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Article

Properties of Hot Mix Asphalt (HMA) with Several Contents of Recycled Concrete Aggregate (RCA) †

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Abstract: Continuous research efforts have been developed in the literature to raise the sustainability components of the road infrastructure industry, i.e., reduce potential contaminants and augment financial profitability. In this regard, this investigation aims to explore the feasibility of producing Hot Mix Asphalt (HMA) with the inclusion of Recycled Concrete Aggregate (RCA) as a partial substitute for coarse Natural Aggregates (NAs). Thus, four different HMAs were considered, namely HMAs with coarse RCA contents of 0, 15, 30, and 45%. Specifically, the mechanical and sustainability properties of the asphalt mixtures were determined. On the one hand, the Marshall design parameters, resilient modulus, moisture susceptibility, rutting resistance, and fatigue life were addressed as mechanical properties. Meanwhile, regarding the sustainability properties, the environmental impacts and production costs were estimated using the Life Cycle Assessment (LCA) and the Life Cycle Cost Analysis (LCCA) methodologies, respectively. Consequently, the following conclusions were obtained: (i) as the coarse RCA content increases, the mechanical behavior of the HMA progressively deteriorates; (ii) this decrease in mechanical performance is acceptable up to a 15% RCA of coarse RCA, whereas for higher dosages this alteration is abrupt; and (iii) the RCA only generates sustainability benefits at a 15% replacement amount.

Keywords: Hot Mix Asphalt; Life Cycle Assessment; Life Cycle Cost Analysis; mechanical performance; pavement materials; Recycled Concrete Aggregate; sustainability

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1. Introduction

The economic growth and improvement in the living standards of the communities require the construction and maintenance of different civil infrastructures, e.g., aqueducts, buildings, dams, embankments, and pavements [1–3]. Among these infrastructures, pavements are particularly necessary because they guarantee the interconnection of urban and rural areas with the production and distribution centers [4–6]. Nonetheless, the road infrastructure industry has two major problems: (i) higher environmental impacts and (ii) elevated production costs [7–9]. The preceding has motivated a growing interest in the state-of-the-art for developing novel sustainable materials [8,10–12]. In light of the above, this research evaluates the feasibility of fabricating Hot Mix Asphalt (HMA) with the inclusion of Recycled Concrete Aggregates (RCA) as a partial replacement for coarse Natural Aggregates (NAs). Notably, the RCA is the recycled material obtained from demolishing and crushing old Portland cement concrete, which typically comes from old buildings and rigid pavements [13–16].

The central idea behind implementing RCA as a substitute for virgin materials is that the decrease in non-renewable resource exploitation mitigates the environmental impacts and production costs associated with HMA production [17–19]. Thus, the design of HMAs with RCA contents has already been addressed in the literature from various standpoints, such as mechanical, environmental, and economic approaches [14,20–24]. From these investigations [14,20–24], it has been possible to reach various consensuses: (i) most of the mechanical properties of the HMAs exhibit progressive deterioration with the increase of the RCA; (ii) by incrementing the RCA dosage, the Optimal Asphalt Content (OAC) of the HMAs also augments; (iii) low quantities of RCA generate environmental benefits, whilst excessive amounts of RCA provoke (due to the higher OAC) more elevated environmental detriments and associated monetary costs; and (iv) the above trends are more pronounced for fine RCA than for coarse RCA.

In order to provide a concise background on the production and performance of RCA-based HMA, several notable investigations are synthesized below. Vega et al. (2020) [17], assessed the environmental impact of HMAs with coarse RCA contents of 15, 30, and 45% under a cradle-to-laid approach. The authors figured out that, from an environmental standpoint, the coarse RCA is only sustainable up to 30% (by replacement of NAs). Similarly, Qasrawi et al. (2016) [20] considered coarse RCA dosages (25, 50, 75, and 100%) to modify the HMA. The authors discover that the RCA dramatically reduces the HMA's moisture resistance (specifically, stripping resistance), but fortunately, the Tensile Strength Ratio (TSR) is (in all cases) over 80%. Likewise, Pasandín et al. (2017) [25] evaluated the fatigue behavior of HMA with the simultaneous inclusion of RCA (0, 35, and 42% of total NA weight) and fine crumb rubber (as an asphalt binder modifier agent). The authors conclude that RCA-based HMAs present low resistance to fragmentation (regarding the conventional HMA), so incorporating RCA is only proper for roads classified under the light and medium traffic categories. Notably, a more in-depth mechanical examination (including contact angle measurement and surface free energy estimations) was conducted by Hou et al. (2018) [26]. In that research, the authors clearly establish that: (i) as the RCA dosage increases, the mechanical behavior of the HMA is progressively declining (at least in terms of residual Marshall stability, TSR, and fatigue life); and (ii) the adhesive energy between RCAs and the asphalt binder is crucial to understanding the HMA's mechanical responses. Another interesting case study was the investigation carried out by Ma et al. (2019) [27]. The authors demonstrate that the mechanical performance of the RCA-based HMAs can be improved when the RCA is pretreated with waste cooking oil residue. On the same line, Singh et al. (2021) [28], reveal that including lime filler in the HMA design can reduce the counterproductive effects of the coarse RCA. Notably, the adverse impacts associated with RCA can also be controlled by including other residues in the mix design, e.g., recycled glass and reclaimed asphalt pavement [29–31].

Despite the considerable state-of-the-art, there is still a significant gap in the literature, i.e., few comprehensive assessments have been made to simultaneously evaluate the mechanical and sustainability properties of HMA with RCA content. Precisely, the above is addressed by this research. This case study evaluates the mechanical and sustainability properties of HMAs with coarse RCA inclusion. Four RCA dosages were considered for these purposes, i.e., 0, 15, 30, and 45% of coarse RCA for replacement (by weight) of coarse NAs. Regarding the mechanical properties, the Marshall design parameters, resilient modulus, moisture susceptibility, rutting resistance, and fatigue life were assessed. Meanwhile, two sustainability properties were evaluated, i.e., the environmental impacts and the production costs. Thus, the Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA) methodologies were employed to estimate the environmental burdens and monetary costs associated with the production of asphalt concrete. Overall, this research effort is expected to be used as a decision-making tool for designers, engineers, state agencies, and other stakeholders to choose eco-friendly materials in the road infrastructure industry.

The subsequent content of this manuscript is described below. Section 2 presents the description and the main characteristics of the raw materials employed in this case study. Next, Section 3 explains the methods used to evaluate the RCA-based HMAs as well as their associated outcomes. In Section 4, a concise discussion of the results is conducted. Finally, Section 5 exhibits the main findings and conclusions of this research.

2. Materials

The raw materials used in this research are described below. The asphalt binder has a 60/70 penetration grade. This asphalt binder was refined in the central Colombian refinery, which is located in the municipality of Barrancabermeja (Department of Santander). Table 1 shows the basic physicochemical characterization of the asphalt binder. On the other hand, the NAs were extracted from a local quarry in the municipality of Arroyo de Piedra (Department of Atlántico). This quarry is formed by sedimentary rocks, mostly of marine origin. Meanwhile, the RCAs were obtained by crushing and sieving old Portland cement concrete, which was demolished from the rigid pavement that gave access to the maritime port of Barranquilla city, i.e., Hamburg Avenue. Table 2 exhibits the physical properties of these aggregates.

Table 1. Properties of the asphalt binder.

Properties	Unit	Results
Absolute viscosity (60 °C)	P	2290
Ductility at 25 °C	cm	>100
Ignition point through the open Cleveland cup	°C	286
Kerosene content	%	1.3
Penetration (25 °C, 100 g, 5 s)	0.1 mm	60.7
Penetration index	-	−1.0
Softening point	°C	49
Specific gravity 25 °C	kg/m^3	1030
Trichloroethylene solubility	%	99.99
Water content	%	0.0

Table 2. Physical characterization of the aggregates.

Parameters	Unit	Fine NA	Coarse NA	Coarse RCA
Dry density	kg/m^3	2597	2555	2304
Saturated surface dry density	kg/m^3	2627	2604	2426
Water absorption	%	1.91	1.14	5.31
Los Angeles abrasion at 100 revs	% loss	-	4.8	5.3
Los Angeles abrasion at 500 revs	% loss	-	21.5	27.3
Micro-Deval	%	-	17	26
Wet/dry ratio of ten percent fines value	%	-	89.7	83.6

The production temperatures for the HMAs were determined by employing the rotational viscometer test (according to the ASTM D4402/D4402M-23 standard [32]), resulting in 149–151 °C and 139–141 °C as the mixing and compaction temperatures, respectively. Considering these temperatures and following the ASTM D6926-20 standard [33], the HMAs were fabricated using the Marshall method. For this purpose, the grain size distribution presented in Table 3 was followed. These granulometry ranges are the official Colombian requirements to manufacture asphalt concrete with 25 mm of nominal maximum aggregate size [34]. Notably, the same apparatus was utilized for crushing the NAs and RCAs; thus, the exact grain size distribution was obtained for all aggregates, as reported in Table 3.

Table 3. Grain size distribution employed in this study.

Sieve		Colombian Requirements for Passing Percentage		Granulometry Used (%)
#	mm	Upper Limit (%)	Lower Limit (%)	
1″	25.400	100	100	100.0
3/4″	19.000	95	80	86.0
1/2″	12.500	85	67	69.0
3/8″	9.500	77	60	60.5
No. 4	4.750	59	43	50.5
No. 10	2.000	45	29	34.6
No. 40	0.475	25	14	15.5
No. 80	0.180	17	8	8.2
No. 200	0.075	8	4	4.1

Color coding: Green—Coarse fraction (only fraction partially replaced by RCA); Blue—Fine fraction; Orange—Filler portion.

3. Methods and Results

3.1. Mechanical Properties

3.1.1. Marshall Parameters

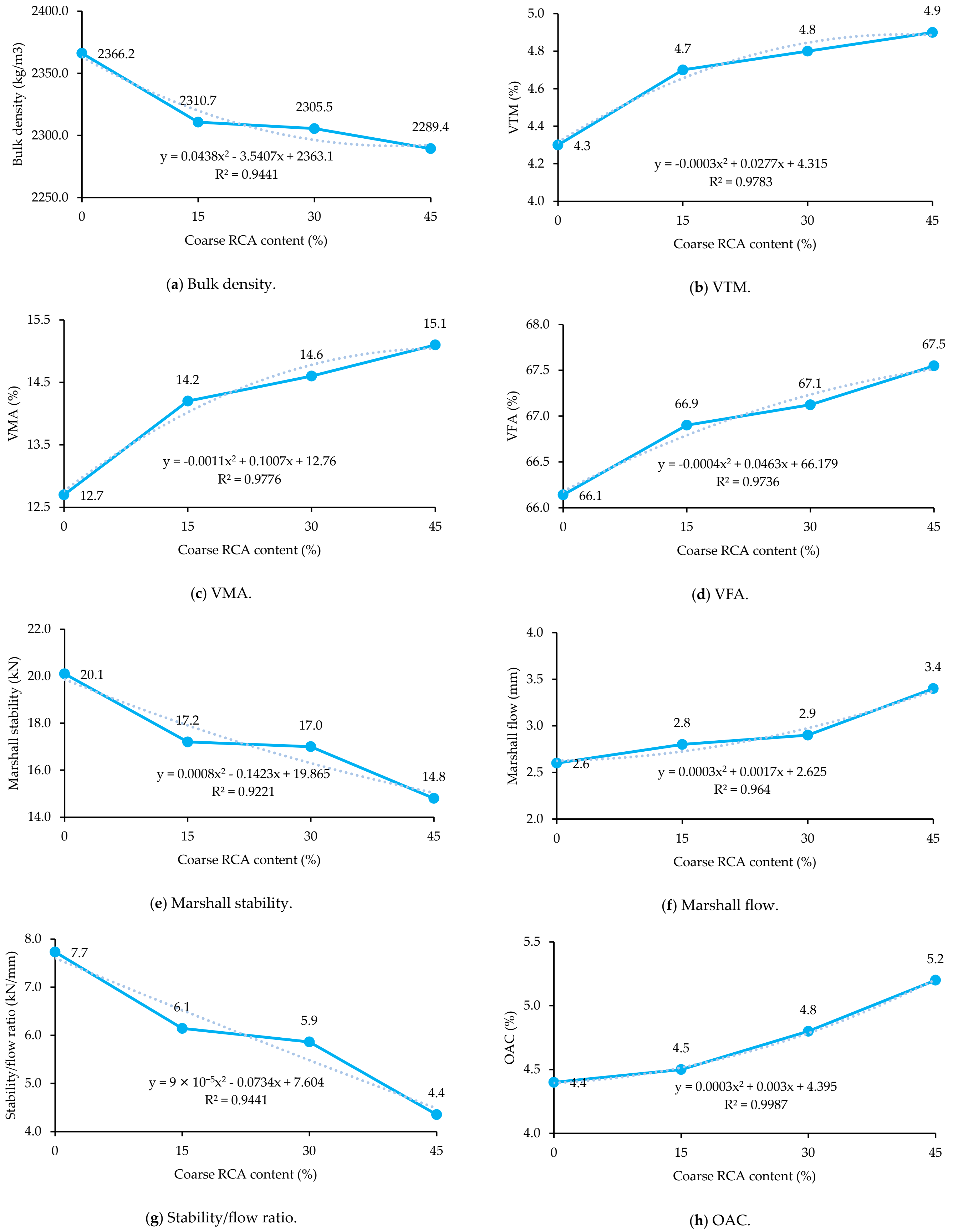
Following the ASTM D6927-22 standard [35], the Marshall design parameters were determined as the initial approach to evaluating the mechanical properties of HMAs with RCA. These parameters are comprised of bulk density, Voids in the Total Mix (VTM), Voids in Mineral Aggregate (VMA), Voids Filled with Asphalt (VFA), Marshall stability, Marshall flow, stability/flow ratio, and OAC. Figure 1 shows the results obtained from these procedures. The reported outcomes correspond to the average values calculated from three tested samples. Based on the OACs specified in Figure 1, the mass fractions for each raw material were calculated for all the asphalt mixture designs; the preceding is exhibited in Table 4. From this graph, it is possible to draw the following conclusions:

- As the coarse RCA content increases, there is a decrease in bulk density, Marshall stability, and stability/flow ratio.
- The VTM, VMA, VFA, Marshall flow, and OAC progressively augment with the increment in the coarse RCA content.
- Although the increase in the RCA dosage generates a rise for all the void indicators (i.e., VTM, VMA, and VFA), it is not possible to affirm that the RCA content marks a strong correlation with these parameters. In most scenarios, these indicators are only incremented by a minuscule quantity (even less than one percentage unit), so it is not feasible to assemble definitive conclusions. Thus, it is essential for future research to evaluate a greater number of samples in order to carry out an analysis of statistical significance.

Table 4. Composition of the asphalt mixture designs.

Designs	Mass Fraction Regarding the Total Mixture Weight (%)				
	Asphalt Binder	Filler NA	Fine NA	Coarse NA	Coarse RCA
HMA with 0% coarse RCA content	4.400	3.920	44.358	47.322	0.000
HMA with 15% coarse RCA content	4.500	3.916	44.312	40.182	7.091
HMA with 30% coarse RCA content	4.800	3.903	44.173	32.987	14.137
HMA with 45% coarse RCA content	5.200	3.887	43.987	25.809	21.117

Note: In all HMA designs, the grain size distribution shown in Table 3 is maintained, i.e., the total aggregate content comprises 4.1, 46.4, and 49.5% of filler, fine, and coarse fractions, respectively.



(**a**) Bulk density.

(**b**) VTM.

(**c**) VMA.

(**d**) VFA.

(**e**) Marshall stability.

(**f**) Marshall flow.

(**g**) Stability/flow ratio.

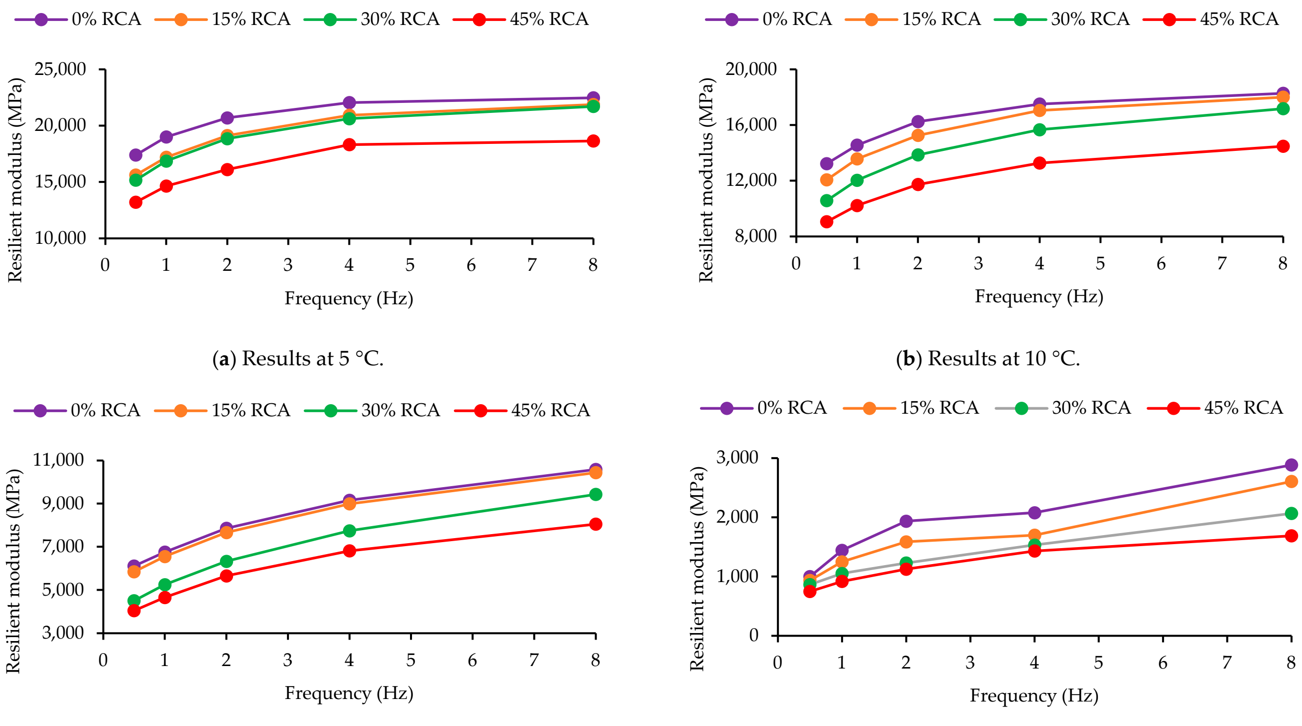
(**h**) OAC.

Figure 1. Marshall parameters of the RCA-based HMAs.

The preceding results are insufficient to understand the asphalt concrete's behavior. Therefore, in order to conduct a deeper inspection of the mechanical performance of the RCA-based HMAs, the resilient modulus, moisture susceptibility, rutting resistance, and fatigue life were assessed. Accordingly, these tests and their outcomes are described below. In all tests, the reported values also correspond with the average value of three samples.

3.1.2. Resilient Modulus

The resilient modulus is an essential parameter to assess the viscoelastic bearing capacity of asphalt concrete [36–38]. The resilient modulus depends on the temperature and the frequency of loading [39–41]. Accordingly, in this research, the behavior of the HMAs was evaluated under 20 scenarios, i.e., the combination of five load frequencies (i.e., 0.5, 1, 2, 4, and 8 Hz) and four temperatures (i.e., 5, 10, 20, and 40 °C). In order to determine the resilient modulus in the laboratory, several methods are available; in this investigation, the indirect tension test was addressed according to the ASTM D7369-20 standard [42]. Overall, this test consists of applying a diametral compression to the HMA sample and recording the displacement provoked by that mechanical load. Figure 2 shows the results obtained. In all scenarios, as the RCA content increases, the resilient modulus of the HMA is progressively reduced. Furthermore, as expected, the stiffness of asphalt mixtures decreases with the decline of the loading frequency and the increase in the testing temperature.



(**a**) Results at 5 °C. (**b**) Results at 10 °C.

(**c**) Results at 20 °C. (**d**) Results at 40 °C.

Figure 2. Influence of temperature, frequency, and coarse RCA content on the resilient modulus of HMAs.

3.1.3. Moisture Susceptibility

The moisture susceptibility of the HMAs was evaluated through the TSR. The TSR is defined as the ratio of Indirect Tensile Strength (ITS) measured in dry and wet conditions. Thus, the TSR can be interpreted as the proportion of bearing capacity remaining in asphalt concrete after its water immersion (i.e., the most extreme humidity condition) [14,43–45]. In this research, the ITSs were determined according to the guidelines of the ASTM D4867/D4867M-22 standard [46]. In this way, the following aspects were addressed: (i) a mechanical load is applied in the diametral axis of the asphalt mixture sample under a progressive increment (at a 50.0 ± 5 mm/min rate) until it reaches the failure state (i.e., that point denotes the maximum resistance of the specimen); (ii) for the dry condition, the samples are tested at 25 ± 1 °C without applying any pretreatment; and (iii) for the wet condition, the samples prior to testing (at 25 ± 1 °C) are subjected to a three-step pretreatment comprised by an initial vacuum saturation process, followed by complete immersion in distilled water during one day at 60 ± 1 °C, and a final (just before the test) water bath at 25 °C for 2 h. Figure 3 exhibits some pictures of this procedure.

(**a**) Immersion of HMA samples in distilled water. (**b**) HMA sample in the testing machine.

Figure 3. Experimental tests to evaluate the HMAs' moisture susceptibility.

Figure 4 shows the laboratory results on HMAs' moisture susceptibility. In this graph, it is notorious that the ITSdry, ITSwet, and TSR are progressively diminished as the RCA dosage increases. The preceding indicates that the moisture susceptibility of the RCA-based HMAs rises with the increase in RCA content. However, at 15% of coarse RCA, the TSR value is higher than 80%, which means that the HMA develops an acceptable resistance to moisture damage [25,30,45,47].

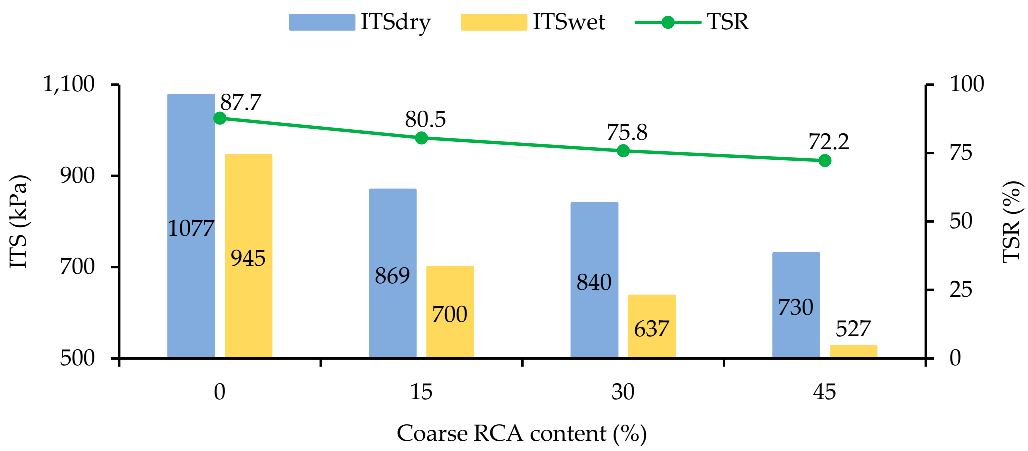


Figure 4. Influence of RCA dosage on HMAs' moisture susceptibility.

3.1.4. Rutting Resistance

In order to assess the rutting resistance of the HMAs, the creep test was conducted according to the EN 12697-25 standard [48]. This test evaluates the sensitivity of the asphalt concrete to the accumulation of permanent deformation (i.e., the rutting phenomenon) [49,50]. Remarkably, the creep test applies repetitive axial stresses (typically a load of 500 kPa) to the asphalt mixture sample, which has a diameter of 100 mm. Thus, a vertical deformation is continuously generated and recorded (generally through transducers). In this research, the samples were previously conditioned at 50 °C for two hours. Consequently, due to this procedure, a creep curve is obtained, i.e., a graph that relates the number of load applications versus the cumulative axial strain (also called the creep rate) [51–53]. Finally, the number of load repetitions necessary to reach the turning point was considered a rutting resistance criterion, i.e., the flow number. This point is graphically observed at the moment in which the creep curve undergoes a transition between its middle part and last part. In this investigation, it was decided to express the creep rate as a percentage of cumulative axial strain instead of microstrain/loading pulse. Figure 5 presents the laboratory results on rutting resistance. According to this figure, the accumulation of permanent deformation exhibits complex behavior. Specifically, the rutting resistance is greatly improved at low coarse RCA content (i.e., 15%); nonetheless, this property deteriorates dramatically at high coarse RCA contents (i.e., 30 and 45%). Notably, both criteria (flow number and final creep rate) are consistent with these findings.

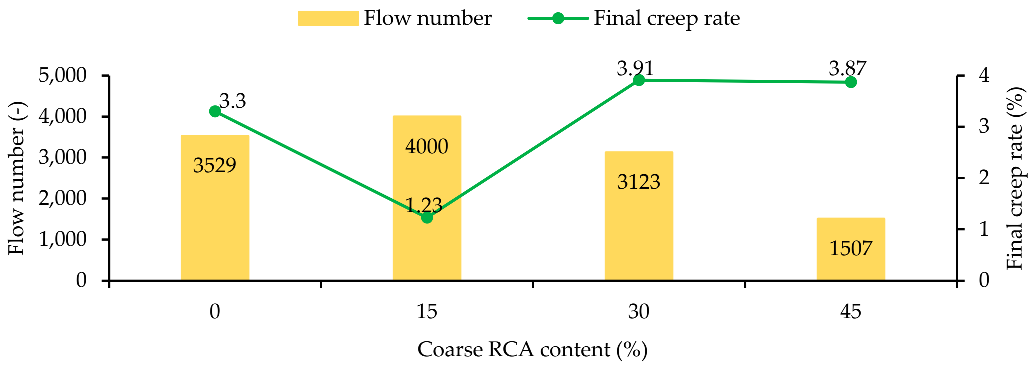


Figure 5. Influence of RCA dosage on HMAs' rutting resistance.

3.1.5. Fatigue Life

Finally, the fatigue life of the HMAs was estimated using the indirect tensile test on cylindrical-shaped samples following the EN 12697-24 standard [54]. This procedure analyzes the behavior of the asphalt mixtures under repeated load fatigue testing with a constant load mode, which is applied in the vertical diametral plane. In this test, the fatigue resistance is expressed as the number of load cycles required to reach the sample's failure state [55–57]. This research conducted this test under two different conditions: (i) the compressive load equals 30% of the ITS dry value, and (ii) the load is 50% of the ITS dry value. Figure 6 shows the results obtained from this test. Based on this graph, it is possible to figure out the following findings: (i) the increase in the RCA dosage decreases the fatigue life of the HMAs; and (ii) at a lower compressive load, the alterations provoked by the coarse RCA content are more elevated.

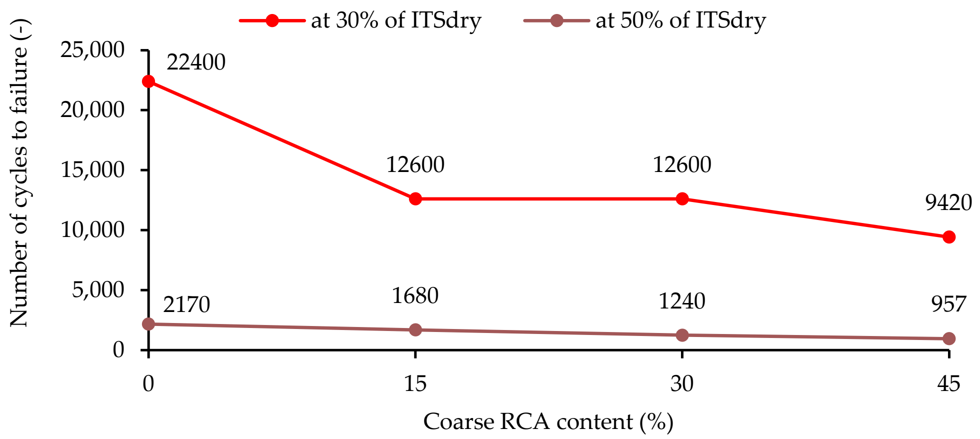


Figure 6. Influence of RCA dosage on HMAs' fatigue life.

3.2. Sustainability Properties

3.2.1. Environmental Impacts

The LCA is the most widely used methodology to estimate the environmental impacts associated with products, processes, activities, or projects [23,58,59]. In this case study, an attributional LCA was conducted through the SimaPro 9.4 software; only for exemplification purposes, Figure 7 shows a screenshot of this software analyzing the asphalt binder under a tree diagram. It is essential to highlight that the ISO-14040 and ISO-14044 standards were considered the main guidelines [60,61]. Moreover, the framework offered by the US Federal Highway Administration has been embraced [62]. Thus, the "cradle-to-gate" approach was implemented, i.e., computing the environmental burden generated from the raw material extraction to the composite material manufacture [7,58,62]. According to this approach, three stages comprised the LCA's system boundaries: raw material extraction, material transport to the asphalt mixing plant, and asphalt mixture production. In light of the above, the functional unit was defined as the production of 1 ton of asphalt mixture.

Table 5 presents the Life Cycle Inventory (LCI) adopted for this research. Notably, the vast majority of the LCI is primary data compiled from previous investigations conducted in the northern region of Colombia [17,23]. According to the LCI, it is necessary to take into account the Thermal Energy (TE) required for the mixing process. Table 6 provides this information. On the other hand, the "cut-off" approach was employed for modeling the RCA. Based on this approach, for recycled materials, only the environmental impacts generated by their incorporation into a new product or process should be considered [63–65]. In other words, the environmental burdens associated with the final disposal alternatives for the waste materials or the activities prior to their recycling are not contemplated [24,66,67].

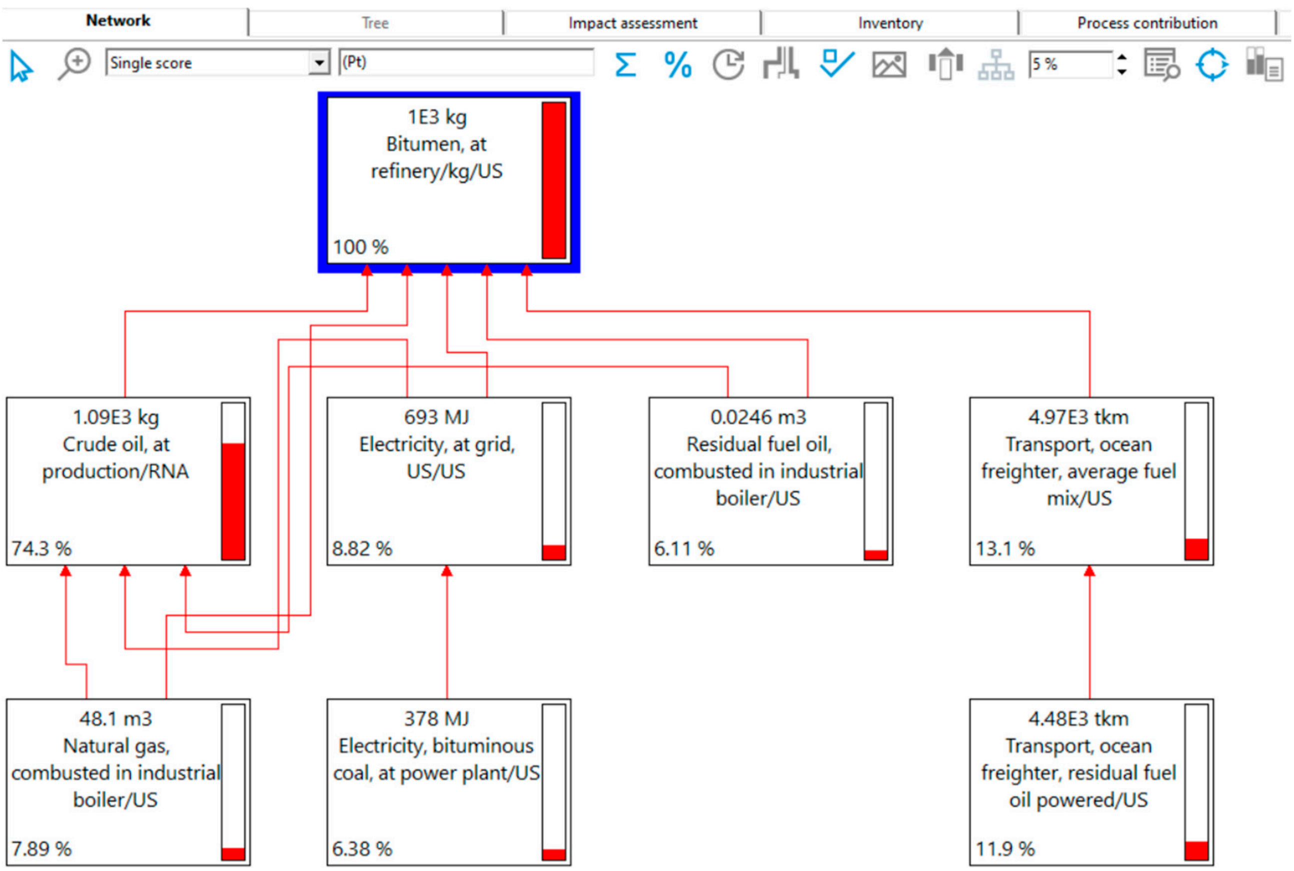


Figure 7. Screenshot of SimaPro's user interface (in its 9.4 version). Taken from: [68]

Table 5. The adapted LCI for this case study. Adapted from: [23,24,69].

LCA Stage	Activities	Unit Processes	Source Database
Raw Material extraction	Coarse NAs extraction	Gravel, crushed {RoW} | production | Cut-off, U	Ecoinvent v.3.8
	Fine NAs extraction	Sand {RoW} | gravel and quarry operation | Cut-off, U	Ecoinvent v.3.8
	Aggregate loading onto the truck	Loader operation, large, INW/RNA	USLCI v.1.6
	RCA crushing	Diesel, burned in building machine {GLO} | processing | Cut-off, U	Ecoinvent v.3.8
	Asphalt binder production	Bitumen, at refinery/kg/US	USLCI v.1.6
Material transport to the asphalt mixing plant	Aggregates transportation (One-way distance: 73 km)	Transport, freight, lorry 16–32 metric ton, EURO4 {RoW} | transport, freight, lorry 16–32 metric ton, EURO4 | Cut-off, U	Ecoinvent v.3.8
	Asphalt binder transportation (One-way distance: 592 km)		
Asphalt Mixture production	NAs processing	Diesel, burned in building machine {GLO} | processing | Cut-off, U	Ecoinvent v.3.8
	Mixing aggregates with the asphalt binder (Required thermal energy)	Heat, district or industrial, other than natural gas {RoW} | heat production, heavy fuel oil, at an industrial furnace 1MW | Cut-off, U	Ecoinvent v.3.8

Table 6. Energy required for mixing 1 ton of HMA. Adapted from: [7,24].

Designs	TE (MJ)
HMA with 0% coarse RCA content	245.7
HMA with 0% coarse RCA content	231.4
HMA with 0% coarse RCA content	217.8
HMA with 0% coarse RCA content	205.3

The "BEES+ v.4.08" model was selected as the impact assessment method. The BEES+ model considers 13 impact categories, i.e., acidification (H+ mmole eq), ecotoxicity (g 2.4-D eq), eutrophication (g N eq), global warming (g CO2 eq), habitat alteration (T & E count), human health cancer (g C6H6 eq), human health criteria air pollutants (microDALYs), human health noncancer (g C7H7 eq), indoor air quality (g TVOC eq), natural resource depletion (MJ surplus), ozone depletion (g CFC-11 eq), smog (g NOx eq), and water intake (liters) [7,70,71]. Accordingly, Table 7 presents the results from the LCA. Based on this table, it is possible to draw the following conclusions: The HMA with 15% coarse RCA exhibits the lowest environmental impacts. However, more elevated RCA dosages generate the opposite effect. Therefore, at low RCA contents, the mitigation of the NAs depletion predominates over the increase in the OAC. Conversely, for high RCA contents, the greater OAC makes the modified HMAs less sustainable than the control mixture.

Table 7. LCA's characterization results.

Impact Categories	Unit	HMA with Coarse RCA Content of 0%	15%	30%	45%
Acidification	H+ mmole eq	1,535,043	1,425,980	1,643,686	1,750,170
Ecotoxicity	g 2.4-D eq	20,131	18,740	21,534	22,943
Eutrophication	g N eq	8559	7897	9225	9892
Global warming	g CO2 eq	3,301,236	3,090,272	3,510,922	3,715,522
Habitat alteration	T&E count	0	0	0	0
Human health cancer	g C6H6 eq	16,772	15,505	18,048	19,327
Human health criteria air pollutants	microDALYs	554	517	592	630
Human health noncancer	g C7H7 eq	17,768,728	16,327,503	19,221,289	20,678,241
Indoor air quality	g TVOC eq	0	0	0	0
Natural resource depletion	MJ surplus	38,544	35,550	41,564	44,599
Ozone depletion	g CFC-11 eq	1,222,781,085	1,217,817,608	1,226,503,694	1,227,744,563
Smog	g NOx eq	15,885	14,771	17,009	18,140
Water intake	liters	3303	3042	3562	3814

Clearly, the results obtained in this case study are limited by the scope of the cradle-to-gate and cut-off approaches. Consequently, in the case of replicating this research, it would be necessary to discern whether these boundaries are appropriate for other particular scenarios. For further discussion on this topic, it is recommended to inspect the following investigations [72–76].

3.2.2. Production Costs

The LCCA (also called life cycle costing) is one of the most robust methodologies available to estimate the associated costs of products, processes, activities, or projects throughout an entire or partial life cycle [7,9,77]. For this study, the LCCA was executed according to the ISO 15686-5 standard [78]. Likewise, in this research, it was decided to implement an LCA-LCCA integration. Therefore, the LCCA assumed the system boundaries, functional unit, LCI, and other aspects presented for the LCA [79,80]. Thus, employing the cradle-to-gate approach, all production costs are generated at "year zero", i.e., a very short period that does not allow for considering inflation, interest rates, or other variables associated with time [7,9]. Accordingly, in order to calculate the production costs, it is proposed to use Equation (1). It is essential to highlight that the variables that constitute this mathematical expression are described in Table 8.

$$PC = \left(\sum_{i=1}^{n} mi * P_{COSTi}\right) + \left(\sum_{i=1}^{n} mi * di * T_{COSTi}\right) + \left(\frac{TE}{LHV} * HFO_{price}\right) \quad (1)$$

Table 8. Variables that constitute Equation (1). Adapted from: [7,23].

Variable	Unit	Description
PC	USD	Production costs of 1 t of asphalt mixture.
P_{COSTi}	USD/t	Production/processing costs of each raw material.
T_{COSTi}	USD/t/km	Hauling costs for each raw material.
mi	t	Mass of each material required to produce 1 t of asphalt mixture.
di	km	One-way transport distance for each raw material.
TE	MJ	TE required to produce 1 t of asphalt mixture.
HFO_{price}	USD/kg	Price of heavy fuel oil (typical fuel for asphalt mixing plants).
LHV	MJ/kg	Lower heating value of heavy fuel oil, i.e., 42.18 MJ/kg.
n	-	Number of raw materials considered.

Table 9 presents the standard producer prices of the Department of Atlántico for all the raw materials and heavy fuel oil. These prices were taken from the official report of the Colombian authorities [81]. It is important to highlight that these values correspond to the second semester of the year 2022, a period in which it was documented that one United States Dollar (i.e., USD) had an average equivalence of 4590.86 Colombian Pesos (i.e., COP). In Table 9, it is noted that the hauling cost depends on the one-way transport distances, which were previously reported in Table 5. According to this table, the asphalt binder and aggregates are transported from Barrancabermeja (Department of Santander) and Arroyo de Piedra (Department of Atlántico), respectively. On the other hand, due to the cut-off approach, the price of the coarse RCA refers to the crushing costs. Furthermore, it was assumed that the crusher machine had a typical (i.e., industrial) efficiency of 70 tons per hour. More details of the LCCA execution can be found in previous investigations [7,23].

Table 9. Standard producer prices of the Department of Atlántico.

Materials		Unit	Price (USD)
Acquisition costs	Heavy fuel oil	1 kg	$ 0.88
	Asphalt binder	1 ton	$ 530.88
	Filler NA		$ 6.81
	Fine NA		$ 6.81
	Coarse NA		$ 6.75
	Coarse RCA		$ 1.67
Hauling costs	Asphalt binder	1 ton*km	$ 0.21
	Filler NA		$ 0.11
	Fine NA		$ 0.11
	Coarse NA		$ 0.11
	Coarse RCA		$ 0.11

Figure 8 shows the results of HMAs' production costs. In this graph, it is notorious that the HMA with 15% coarse RCA requires the lowest production costs. Nevertheless, higher RCA dosages yield the opposite effect. Hence, at low RCA contents, the mitigation of the NAs depletion predominates over the increase in the OAC. Contrariwise, for high RCA contents, the greater OAC makes the RCA-based HMAs less profitable than the traditional mixture. Regardless, the financial savings caused by the incorporation of 15% coarse RCA are dramatically low, i.e., 0.02 USD/ton. Therefore, the RCA-based HMA would only be helpful (from an economic standpoint) in a large-scale construction project.

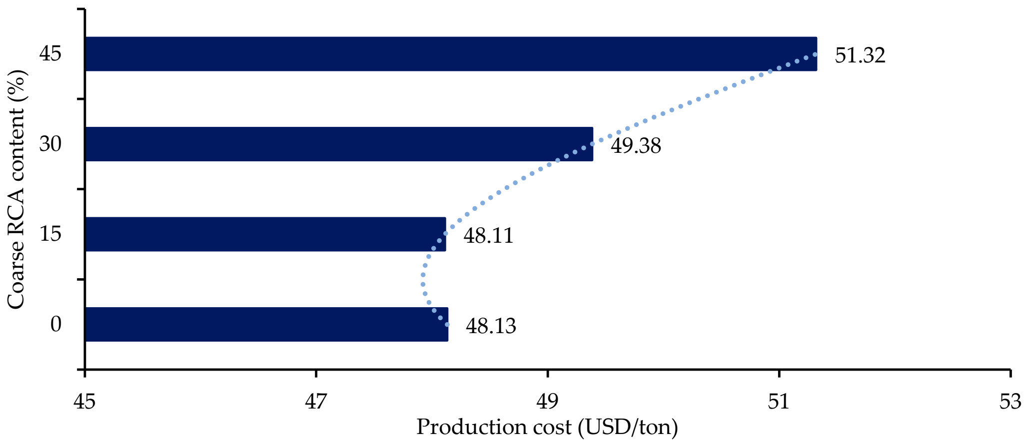


Figure 8. Influence of coarse RCA content on HMAs' production costs.

It is important to note that the production costs calculated by the proposed LCCA are an initial appraisal that does not consider important aspects such as fixed costs, variable costs, taxes, and profits, among others. Hence, the results obtained are below typical market prices. Thus, the reported outcomes should only be understood as an initial estimation used to contrast the influence of coarse RCA content on HMAs' production costs and not as an exhaustive examination of Colombian market conditions.

4. Discussion

In order to analyze in greater depth the effect that the coarse RCA content has on the HMA's properties, the relative changes were calculated by taking the control mixture as the reference point. These values are presented in Figures 9–11. Notably, two environmental impact categories (i.e., habitat alteration and indoor air quality) were not considered in this analysis because, for HMA production (at least in the context of this case study), these types of environmental burdens are not relevant (as can be seen in Table 7). In this way, from Figures 9–11, the following findings can be drawn:

- The incorporation of RCA reduced the resilient modulus of the HMA by about 45%. The higher alterations were presented at higher temperatures.
- VTM, VMA, Marshall stability, Marshall flow, and Stability/flow ratio exhibit changes around 10–45% regarding the control mixture. Nonetheless, the other Marshall parameters (i.e., bulk density, VFA, and OAC) undergo the tiniest percentual influences in their magnitudes (due to the elevated coarse RCA contents). According to these findings, it is notorious that the RCA dosage significantly influences most Marshall parameters.
- Except for the fatigue resistance measured at a compressive load equal to 30% of the ITS dry value, the 15% coarse RCA generates a decrease in the mechanical performance of the HMA that may be acceptable; even this dosage improves the rutting resistance. However, higher RCA contents yield much more significant detriments.
- Most of the environmental impacts generated by HMA production are reduced by 5–10% by partially substituting 15% coarse NAs with coarse RCA. Nevertheless, higher RCA dosages increase environmental impacts by 6–17%. On the other hand, a similar behavior (but with smaller relative changes) is exhibited by production costs. Therefore, the dramatic influence of this waste material on the HMA's sustainability properties is notorious.
- Including RCA in the HMA design causes minimal differences in production costs. Nonetheless, considering the typical high volumes of materials required for road infrastructure projects, this variation could become economically significant for the cost-effectiveness of some specific contexts.

Although each case study is entirely different from the others, it is promising that the findings of this research are primarily consistent with the results of several investigations developed worldwide, for instance, in Jordan [29], Malaysia [82], the People's Republic of China [83], Australia [84], Turkey [85], Iran [86], Switzerland [87], Serbia [88], India [89], Spain [90], and Portugal [91].

Due to the scope of this research, no field evaluation or simulation of the performance of pavement structures containing RCA in the asphalt layers was performed. Therefore, the RCA-based HMAs were presumed to have a field behavior comparable to traditional asphalt concretes (at least regarding low coarse RCA dosages). This assumption is supported by the findings of previous investigations developed in Colombia [17] and Canada [92]. Regardless, future research efforts must verify on a field scale the compliance of the technical criteria by the HMA with coarse RCA.

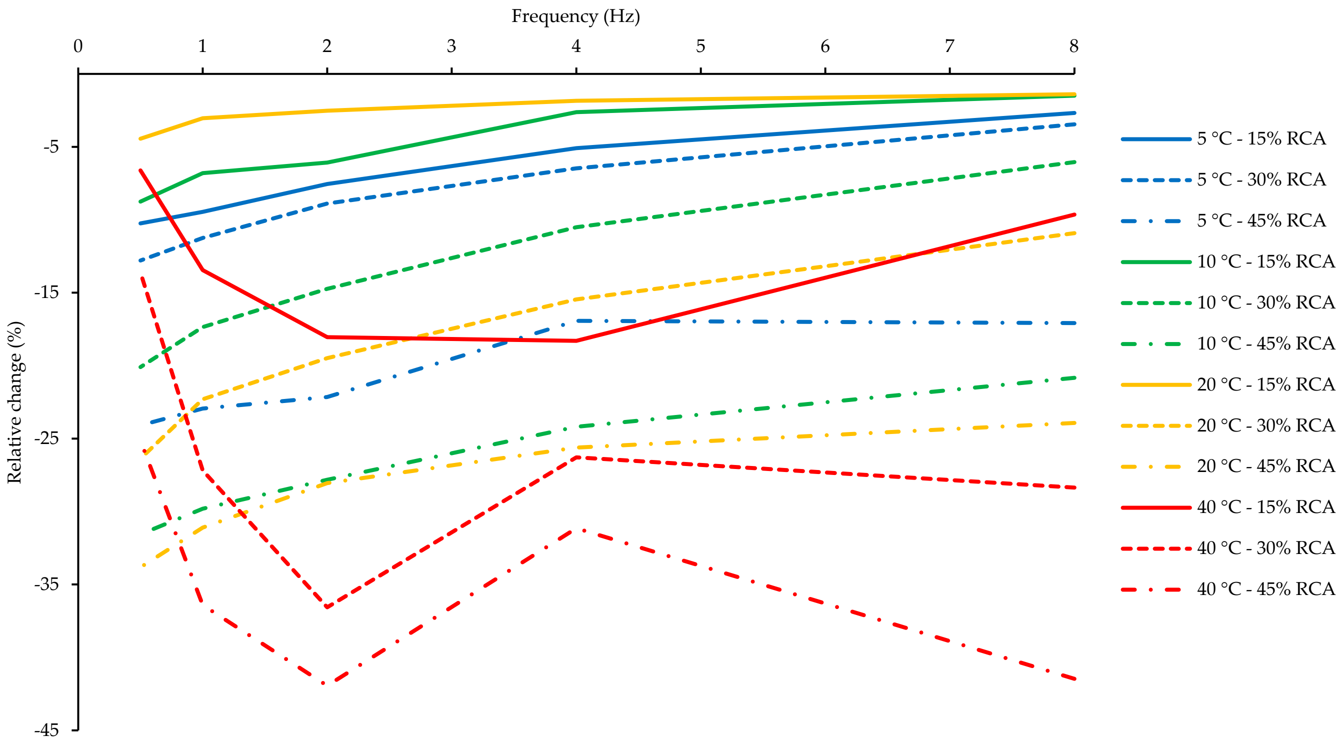


Figure 9. Analysis of relative changes for resilient modulus.

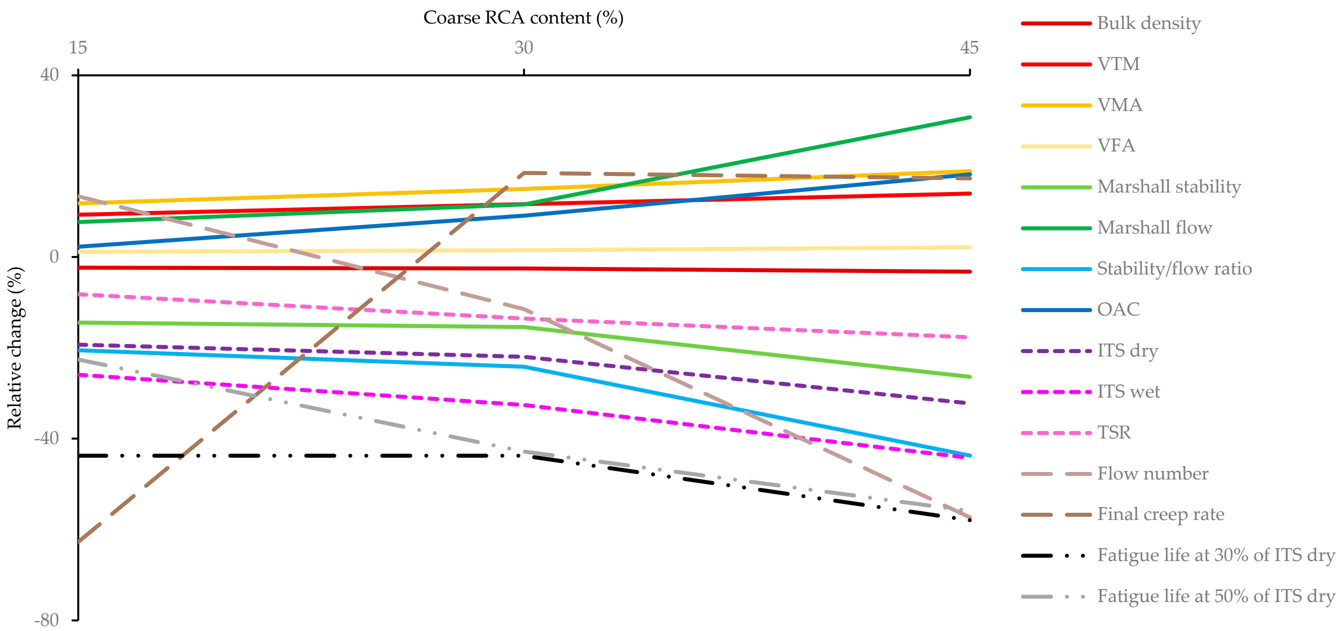


Figure 10. Analysis of relative changes for the other mechanical properties.

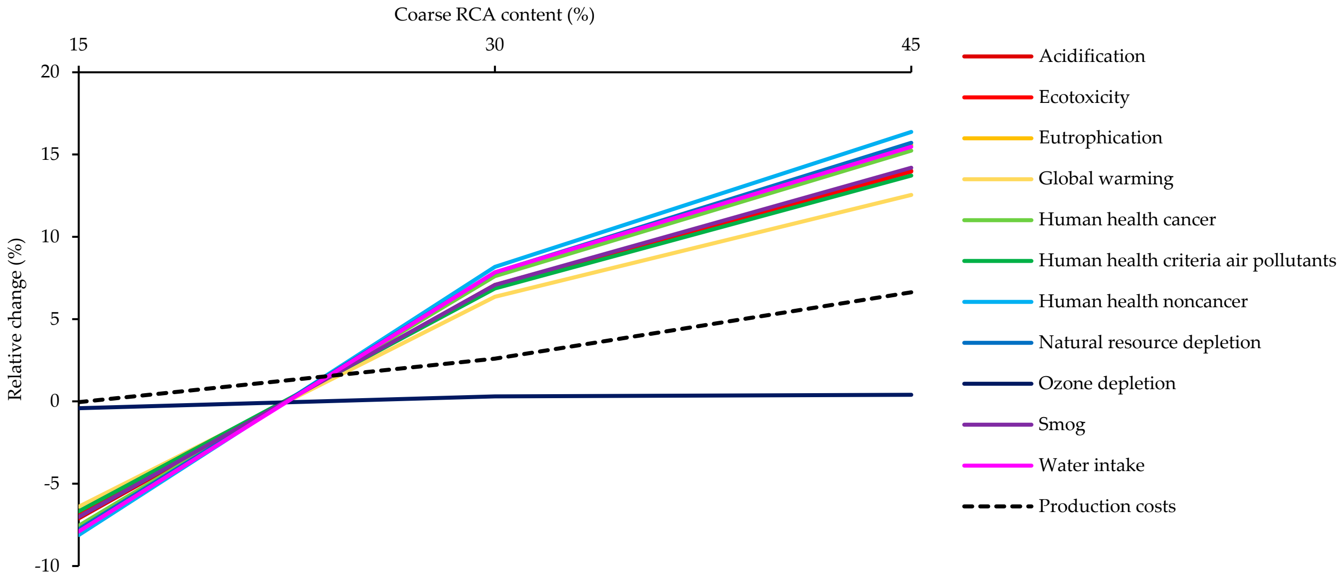


Figure 11. Analysis of relative changes for sustainability properties.

5. Conclusions

In this case study, a comprehensive evaluation of the mechanical and sustainable properties of HMA produced with RCA content was conducted. For this purpose, four coarse RCA dosages (by coarse NA replacement) were considered, i.e., 0, 15, 30, and 45%. From this research effort, the following main conclusions can be drawn:

- A coarse RCA content of 15% increases the HMA's rutting resistance. However, higher replacement dosages cause the opposite effect. Conversely, for all other mechanical properties, any RCA content causes degradation in the HMA's performance. Regardless, that decrease in engineering behavior may be tolerable at low dosages (i.e., 15%). Therefore, from a mechanical standpoint, it is concluded that the optimal content of coarse RCA is 15%.
- Concerning the control mixture (i.e., HMA without RCA), the HMA with 15% coarse RCA presents an improvement in its sustainability performance, comprised of a reduction in its environmental impacts and production costs. Nevertheless, higher RCA contents considerably increase both sustainability benchmarks, i.e., environmental burdens and monetary costs. Thus, at a 15% coarse RCA, the mitigation of NA depletions is more significant than the growth in the OAC. Meanwhile, at 30 and 45% of coarse RCA, the OAC is so elevated that there is no environmental or economic benefit from employing recycled aggregates.
- Overall, in terms of mechanical and sustainability properties, the optimal HMA design was achieved by incorporating coarse RCA at a 15% dosage. Accordingly, it is not recommended to use greater RCA dosages.

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