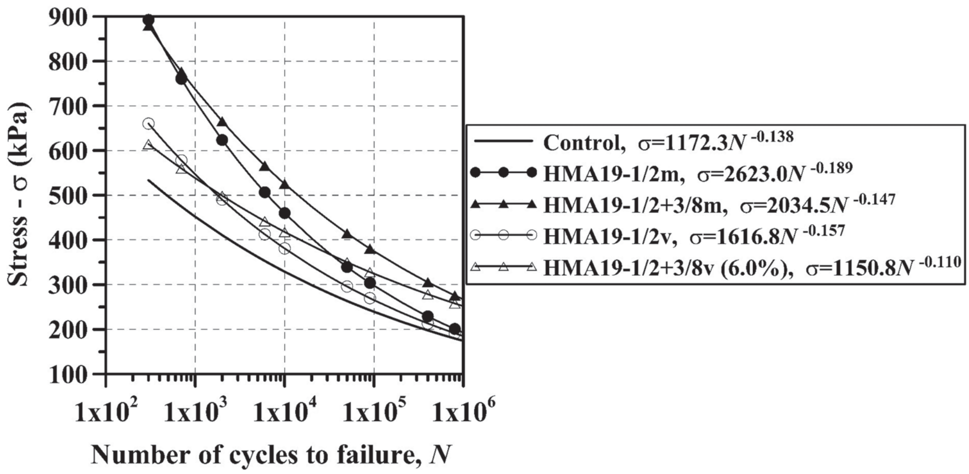


Figure 6. Fatigue test results.

Table 11. σ_6, σ_7 and b parameters.

Mixture	OAC (%)	r^2	b	σ_6 (kPa)	σ_7 (kPa)
Control	5.5	0.916	−0.138	174.20	126.78
HMA19-1/2-m	6.0	0.900	−0.189	192.66	124.68
HMA19-1/2 + 3/8-m	6.5	0.846	−0.147	266.97	190.31
HMA19-1/2-v	5.5	0.854	−0.157	184.74	128.72
HMA19-1/2 + 3/8-v	6.0	0.878	−0.110	251.77	195.43

Table 12. Summary of results.

Mixture	*S/F*	*ITSd*	*ITSw*	TSR	RM	σ_6	σ_7	Displacement	*a*
Control (5.5%)	6	6	6	1	6	5	4	2	1
HMA19-1/2-m (6.0%)	3	5	3	2	5	3	5	3	3
HMA19-1/2 + 3/8-m (6.5%)	4	3	2	4	2	1	2	5	4
HMA19-1/2-v (5.5%)	5	2	4	6	3	4	3	6	2
HMA19-1/2 + 3/8-v (6.0%)	2	4	5	5	1	2	1	4	5
HMA19-1/2 + 3/8-v (6.5%)	1	1	1	3	4	NA	NA	1	6

HMA19-1/2 + 3/8-m mix (6.5%). Likewise, under cyclic loading, the highest stiffness (RM) and fatigue strength (σ_6, σ_7) is presented in HMA19-1/2 + 3/8-m (6.0%), while the highest resistance to permanent deformation is evidenced in HMA19-1/2-v (5.5%). Better performance is observed when substitution is done by volume.

Life cycle cost analysis

The thicknesses of the pavement layers using the Control mix and the RCA mixes are presented in Figure 7. The use of RCA mixes reduces the pavement base asphalt thickness. This reduction is greater for the pavement with the HMA19-1/2 + 3/8-v mix (6.0%). This is attributed to the higher stiffness of this mix in the RM tests.

The manufacturing costs of the asphalt mixtures (Control, HMA19-1/2-m, HMA19-1/2-v, HMA19-1/2 + 3/8-m, HMA19-1/2 + 3/8-v), as well as the construction and maintenance costs of the pavement for the conditions established in this study are presented in Figures 8–9. The results indicate that the cost of asphalt mixes increases with the incorporation of RCA between approximately 1.0% to 8.5%, which is mainly attributed to the increase in asphalt content. Likewise, the processes of classification,

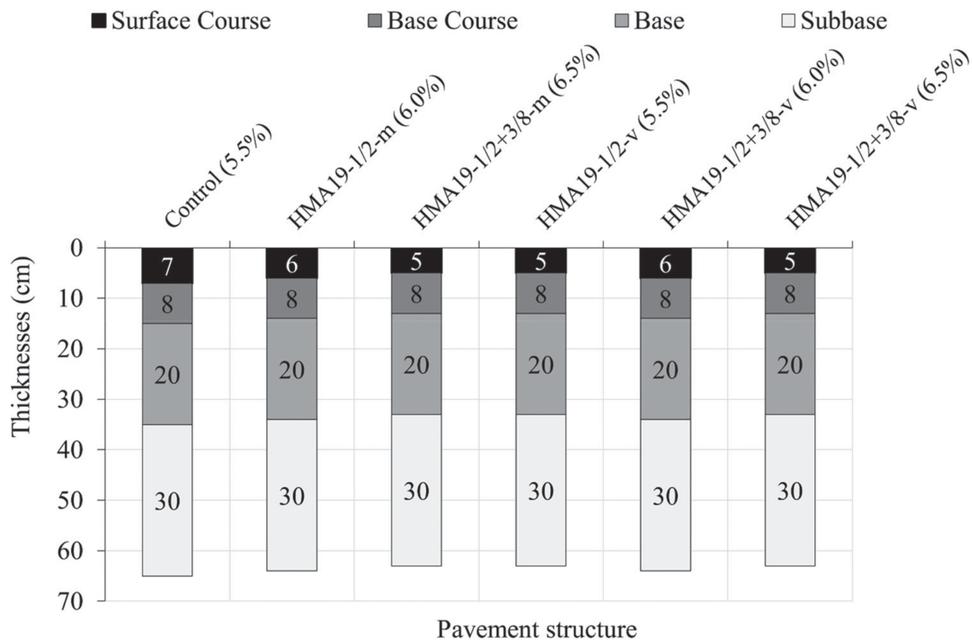


Figure 7. Pavement design thicknesses.

separation, and transformation of RCA increase the manufacturing costs of mixes with this residue. However, the reduction of pavement thicknesses leads to lower construction costs of RCA pavements by approximately 1.0% to 6.0%.

The pavements with HMA19-1/2-v and HMA19-1/2 + 3/8-v (6.0%) presented higher maintenance costs compared to the pavement with the Control mix. These results are attributed to the lower structural capacity (higher relative damage) due to its lower mechanical performance. This leads to the development of a larger cracked area and increased costs associated with restoration activities. These pavements exhibit higher costs during their life cycle. Contrary to the above, pavements with HMA19-1/2-m (6.0%), HMA19-1/2 + 3/8-m (6.5%), and HMA19-1/2 + 3/8-v (6.0%) showed lower total costs (construction and maintenance) to the Control mix (Figures 10–11).

Conclusions

The present study evaluated the behavior of an HMA mix type HMA-19 when the coarse fraction of the Nag is partially replaced (by mass and by volume) by RCA. Based on the results obtained, it is concluded:

- RCA has higher abrasion wear and lower resistance to particle fracture compared to Nag. Despite the above, RCA met the quality requirements for HMA-19 mixes subjected to low and medium traffic volumes.
- The higher porosity and lower specific gravity of RCA particles compared to Nag generate the need to increase the OAC in mixtures, especially when substituted by mass. However, substitution by volume could help to decrease the asphalt binder content.
- By partially replacing the coarse fraction of Nag with RCA (both by mass and volume), the HMA-19 mixes met the volumetric and strength parameters established by the IDU (2018) and INVIAS (2022) standards, making their use feasible (especially for roads with low traffic volumes).

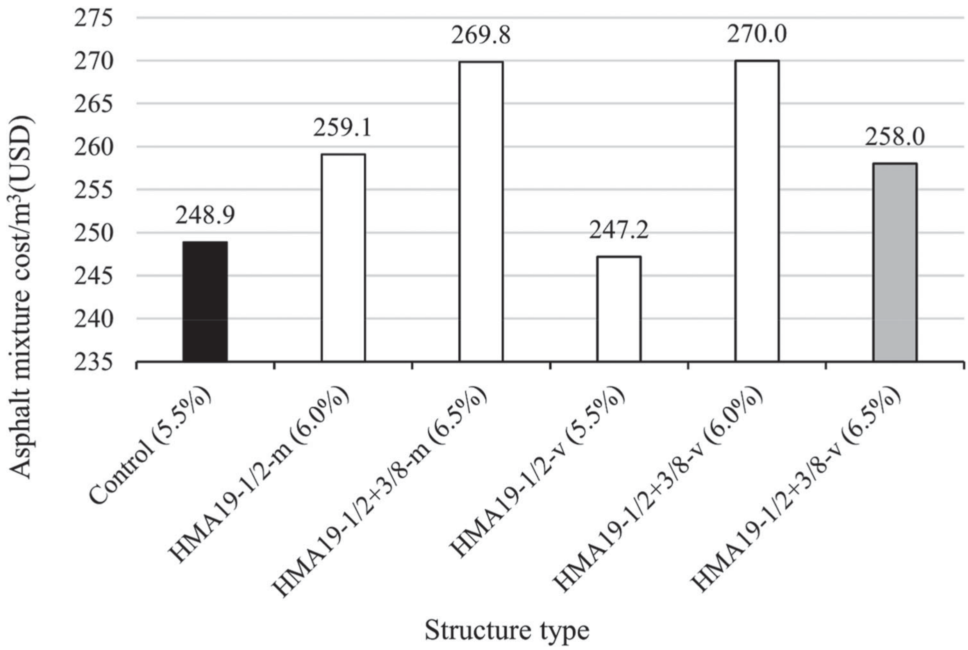


Figure 8. Asphalt mixture cost.

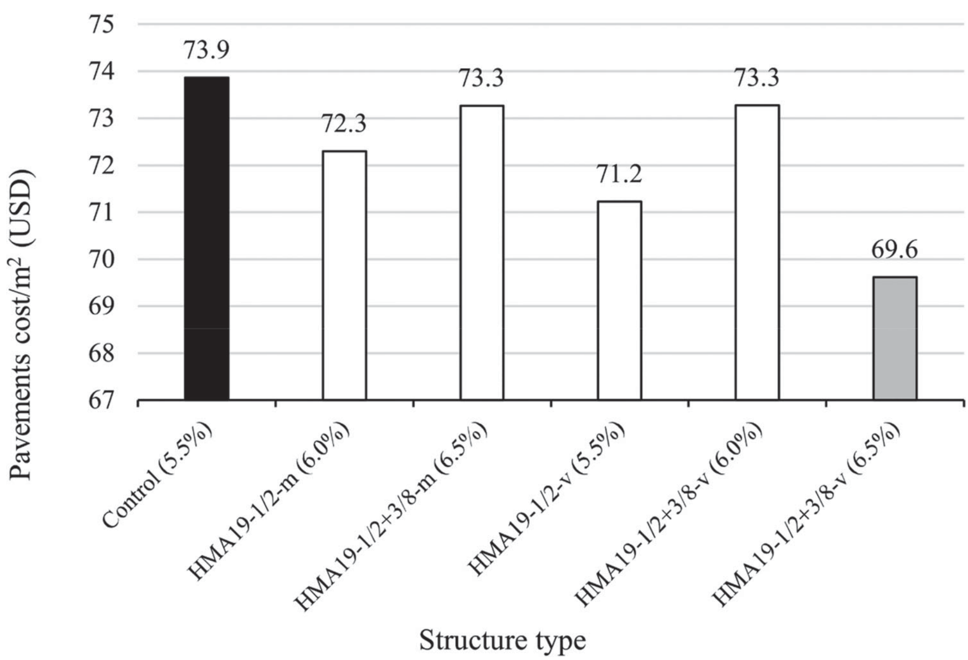


Figure 9. Pavement costs.

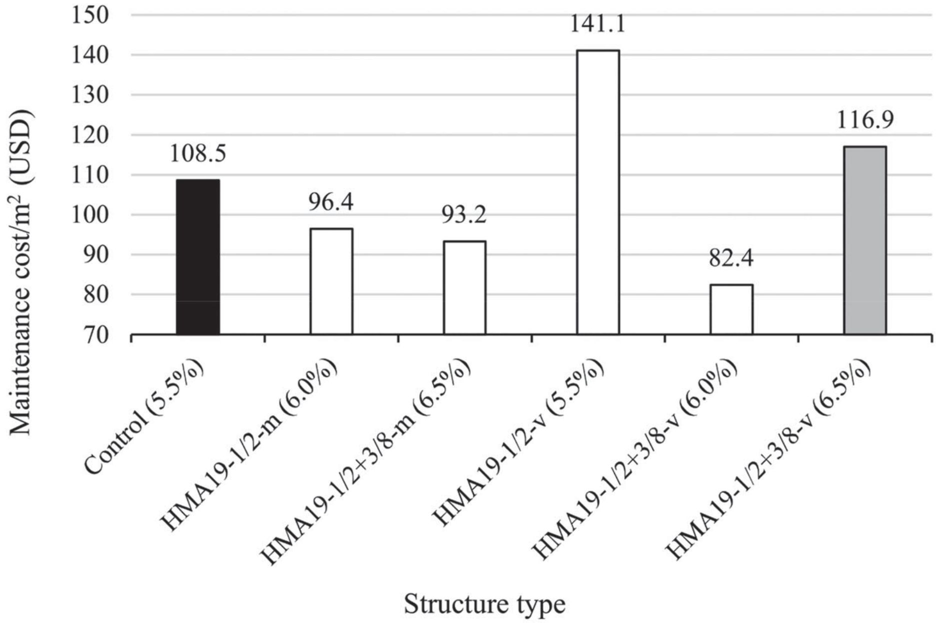


Figure 10. Maintenance cost.

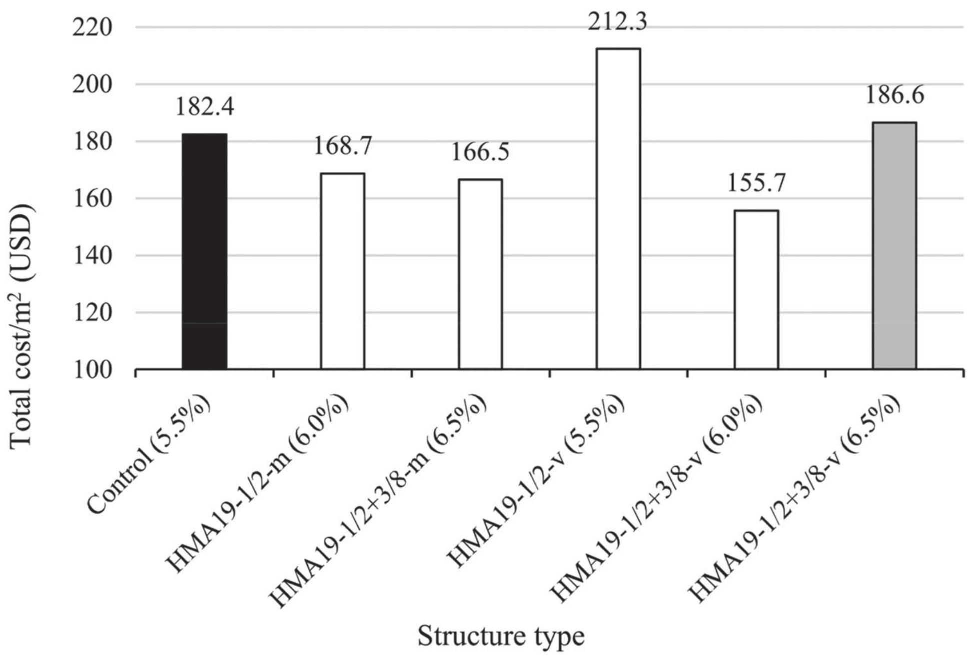


Figure 11. Total cost.

- In general terms, the substitution of Nag by RCA generated mixtures with better mechanical performance since: (i) increased resistance under monotonic (higher *S/F*, *ITSd*, *ITSw*) and cyclic loading (higher *RM*, resistance to permanent deformation and fatigue); (ii) increased resistance to abrasive wear. The above, generally when the percentage of substitution increased (1/2″+3/8″) and the substitution is done by volume.
- Most of the RCA mixes undergo similar resistance to moisture damage as the Control mix. However, this resistance can be compromised when dosing by volume as the asphalt binder content decreases.
- With respect to the method of substitution (mass or volume), there is no clear trend in the resistance results obtained, since several variables are involved, such as asphalt binder content and RCA heterogeneity, among others. However, the general tendency is to undergo better performance when the dosing is done by volume.
- According to the LCCA, the manufacturing costs of RCA mixes increase due to the increase in asphalt content and the cost associated with the treatment for the production of RCA. However, increases in stiffness allow optimizing the thickness of the asphalt layer, obtaining lower construction costs. Adding to the above, the analysis of the costs associated with maintenance, the use of RCA in asphalt mixes can be viable from the technical and economic point of view, mainly when replacing the 1/2 + 3/8 fractions by volume (HMA19-1/2 + 3/8-m 6.5%).
- Some recommendations for future studies are: (i) evaluate the influence of the type of substitution (mass or volume) keeping the asphalt content constant (in order to facilitate the analysis of the results); (ii) extend the present study by conducting tests that measure the effect of aging, long-term performance and skid resistance; (iii) increase the substitution content; (iv) use mixtures with other gradations and types of asphalt binder; (v) conduct full-scale tests; (vi) conduct life cycle analyses and economic-environmental impact studies; (vii) evaluate phenomena of attrition, crushing and abrasion during the manufacturing process on plant.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

Some or all data, models, or code generated or used during the study are available from the corresponding author by request.

References

Agrela, F., Díaz-López, J. L., Rosales, J., Cuenca-Moyano, G. M., Cano, H., & Cabrera, M. (2021). Environmental assessment, mechanical behavior and new leaching impact proposal of mixed recycled aggregates to be used in road construction. *Journal of Cleaner Production*, *280*, 124362. https://doi.org/10.1016/j.jclepro.2020.124362

Al-Bayati, H. A. K., & Tighe, S. L. (2019). Effect of recycled concrete aggregate on rutting and stiffness characteristics of asphalt mixtures. *Journal of Materials in Civil Engineering*, *31(10)*(10), 04019219. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002810

Alnedawi, A., & Rahman, M. A. (2021). Recycled concrete aggregate as alternative pavement materials: Experimental and parametric study. *Journal of Transportation Engineering, Part B: Pavements*, *147*(1), 04020076. https://doi.org/10.1061/jpeodx.0000231

American Association of State Highway and Transportation Officials (AASHTO). (1993). *AASHTO guide for design of pavement structures*. American Association of State Highway and Transportation Officials.

Arabani, M. (2011). Effect of glass cullet on the improvement of the dynamic behaviour of asphalt concrete. *Construction and Building Materials*, *25*(3), 1181–1185. https://doi.org/10.1016/j.conbuildmat.2010.09.043

Arabani, M., & Azarhoosh, A. R. (2012). The effect of recycled concrete aggregate and steel slag on the dynamic properties of asphalt mixtures. *Construction and Building Materials*, *35*, 1–7. https://doi.org/10.1016/j.conbuildmat.2012.02.036

Balaguera, A., Carvajal, G. I., Albertí, J., & Fullana-i-Palmer, P. (2018). Life cycle assessment of road construction alternative materials: A literature review. *Resources, Conservation and Recycling*, *132*, 37–48. https://doi.org/10.1016/j.resconrec.2018.01.003

Bastidas-Martinez, J. G., Camapum de Carvalho, J., Cristhiane, L. L., Muniz de Farias, M., & Rondón-Quintana, H. A. (2022a). Effects of iron ore tailing on performance of hot-mix asphalt. *Journal of Materials in Civil Engineering*, *34*(1), 04021405. https://doi.org/10.1061/(ASCE)MT.1943-5533.0004034

Bastidas-Martínez, J. G., Reyes-Lizcano, F. A., & Rondón-Quintana, H. A. (2022). Use of recycled concrete aggregates in asphalt mixtures for pavements: A review. *Journal of Traffic and Transportation Engineering (English Edition)*, *9*(5), 725–741. https://doi.org/10.1016/j.jtte.2022.08.001

Bastidas-Martínez, J. G., & Rondón-Quintana, H. A. (2020). *Caracterización de mezclas de concreto asfáltico*. Universidad Piloto de Colombia. Bogotá D.C., Colombia.

Bastidas-Martínez, J. G., Rondón-Quintana, H. A., Contreras-Zartha, L., Forero-Castaño, S., & Rojas-Rozo, L. (2021). Evaluación de una mezcla de concreto asfáltico con incorporación de agregados reciclados de concreto. *Revista UIS Ingenierías*, *20*(2), 75–84. https://doi.org/10.18273/revuin.v20n2-2021007

Bharath, G., Reddy, K. S., Tandon, V., & Reddy, M. A. (2021). Aggregate gradation effect on the fatigue performance of recycled asphalt mixtures. *Road Materials and Pavement Design*, *22*(1), 165–184. https://doi.org/10.1080/14680629.2019.1620116

Bui, N. K., Satomi, T., & Takahashi, H. (2018). Mechanical properties of concrete containing 100% treated coarse recycled concrete aggregate. *Construction and Building Materials*, *163*, 496–507. https://doi.org/10.1016/j.conbuildmat.2017.12.131

Castaño, J. O., Rodríguez, R. M., Lasso, L. A., Gómez-Cabrera, A., & Ocampo, M. S. (2013). Gestión de residuos de construcción y demolición (CDW) en bogotá: Perspectivas y limitantes. *Revista Tecnura*, *17*(38), 121–129. https://doi.org/10.14483/udistrital.jour.tecnura.2013.4.a09

Cox, B. C., Smith, B. T., Howard, I. L., & James, R. S. (2017). State of knowledge for cantabro testing of dense graded asphalt. *Journal of Materials in Civil Engineering*, *29*(10), 04017174. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002020

Doyle, J., & Howard, I. (2016). Characterization of dense-graded asphalt with the cantabro test. *Journal of Testing and Evaluation*, *44*(1), 77–88. https://doi.org/10.1520/JTE20140212

Gabr, A. R., & Cameron, D. A. (2012). Properties of recycled concrete aggregate for unbound pavement construction. *Journal of Materials in Civil Engineering*, *24*(6), 754–764

Instituto de Desarrollo Urbano (IDU). (2018). *Especificaciones técnicas generales de materiales y construcción*. para proyectos de infraestructura vial y de espacio público.

Instituto de Desarrollo Urbano (IDU). (2023, december 15). *Precios Unitarios de Referencia 2023-I Fase II + M.O. Ley 2101 de 2021*. https://www.idu.gov.co/page/siipviales/economico/portafolio

Instituto Nacional de Vías (INVIAS). (2022). *Especificaciones generales de construcción de carreteras*.

Jin, R., & Chen, Q. (2019). Overview of concrete recycling legislation and practice in the United States. *Journal of Materials in Civil Engineering*, *145*(4), 05019004. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001630

Jitsangiam, P., Nusit, K., Nikraz, H., & Leng, Z. (2021). Dense-graded hot mix asphalt with 100% recycled concrete aggregate based on thermal-mechanical surface treatment. *Journal of Materials in Civil Engineering*, *33*(7), 04021156. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003805

Kar, D., Giri, J. P., Panda, M., & Chattaraj, U. (2021). Investigations on stone matrix asphalt mixes containing recycled concrete aggregate treated with nanosilica. *Journal of Materials in Civil Engineering*, *33*(9), 04021228. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003834

Kareem, A. I., Nikraz, H., & Asadi, H. (2019). Application of double-coated recycled concrete aggregates for hot-mix asphalt. *Journal of Materials in Civil Engineering*, *31*(5), 04019036. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002670

Khasawneh, M. A., & Alsheyab, M. A. (2020). Effect of nominal maximum aggregate size and aggregate gradation on the surface frictional properties of hot mix asphalt mixtures. *Construction and Building Materials*, *244*, 118355. https://doi.org/10.1016/j.conbuildmat.2020.118355

Liu, N., Wang, Y., Bai, Q., Liu, Y., Wang, P., Xue, S., Yu, Q., & Li, Q. (2022). Road life-cycle carbon dioxide emissions and emission reduction technologies: A review. *Journal of Traffic and Transportation Engineering (English Edition)*, *9*(4), 532–555. https://doi.org/10.1016/j.jtte.2022.06.001

Liu, Y., Wang, Y., & Li, D. (2017). Estimation and uncertainty analysis on carbon dioxide emissions from construction phase of real highway projects in China. *Journal of Cleaner Production*, *144*, 337–346. https://doi.org/10.1016/j.jclepro.2017.01.015

Martinez-Arguelles, G., Dugarte-Coll, M., Fuentes-Pumarejo, L. G., Sánchez-Cotte, E. H., Rondón-Quintana, H. A., Pacheco-Bustos, C. A., Yepes-Martínez, J., & Lagares-Espinoza, R. G. (2019). Characterization of recycled concrete aggregate as potential replacement of natural aggregate in asphalt pavement. *IOP Conference Series: Materials Science and Engineering*, *471*(10), 102045. https://doi.org/10.1088/1757-899X/471/10/102045

Martinho, F. C. G., Picado-Santos, L. G., & Capitão, S. D. (2018). Feasibility assessment of the use of recycled aggregates for asphalt mixtures. *Sustainability*, *10*(6), 1737. https://doi.org/10.3390/su10061737

Mikhailenko, P., Kakar, M. R., Piao, Z., Bueno, M., & Poulikakos, L. (2020). Incorporation of recycled concrete aggregate (RCA) fractions in semi-dense asphalt (SDA) pavements: Volumetrics, durability and mechanical properties. *Construction and Building Materials*, *264*, 120166. https://doi.org/10.1016/j.conbuildmat.2020.120166

Monu, K., Ransinchung, G., Pandey, G. S., & Singh, S. (2020). Performance evaluation of recycled-concrete aggregates and reclaimed-asphalt pavements for foam-mix asphalt mixes. *Journal of Materials in Civil Engineering*, *32*(10), 04020295. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003356

Motter, J. S., Miranda, L. F. R., & Bernucci, L. L. B. (2015). Performance of hot mix asphalt concrete produced with coarse recycled concrete aggregate. *Journal of Materials in Civil Engineering*, *27*(11), 04015030. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001284

Muniz de Farias, M., Quiñonez Sinisterra, F., & Rondón-Quintana, H. A. (2018). Behavior of a hot mix asphalt made with recycled concrete aggregate and crumb rubber. *Canadian Journal of Civil Engineering*, *46*(6), 544–551. https://doi.org/10.1139/cjce-2018-0443

Naser, M., Abdel-Jaber, M., Al-shamayleh, R., Louzi, N., & Ibrahim, R. (2022). Evaluating the effects of using reclaimed asphalt pavement and recycled concrete aggregate on the behavior of hot mix asphalts. *Transportation Engineering*, *10*, 100140. https://doi.org/10.1016/j.treng.2022.100140

Nejad, F. M., Azarhoosh, A. R., & Hamedi, G. H. (2013). The effects of using recycled concrete on fatigue behavior of hot mix asphalt. *Journal of Civil Engineering and Management*, *19*, 37–41. https://doi.org/10.3846/13923730.2013.801892

Nwakaire, C. M., Yap, S. P., Onn, C. C., Yuen, C. W., & Ibrahim, H. A. (2020). Utilisation of recycled concrete aggregates for sustainable highway pavement applications: A review. *Construction and Building Materials*, *235*, 117444. https://doi.org/10.1016/j.conbuildmat.2019.117444

Pacheco-Bustos, C. A., Fuentes-Pumarejo, L. G., Sánchez-Cotte, E. A., & Rondón-Quintana, H. A. (2017). Residuos de construcción y demolición (CDW), una perspectiva de aprovechamiento para la ciudad de barranquilla desde su modelo de gestión [Construction demolition waste (CDW), a perspective of achievement for the city of Barranquilla since its management model]. *Ingeniería y Desarrollo*, *35*(2), 533–555. https://www.redalyc.org/pdf/852/85252030015.pdf

Paranavithana, S., & Mohajerani, A. (2006). Effects of recycled concrete aggregates on properties of asphalt concrete. *Resources, Conservation and Recycling*, *48*(1), 1–12. https://doi.org/10.1016/j.resconrec.2005.12.009

Pasandín, A. R., & Pérez, I. (2013). Laboratory evaluation of hot-mix asphalt containing construction and demolition waste. *Construction and Building Materials*, *43*, 497–505. https://doi.org/10.1016/j.conbuildmat.2013.02.052

Pasandín, A. R., & Pérez, I. (2014). Mechanical properties of hot-mix asphalt made with recycled concrete aggregates coated with bitumen emulsion. *Construction and Building Materials*, *55*, 350–358. https://doi.org/10.1016/j.conbuildmat.2014.01.053

Pasandín, A. R., & Pérez, I. (2015). Overview of bituminous mixtures made with recycled concrete aggregates. *Construction and Building Materials*, *74*, 151–161. https://doi.org/10.1016/j.conbuildmat.2014.10.035

Pérez, I., & Pasandín, A. R. (2017). Moisture damage resistance of hot-mix asphalt made with recycled concrete aggregates and crumb rubber. *Journal of Cleaner Production*, *165*, 405–414. https://doi.org/10.1016/j.jclepro.2017.07.140

Purohit, S., Panda, M., & Chattaraj, U. (2021). Use of reclaimed asphalt pavement and recycled concrete aggregate for bituminous paving mixes: A simple approach. *Journal of Materials in Civil Engineering*, *33*(1), 04020395. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003480.

Radević, A., Đureković, A., Zakić, D., & Mladenović, G. (2017). Effects of recycled concrete aggregate on stiffness and rutting resistance of asphalt concrete. *Construction and Building Materials*, *136*, 386–393. https://doi.org/10.1016/j.conbuildmat.2017.01.043

Raman, J. V. M., & Ramasamy, V. (2021). Various treatment techniques involved to enhance the recycled coarse aggregate in concrete: A review. *Materials Today: Proceedings*, *45*(7), 6356–6363. https://doi.org/10.1016/j.matpr.2020.10.935

Rondón-Quintana, H. A., Cárdenas, J. C., & Muniz de Farias, M. (2019). Behavior of hot-mix asphalt containing blast furnace slag as aggregate: Evaluation by mass and volume substitution. *Journal of Materials in Civil Engineering*, *31*(2), 04018364. https://doi.org/10.1061/(asce)mt.1943-.5533.0002574

Rondón-Quintana, H. A., & Reyes-Lizcano, F. A. (2022). *Pavimentos: Materiales, Construcción y Diseño [Pavements – Materials, Construction and Design]* (2nd ed.). Editorial: ECOE

Rondón-Quintana, H. A., Ruge-Cárdenas, J. C., Reyes-Lizcano, F. A., Bastidas-Martínez, J. G., & Zafra-Mejía, C. A. (2023). Mechanical resistance of hot-mix asphalt using phosphorite as filler. *Journal of Materials in Civil Engineering*, *35*(9), 04023274. https://doi.org/10.1061/JMCEE7.MTENG-15720

Rondón-Quintana, H. A., Zafra-Mejía, C. A., & Ruge-Cárdenas, J. C. (2020). Use of recycled concrete aggregate as a substitute of a natural aggregate by mass and volume within an asphalt concrete base. *International Journal of Advanced Science and Technology*, *29*(4), 10845–10850. http://sersc.org/journals/index.php/IJAST/article/view/33595

Sanchez-Cotte, E. H. (2021). *Investigación experimental para el diseño de mezclas asfálticas tibias – MAT con diferentes contenidos de agregados de concreto reciclado RCA* [Unpublished doctoral dissertation]. Facultad de Ingeniería, Universidad del Norte, Barranquilla, Colombia.

Sanchez-Cotte, E. H., Fuentes, L., Martinez-Arguelles, G., Rondón-Quintana, H. A., Walubita, L. F., & Cantero-Durango, J. M. (2020). Influence of recycled concrete aggregates from different sources in hot mix asphalt design. *Construction and Building Materials*, *259*, 120427. https://doi.org/10.1016/j.conbuildmat.2020.120427

Sánchez de Juan, M., & Alaejos-Gutiérrez, P. (2009). Study on the influence of attached mortar content on the properties of recycled concrete aggregate. *Construction and Building Materials*, *23*(2), 872–877. https://doi.org/10.1016/j.conbuildmat.2008.04.012

Soltanabadi, R., & Behfarnia, K. (2022). Evaluation of mechanical properties of concrete containing recycled concrete aggregate and recycled asphalt pavement. *Journal of Materials in Civil Engineering*, *34*(12), 04022348. https://doi.org/10.1061/(ASCE)MT.1943-5533.0004514

Tahmoorian, F., & Samali, B. (2018). Laboratory investigations on the utilization of RCA in asphalt mixtures. *International Journal of Pavement Research and Technology*, *11*(6), 627–638. https://doi.org/10.1016/j.ijprt.2018.05.002

Tahmoorian, F., Samali, B., Yeaman, J., & Mirzababaei, M. (2022). Evaluation of volumetric performance of asphalt mixtures containing recycled construction aggregate (RCA). *International Journal of Pavement Engineering*, *23*(7), 2191–2205. https://doi.org/10.1080/10298436.2020.1849686

Tang, Q., Xiao, P., Kou, C., Lou, K., Kang, A., & Wu, Z. (2021). Physical, chemical and interfacial properties of modified recycled concrete aggregates for asphalt mixtures: A review. *Construction and Building Materials*, *312*, 125357. https://doi.org/10.1016/j.conbuildmat.2021.125357

Tefa, L., Bianco, I., Blengini, G. A., & Bassani, M. (2022). Integrated and comparative structural-LCA analysis of unbound and cement-stabilized construction and demolition waste aggregate for subbase road pavement layers formation. *Journal of Cleaner Production*, *352*, 131599. https://doi.org/10.1016/j.jclepro.2022.131599

Unidad de Planeación Minero Energética (UPME). (n.d.). *Explotación de materiales para la construcción*. https://www1.upme.gov.co/simco/Cifras-Sectoriales/Paginas/materialesdeconstruccion.aspx

Upshaw, M., & Cai, C. S. (2020). Critical review of recycled aggregate concrete properties, improvements, and numerical models. *Journal of Materials in Civil Engineering*, *32*(11), 03120005. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003394

Wöhler, A. (1858). Bericht uber die Versuche, welche auf der Konigl. Niederschlesisch-Markischen Eisenbahn mit Apparaten zum Messen der Biegung und Verdrehung von Eisenbahnwagen-Achsen wahrend der Fahrt angestellt wurden. *Z Fur Bauwes*, *8*, 641–652.

Xie, J., Wu, S., Lin, J., Cai, J., Chen, Z., & Wei, W. (2012). Recycling of basic oxygen furnace slag in asphalt mixture: Material characterization & moisture damage investigation. *Construction and Building Materials*, *36*, 467–474. https://doi.org/10.1016/j.conbuildmat.2012.06.023

Xu, X., Luo, Y., Sreeram, A., Wu, Q., Chen, G., Cheng, S., Chen, Z., & Chen, X. (2022). Potential use of recycled concrete aggregate (RCA) for sustainable asphalt pavements of the future: A state-of-the-art review. *Journal of Cleaner Production*, *344*, 130893. https://doi.org/10.1016/j.jclepro.2022.130893

Zulkati, A., Wong, Y. D., & Sun, D. D. (2013). Mechanistic performance of asphalt-concrete mixture incorporating coarse recycled concrete aggregate. *Journal of Materials in Civil Engineering*, *25*(9), 1299–1305. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000668

Zuluaga-Astudillo, D. A., Rondón-Quintana, H. A., & Zafra-Mejía, C. A. (2021). Mechanical performance of gilsonite modified asphalt mixture containing recycled concrete aggregate. *Applied Science*, *11*(10), 4409. https://doi.org/10.3390/app11104409