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STUDY OF HOT MIX ASPHALT CONTAINING RECYCLED CONCRETE AGGREGATES THAT WERE MECHANICALLY TREATED WITH A LOS ANGELES MACHINE

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ABSTRACT

Great quantities of recycled concrete aggregates (RCA) are produced as waste throughout the world. The foregoing study evaluated within a laboratory, the possible use of RCA when it is incorporated as a substitute for the coarse aggregate in a HMA-19 Hot Mix Asphalt. The main problem in the use of RCA in HMA is its high absorption originated by the mortar that coats the particles. This generates an increase of optimum asphalt content within the mix and increases production and construction costs. In addition, said adhered mortar is fragile and brittle. In order to solve such problem, mechanical treatments were carried out on the RCA aggregate's surface by using 50, 100 and 200 revolutions in the Los Angeles machine. Marshall, Indirect Tensile Strength - ITS (under dry and wet conditions), moistures damage resistance (Tensile Strength Ratio – TSR) and Cantabro tests were carried out on HMA mixtures using RCA (with and without the mechanical treatment). An (ANOVA) variance analysis was carried out in order to verify if the results obtained are statistically significant. A general conclusion reports that the superficial treatment of the RCA aggregate in the Los Angeles machine contributes to the increase of resistance under monotonic load, reduces the volume of air within the mix, increases ITS under moisture conditions as well as TSR, which provides better cohesion, adherence and moisture damage resistance. This especially happens when subjecting RCA to 100 and 200 revolutions in the mechanical treatment. However, when using RCA, there is an increase in Cantabro abrasion with regards to the control mix. However, said increase is not statistically significant and mechanical treatment helps to improve response within the test.

Keywords: Recycled concrete aggregate, RCA, mechanical treatment, hot mix asphalt

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1. INTRODUCTION

1.1. Environmental issue with construction and demolition wastes (CDW)

The construction of flexible pavement structures for roadways requires large volumes of aggregates of a natural origin, which may be replaced partially or completely with alternative materials. The demand for natural aggregates materials for the construction of civil construction works, leads to the search for alternative materials that contribute to reducing the exploitation of virgin aggregates, with the purpose of reducing environmental impacts and in order to help preserve ecosystems. In this regard, the substitution of natural aggregates (NA) for alternative aggregates could help to preserve the environment and to reduce economic costs [1].

Construction and Demolition Waste (CDW) is one of the main wastes generated in the world which negatively affects environmental preservation. CDW is a sub product of construction, demolition actions and of the re-shaping of construction works. This waste is mainly comprised of concrete residues, bricks, wood, ceramics, cast, glass, plastics and excavation soils, among others [2-3]. CDW may produce environmental problems, reduce the useful life of sanitary landfills and places of final waste disposal, as well as contaminating water sources and changing the soil's use, among others. According to [4], CDW represents approximately 40% of the total urban wastes of continental China, 26% is the total solid waste of USA and 34% corresponds to all industrial wastes in European countries. On the other hand, in the United Kingdom and Australia, CDW constitutes approximately 50% and 44% of solid waste generation respectively [5].

According to [6], on 2016, European countries generated an approximate CDW quantity of 322 million tons, indicating that Germany is the biggest producer of CDW, with an approximate quantity of 86.4 million tons, followed by the United Kingdom, France, Italy and the Netherlands, with generation of approximately 63.5, 60.2, 34.9 y 19.3 million tons, respectively. Before this scenario, the European Union (EU) proposes Directive (EU) 2018/851 [7], where it establishes that wastes shall be valued as resources, with the purpose of promoting a sustainable management of materials and to contribute in protecting, preserving and improving the quality of the environment, and in consequence, the protection of human and animal health. For such purpose, it is essential to have a sustainable management of resources, which promotes the reutilization and recycling of materials, with the purpose of generating a circular economy. China reports the generation of 2.36 tons of CDW waste during 2003 and 2013 [8]. For the case of Colombia, the main cities such as Bogotá, Medellín, Cali, Barranquilla, Bucaramanga, Pereira and Armenia generate more than 100,000 tons of CDW per day [9].

In relation to this scenario of generation and final disposal of CDWs, several technical studies have been carried out with the purpose of reusing and recycling them as construction materials, mainly in roadway infrastructure construction works [10-11]. The studies found on literature seek to establish several adequate technical and environmental applications of CDWs as construction materials.

1.2. Recycled Concrete Aggregates – RCA

Concrete is the most used construction material in the world. In consequence, it generates concrete residues [12]. In this regard, concrete wastes drawn from CDW may be considered a valuable source of construction material for use. Some studies indicate that concrete residue contents found in construction, demolition, renovation activities, and in various civil engineering activities, oscillates between 40 and 75% [2]. Before this scenario, concrete wastes are subjected to crushing and size reducing processes, which generate a material known as Recycled Concrete Aggregate - RCA [13-14]. RCAs may partially or completely replace natural origin aggregates. According to [12], Japan reports that 98% of RCAs are processed and generate alternative aggregates for construction materials. RCA aggregates are produced mainly through the demolition of elements found in concrete structures, resulting from construction, demolition and repair activities conducted on civil construction works [12]. RCA differ from natural origin conventional aggregates, because of the cement mortar which is bound to their surface after the recycling process. The adhered mortar, is highly porous, increasing water absorption, and contributes to a lower particle density [15]. In addition, said mortar may detach and fracture easily. However, RCAs may present a high utilization potential as alternative aggregates because of its high level of production [6]. This way, the use of RCAs in civil construction contributes to the preservation of the environment, in terms of reducing the exploitation of natural aggregates, minimizing environmental liabilities, cleaning and reducing abandoned terrains and possibly, economic growth produced by the incorporation of alternative materials in construction activities [16].

1.3. Background

Diverse studies report the use of CDW and RCA as materials for civil engineering construction works, such as layers for sub-bases and bases for pavements [17-19], structural concretes [20-30], mortars, rigid pavements [31], and hot mix asphalts - HMA [16, 20, 26, 32-35], among others.

Regarding HMAs, multiple studies (e.g., [15-16, 33-34, 36-37]) have evaluated the partial and total incorporation of RCA aggregates with the purpose of finding a solution to these environmental liabilities, and to this way, propose a sustainable practice in civil engineering [38]. Most of these studies generally conclude that the volumetric and resistance parameters comply with quality requirements demanded by specifications for the manufacturing of HMAs. However, HMAs with RCA require more asphalt contents due to their high absorption and surface area [37, 39], which in many cases, present less mechanical resistance in compared to control mixes manufactured with NA. [1, 33, 36, 40] report that HMAs with RCA display a reduction in indirect tensile resistance, however, [33] evidenced the increase of Tensile Strength Ratio (TSR), compared to conventional HMAs. [34] report a reduction of cohesion in HMAs with RCA aggregates and asphalt modified with crumb rubber, when evaluated in induced moisture damage resistance. However, the authors justify the loss of cohesion with the high viscosity of the modified asphalt. According to [2, 15], resilient modulus with RCA mixes reduced compares to conventional mixes. This was attributed to the coating mortar’s low resistance in RCAs. [36, 39] report the reduction of the dynamic modulus in HMAs in function of the percentage increase of RCA aggregates added. [41] registered increases in permanent deformation in function of the RCA content in the HMA, which may be associated to the increase in asphalt content. On the other hand, [39] concluded that low RCA contents in an HMA contribute to the reduction of permanent deformation. According to [40], the reduction of resistance under monotonic load of ITS and dynamic tests (resilient modulus) can be attributed to the increase of air volume within RCA mixes. The increase of surface voids or the absorption of RCAs, generates the increase of asphalt content and the reduction of a surface coating asphalt layer, consequently generating more air voids between the particles of the HMA. However, in regards to permanent deformation, in a contradictory manner, some studies report that mixes with RCA display a better behavior than control mixes, which may be explained by the greater number of contact points between particles (due to the lesser specific gravity of RCA in comparison to natural origin aggregates), generating a greater asphalt-aggregate binding [40].

According to consulted literature, the incorporation of CDW and RCA aggregates in HMAs is viable from a technical and environmental standpoint because they allow for an environmentally safe process of final disposal. However, due to the heterogeneousness of RCAs, caused by their origin and sources, there are studies that showed contrary conclusions in regards to its application in HMAs [42]. However, there is consensus in regards to the presence of RCA in mixes considerably increasing the optimal asphalt content [37, 39, 43]. Before this scenario, [33, 35] propose some considerations for the use of CDW and RCAs in HMAs: (i) not using the fine fraction of CDW and RCA due to its high content of mortar, cement and impurities; (ii) eliminating the content of cast and ceramic in coarse CDW fractions; (iii) guaranteeing a minimum amount of time and an elevated temperature for the mix in order to fill voids with RCA asphalt; (iv) using additives in order to promote adherence between aggregates and asphalt. Other authors recommend the use of chemical additives, asphalt emulsions and cooking oil residues, among others, in order to treat the surface of recycled aggregates and to reduce absorption [1, 44-47]. Among the most used chemical additives for reducing the absorption of RCAs, the following can be found: silicon resin solution, silane solution, nano silica, silane siloxane in Hydrochloric, Acid (HCl) and Calcium Metasilicate (CM). The use of these superficial chemical treatments have improved the mechanical behavior of evaluated HMAs [45-47]. However, there are limitations that arise due to high economic costs, specific environmental conditions for use, and the lack of homogenization of RCA treated on the field [1].

1.4. Problem statement and objective

Based on the bibliographical review carried out, the studies reported by [1, 44-47], used chemical treatments on the surface of recycled aggregates (CDW and RCA) in order to reduce asphalt content in HMAs. Differently to other studies, the foregoing study carried out a previous mechanical treatment on the coarse fraction of RCA in a Los Angeles Machine for its posterior use in HMAs. Said treatment was carried out with the purpose of reducing the amount of mortar adhered to RCA, as well as the probability of fracture and abrasion wear of said mortar under mechanical load, as well as its porosity, superficial absorption, and also to reduce the content of asphalt needed in order to coat mix aggregates.

Marshall, Indirect Tensile Strength - ITS (under dry and wet conditions), moistures damage resistance (Tensile Strength Ratio – TSR) and Cantabro tests were carried out in an HMA, when using a mechanically Los Angeles Machine treated RCA as a substitute for part of the coarse fraction of a NA. This study used an innovative technique, given that the mechanical treatment proposed on the coarse fraction of RCA aggregates has not been studied in asphaltic mixes.

2. MATERIALS AND METHODS

2.1. Materials

RCA is extracted from the collection and crushing process of a CDW from the city of Bogotá. D.C. (Colombia). Table 1 presents the properties of the NA and RCA. Control mix is HMA-

19 type [48]. The used particle size distribution was central curve (see Figure 1) recommended for HMA-19 mixes.

Table 1 Physical properties of aggregates

Test	Standard	Unit	NA	RCA	Requirement
Abrasion in Los Angeles machine	ASTM C131-06	%	19.5	32	25-35
Micro-Deval	ASTM D6928-03	%	22.3		25 maximum
Flattening index	NLT 354-91	%	19	13	10 maximum
Elongation index	NLT 354-91	%	14	12	10 maximum
Fractured particles (1 side)	ASTM D 2419-95	%	85.2	91.4	85 minimum
Sand equivalent value	ASTM D2419-09	%	63	62	50 minimum
Soundness of aggregates by use of magnesium sulfate	ASTM C 88-05	%	13.34	45.94	18 maximum
Bulk specific gravity	ASTM C127-07	g/cm^3	2.60	2.40	-
Absorption	ASTM C127-07	%	3.1	6.5	-
Specific gravity fine aggregates	ASTM C128-07a	g/cm^3	2.64	2.79	-

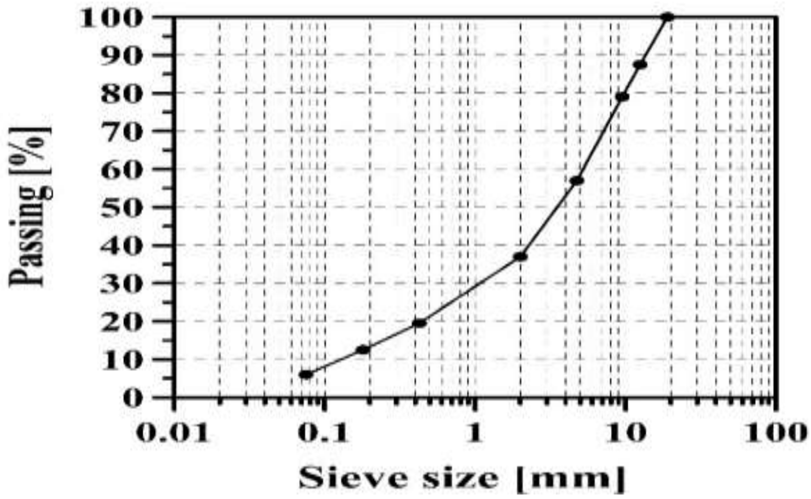

Figure 1 Particle size distribution of HMA-19

The physical characteristics of asphalt cement used (AC 60-70) are displayed on Table 2, and comply with the quality requirements demanded for the manufacturing of HMA-19 mixes according to [48].

Table 2 General properties of AC 60-70

Test	Method	Unit	Recommended value	Result
Tests on the original asphalt				
Specific gravity	AASHTO T228-04	-	-	1.012
Penetration (25°C, 100 g, 5 s)	ASTM D5/D5M-13	0.1 mm	60-70	62.5
Penetration Index	NLT 181-88	-	-1.2/+0.6	-0.94
Viscosity (60°C)	ASTM D4402-15	Poises	1500 minimum	1770
Softening point	ASTM D36-06	°C	48-54	49
Ductility (25°C, 5cm/min)	ASTM D113-99	cm	100 minimum	>105
Flash and fire points	ASTM D92-01	°C	230 minimum	289
Tests on the residue after RTFOT (Rolling Thin Film Oven Test)				
Mass loss	ASTM D2872-12e1	%	0.8 maximum	0.63
Penetration (25°C, 100 g, 5 s)	ASTM D5/D5M-13	%	50 minimum	77

2.2. RCA Mechanical Treatment in the Los Angeles Machine

Before incorporating RCA into the HMA, there was a wear related mechanical treatment carried out in the Los Angeles Machine. For such purpose, dry samples of 5000 grams of the coarse fraction of RCA were subjected to a Los Angeles machine in 50,100 and 200 revolutions, with an abrasive load of 10 spheres and speed of 40 revolutions/minute. After mechanical treatment, separation was carried out in two fractions that comprise sizes between ¾"-½" y ½"-3/8". With the purpose of evaluating the physical properties of RCAs, gradation tests were carried out, as well as abrasion tests in the Los Angeles Machine (ASTM C131-06), elongation and flattening index tests (NLT 354-91), fractured faces (ASTM D 2419-95), specific gravity and absorption (ASTM C127-07) were also carried out. Figure 2 presents the equipment for superficial treatment, as well as the RCA aggregate samples with treatments of 50, 100 and 200 revolutions in the Los Angeles Machine. These aggregates were named RCA-50, RCA-100 y RCA-200, respectively.

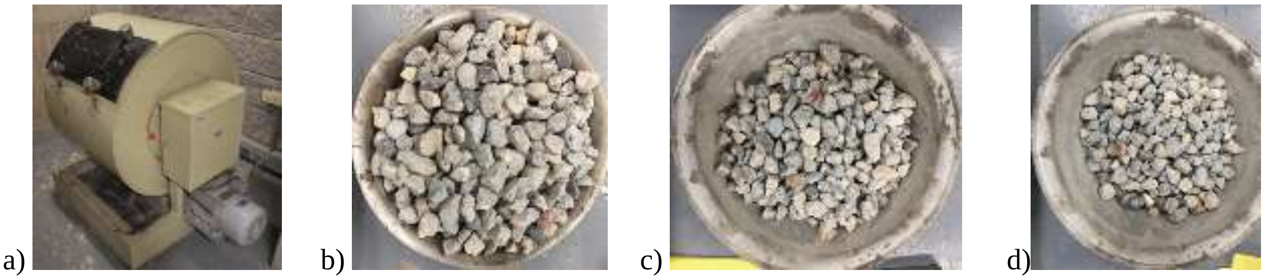

Figure 2 Mechanical treatment on the coarse fraction of RCA: (a) Los Angeles Machine; (b) RCA after 50 revolutions; (c) RCA after 100 revolutions; (d) RCA after 200 revolutions

2.3. Asphalt mix design and Marshall test

Initially, 16 Marshall samples were manufactured (4 samples with 4 asphalt percentages), compacted by 75 blows per face with dimensions of 4'' diameter and 2.5" height, following the guidelines established by the ASTM D1559. These samples named as control samples (HMA-19), employed AC 60-70 and the NA. The reference particle size distribution curve used is depicted in Figure 1. Compacting and mix temperatures were 140°C and 150°C, respectively. These temperatures were obtained based on the criteria established by the ASTM D6925 specification for HMAs (required viscosity for obtaining mix and compacting temperatures is of 170 cP and 280 cP, respectively).

Posteriorly, 64 Marshall samples were manufactured (4 samples with 4 asphalt percentages, and 4 RCA incorporations), following the same process carried out on control samples, but substituting part of the coarse fraction of NA with RCA (particles that pass through sieve 3/4" and withheld in sieve 3/8"; 21% of substitution in mass of the total NA). This percentage was chosen given that the reference literature generally recommends the use of RCA as a substitution of the coarser fractions of the aggregate. The incorporation of RCA was carried out without treatment (0 revolutions in the Los Angeles machine) and with prior mechanical treatments of 50, 100 and 200 revolutions in the Los Angeles Machine. These mixes were named HMA-RCA, HMA-RCA50, HMA-RCA100 y HMA-RCA-200, respectively.

Marshall tests (ASTM D1559) were carried out on HMA-19 samples (control), HMA-RCA, HMA-RCA50, HMA-RCA100 and HMA-RCA-200 with the purpose of obtaining parameters for resistance under monotonic load (stability – *S*, flow – *F* and *S/F* ratio) and the volumetric compositions of mixes (volume of air voids – *Va*, voids in the mineral aggregate – *VMA* and voids filled with asphalt – *VFA*). *S* and *F* were obtained at a deformation velocity of

48mm/minute until rupture, and the temperature for samples was 60°C. Based on the results obtained in this phase, the optimal asphalt content in percentage (*OAC*) for use was chosen for the execution of posterior phases.

2.4. Indirect Tensile Strength (ITS)

Using the *OAC* determined in the Marshall test, 6 Marshall samples for each type of mix (HMA-19, HMA-RCA, HMA-RCA50, HMA-RCA100 and HMA-RCA-200) with the purpose of measuring indirect tensile strenght at 25 °C, following the guidelines established by ASTM D6931. Each sample was subjected to the application of a monotonic load with a deformation velocity of 50 mm/minute until rupture.

The resistance determination process was carried out on conditioned samples (wet - ITS_W) and unconditioned samples (dry – ITS_D). Conditioned samples were submerged in a water bath at 60 °C for 24 h. Prior to the indirect tensile tests, the conditioned samples were submerged in water at 25°C for 2 h. With the test results, the resistance to moisture damage parameter *TSR* was calculated using the ratio of indirect tensile strengths (ITS_W/ITS_D). Samples were not manufactured to reach a void content of 7±1%, according to ASTM D6931, in order to evaluate sample resistance in relation to air void content achieved with the *OAC*.

2.5. Cantabro Test

Cantabro tests (with no abrasive load) were performed on 3 Marshall samples per each type of mix (HMA-19, HMA-RCA, HMA-RCA50, HMA-RCA100 and HMA-RCA-200) in the Los Angeles Machine by applying 300 revolutions at 33 revolutions per minute (Cantabro test - NTL 352 (NLT-352/00, 2000). Samples employed the *OAC* determined by the Marshall Test. Sample temperature during test was 25°C. The specimen mass loss is determined as a percentage of the original specimen mass and final mass after of test. Cantabro abrasion loss test was developed as a relative measure of the resistance to disintegration (e.g., raveling) of open graded mixtures. However, for the case of dense HMA mixtures, it can be used in order to evaluate durability (generally including non-load-associated cracking and raveling or weathering) and cohesion properties [49-50].

2.6. ANOVA analysis

In order to evaluate whether the RCA produced statistically significant effects on the HMA mix properties, an analysis of variance (ANOVA) was performed with F-test with a reliability level of 95%. In said analysis, if $F>F_{0.05}$ means that changes in evaluated parameters are significant in relation to control mix.

3. RESULTS AND DISCUSSION

3.1. Properties of mechanically treated RCAs

Figure 3 presents the abrasion results of the RCA coarse fraction subjected to mechanical treatments of 50, 100 and 200 revolutions in the Los Angeles Machine. Logically, it's possible to observe a proportional increase of mass loss in function of the number of revolutions applied. The increase of mass loss is mainly attributed to the detachment of mortar in the coating of RCA particles, which generates an increase of the fine fraction. The increase of fine fraction may be evidenced through the gradation analysis carried out after each mechanical treatment (see Figure 4). Gradation analysis evidences superior curve displacement in function of the number of revolutions applied in the Los Angeles Machine.

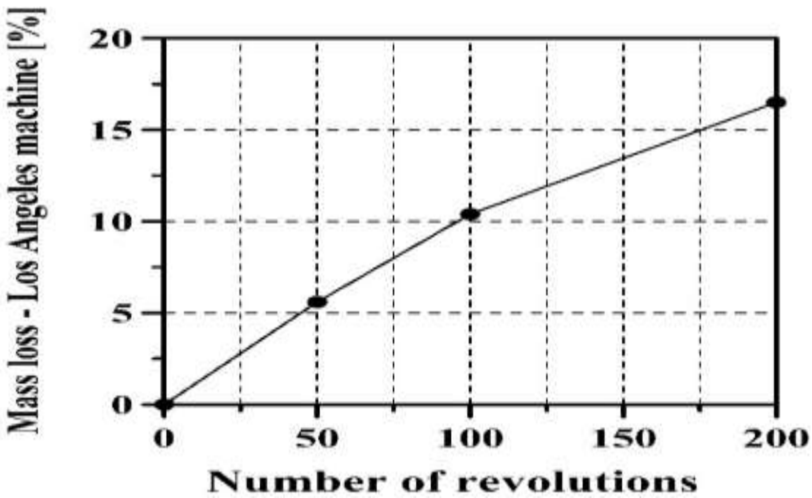

Figure 3 Evolution of mass loss of RCA with number of revolutions in Los Angeles machine

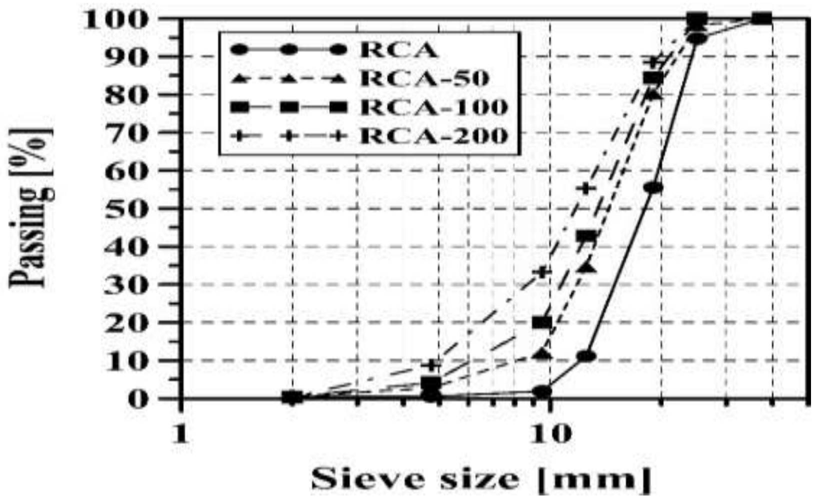

Figure 4 Gradation analysis of the coarse fraction of RCA after abrasion in the Los Angeles Machine

Figures 5-6 depict the evolution of specific gravity (SG) and the absorption of the coarse fraction of RCA with relation to the number of revolutions carried out in mechanical treatment with the Los Angeles Machine. It is possible to observe that the application of mechanical treatment generates an increase in SG within RCA and the reduction of absorption occurs in proportion to the number of revolutions applied in the Los Angeles Machine, which is also attributed to the detachment of coating mortar in RCA.

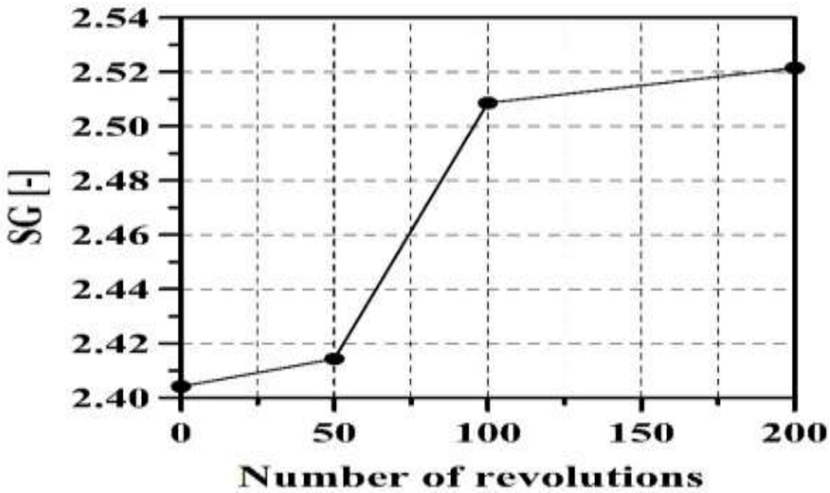

Figure 5 Evolution of RCA SG with number of revolutions

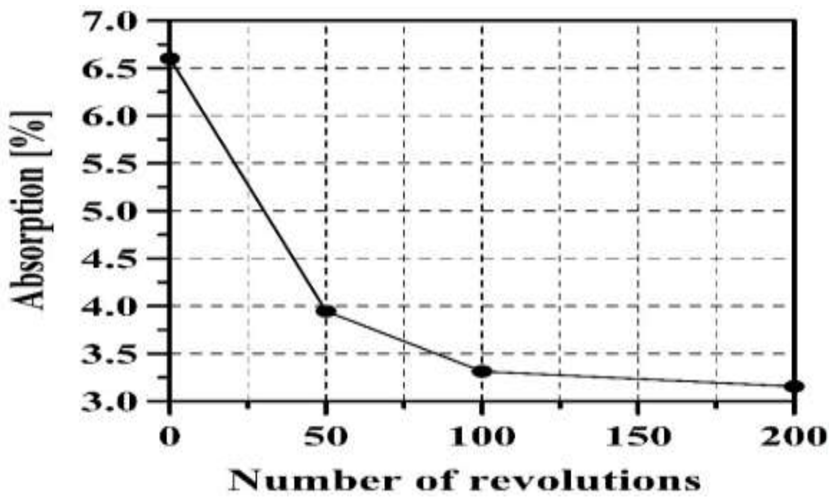

Figure 6 Evolution of RCA absorption with number of revolutions

Figures 7- 8 evidence the results regarding RCA coarse fraction particle shapes, through the elongation index, flattening index and the percentage of fractured faces, with relation to the number of revolutions applied as mechanical treatment in the Los Angeles Machine. According to the results obtained, it is possible to state that the particle shapes of RCA aggregate vary due to mechanical treatment, because of the abrasive contact of particles with steel spheres. In this regard, RCA aggregate particles tend to have a cubic shape, evidenced through the proportional reduction of flattening and elongation indexes and the percentage of fractured faces in relation to the number of revolutions applied. The variation of shape in RCA aggregate particles is also attributed to the detachment of coating mortar.

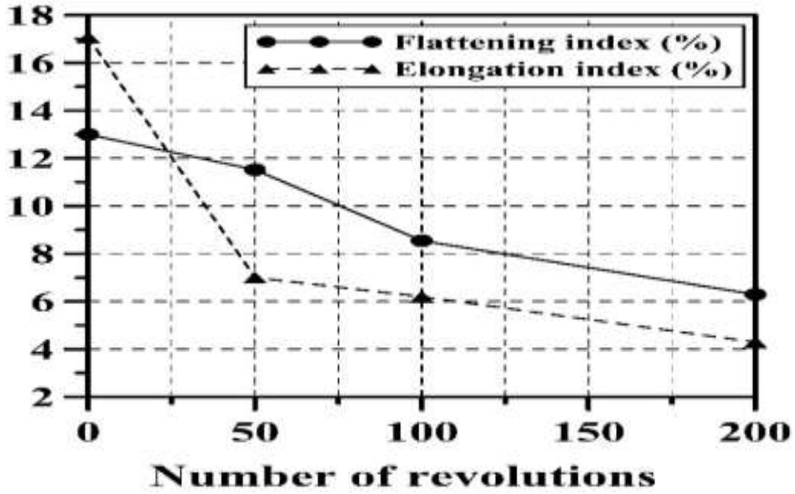

Figure 7 Evolution of the elongation and flattening index of RCA with the number of revolutions applied

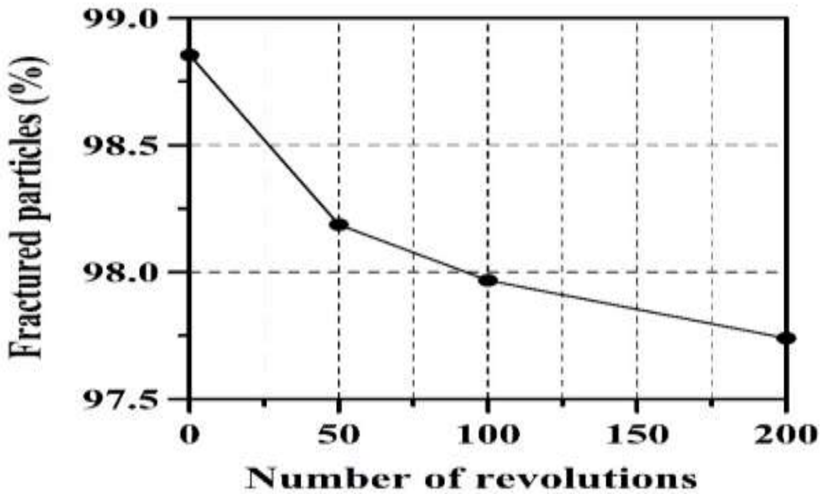

Figure 8 Evolution of the percentage of fractured RCA faces with the number of revolutions applied

3.2. Marshall Test

Table 3 presents the results of the Marshall tests carried out on control sample HMA-19 while considering design criteria for the [48] specification. In this regard, *OAC* is 5.5% (*Va* between 4.0-6.0%, minimum *VMA* of 15%, *VFA* between 65-75%, minimum *S* of 9 kN, *F* between 2-3.5 mm).

Table 3 Control mix Marshall Test

AC (%)	*S* [kN]	*F* [mm]	*S/F* (kN/mm)	*Va* (%)	*VMA* (%)	*VFA* (%)
4.5	10.64	1.76	6.04	7.54	18.28	58.73
5.0	11.52	1.96	5.88	4.96	17.01	70.88
5.5	13.06	2.01	6.48	4.44	17.57	74.75
6.0	11.97	2.68	4.47	4.05	18.24	77.80

The results of the Marshall Tests carried out on mixes that replaced NA with RCA (with and without mechanical treatment) are presented in Figure 9 (*S/F*), 10 (*Va*) and 11 (*VFA*). It is possible to observe a notorious reduction of *S/F* ratio when using 5.5% of asphalt content and RCA with no mechanical treatment (reduction of 0.9 kN/mm or 14%; said reduction is statistically significant based on ANOVA: $F=24.5>F_{0.05}=6$). This is mainly because: 1) the greatest *Va* content (see Figure 10); 2) the lesser coating of particles with asphalt (see Figure 11) as a product of the greater absorption and replacement in mass of NA with RCA (this process generates an increase in the number of particles in the mix due to the lesser SG of RCA in comparison to NA); 3) the lesser abrasion resistance of RCA in comparison to NA.

Contrary to what was mentioned above, when RCA is mechanically treated in the Los Angeles Machine, resistance under monotonic load significantly increases (based on ANOVA, $F>F_{0.05}=6$) with relation to control mix (see Figure 9), and said increases are greater as asphalt content increases. For 5.5% asphalt, the greatest increase is observed (1.2 kN/mm or 16.5%; $F=65.3>F_{0.05}=6$), when RCA is treated in the Los Angeles machine, subjecting it to 200 revolutions. These increases are because of the RCA treatment in the Los Angeles Machine, given that RCA particles reduced their content of adhered mortar, and as a product, a new RCA is obtained with greater wear resistance by abrasion, with less absorption and greater SG, which also generates the reduction of *Va* content (see Figure 10) and a greater coating of particles with asphalt (see *VFA* in Figure 11), in comparison to mixes that used RCA with no mechanical treatment. In addition, mechanically treated RCA undergo a reduction of elongation and flattening indexes, which generates a better accommodation of particles in the mix granular skeleton, which also forms a greater degree of interlocking between aggregates, and in consequence, a better resistance to monotonic load action. On the other hand, mechanical treatment generated superficial wear of RCA particles, which reduces the possibility of generating fine particles during the process of manufacturing and compacting the mix. All of the above impacts in the increase of internal cohesion of mixes that replaced NA with mechanically treated RCA.

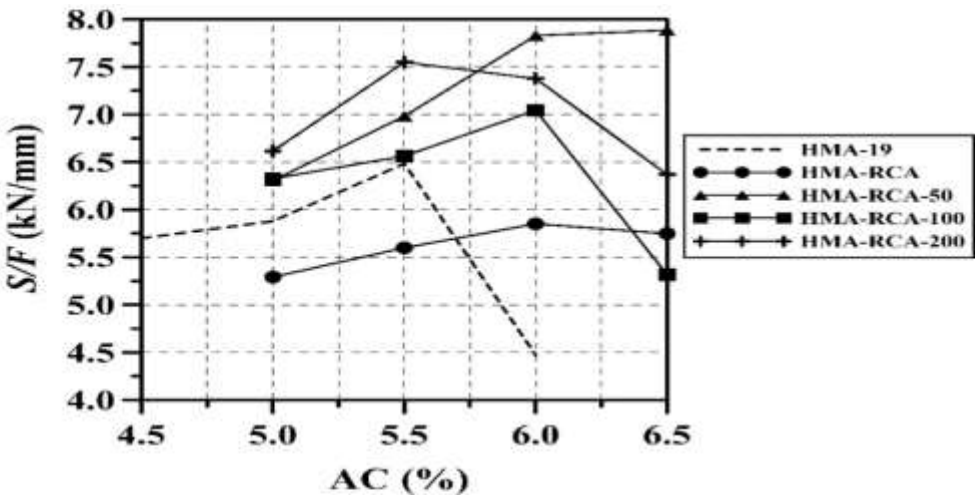

Figure 9 Evolution of S/F ratio with asphalt content

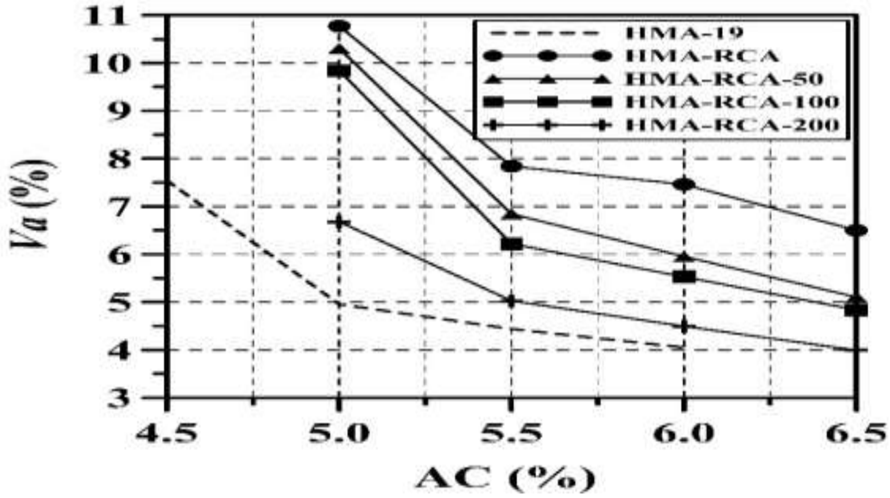

Figure 10 Evolution of Va with asphalt content

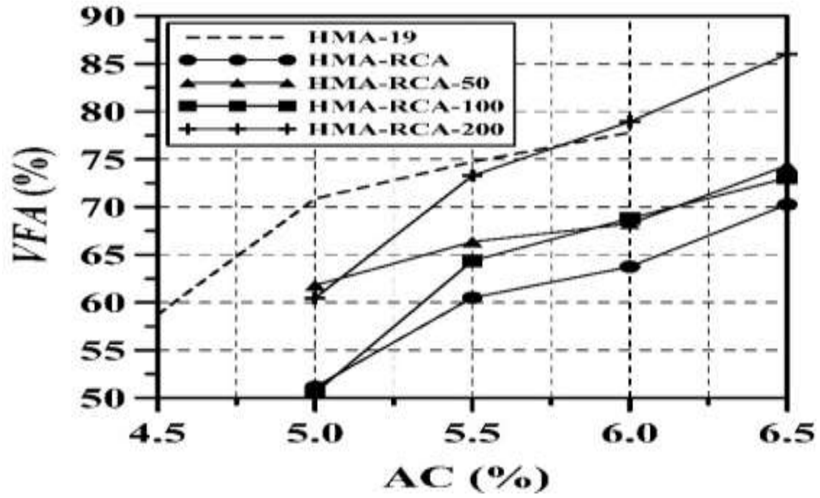

Figure 11 Evolution of VFA with asphalt content

Based on the previously described results, one single asphalt content to be used was defined in 5.5% for the execution of the following experimental phases (ITS and Cantabro tests). Another criterion for defining 5.5% was not increasing OAC, because if this was to be done, in practice, there is a cost increase incurred for mixes.

3.3. ITS tests

Figures 12-13 present *ITS* test results (conditioned and unconditioned) and *TSR* ratio for HMAs (HMA-19, HMA-RCA, HMA-RCA50, HMA-RCA100 and HMA-RCA200). Each type of HMA was manufactured with an *OAC* of 5.5%, as mentioned earlier. Regarding the control mix, RCA mixes display less ITS_D. Despite this, this mechanical parameter increases as the number of RCA mechanical treatment revolutions increases, and the HMA-RCA-200 does not statistically differ to control sample ($F<F_{0.05}=7.7$). Regarding ITS_W, HMA-RCA-100 and HMA-RCA-200 mixes display a greater magnitude in comparison to the control mix and said increase in ITS_W is statistically significant ($F>F_{0.05}=7.7$). This happens despite the fact that RCA mixes present greater *Va*. The opposite case happens for HMA-RCA and HMA-RCA-50 mixes, where it is possible to observe a reduction in ITS_W compared to the control mix. However, for the case of HMA-RCA-50, this reduction is not statistically significant ($F<F_{0.05}=7.7$) with regard to the control mix. In general terms, we observe an increase in *TSR*

ratio when NA is replaced by RCA, and said increases are statistically significant for HMA-RCA-100 and HMA-RCA-200 ($F>F_{0.05}=7.7$). *TSR* ratio is considered to be a moisture damage resistance indicator. In this regard, mechanical treatment in the Los Angeles Machine on RCA surface possibly originated an increase in the adherence of asphalt-aggregate within the asphaltic mix, obtaining the maximum value in HMA-RCA-100 mix. Equally as with the Marshall test, the increase of adherence may be attributed to the reduction of *Va* in RCA mixes, the reduction of coating mortar in RCA particles, the increase of *VFA* and the reduction of elongation and flattening indexes. Likewise, asphalt could more easily adhere to RCA due to its greater surface porosity and rough texture.

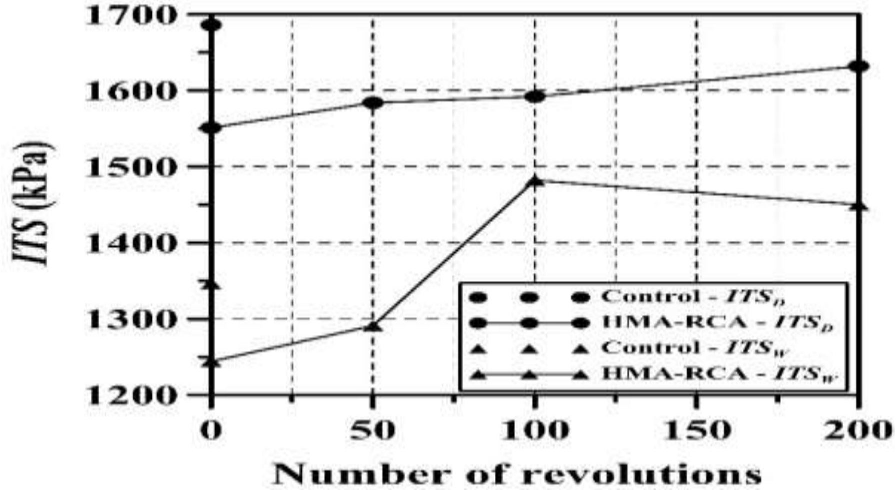

Figure 12 Evolution of ITS with number of revolutions in Los Angeles machine

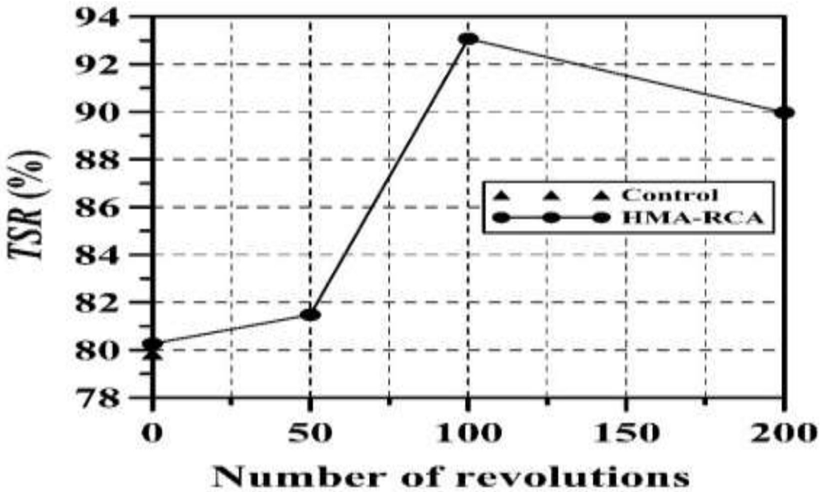

Figure 13 Evolution of TSR with number of revolutions in Los Angeles machine

3.4. Cantabro test

Figure 14 presents Cantabro Test results, which evidence that HMA-RCA mixes present a greater Cantabro mass loss in relation to HMA-19 control mix, mainly as a product of the greater *Va* content and the lesser wear resistance in the Los Angeles Machine of RCA particles that occurs due to the presence of adhered mortar, which could facilitate the detachment of particles during the testing process. This reduction was statistically significant ($F>F_{0.05}=7.7$). Despite the above, RCA mechanical treatment in the Los Angeles Machine for HMA-RCA50, HMA-RCA100 and HMA-RCA200 mixes helped to increase Cantabro resistance, and when compared to the control sample, test results were not statistically significant ($F < F_{0.05}=7.7$).

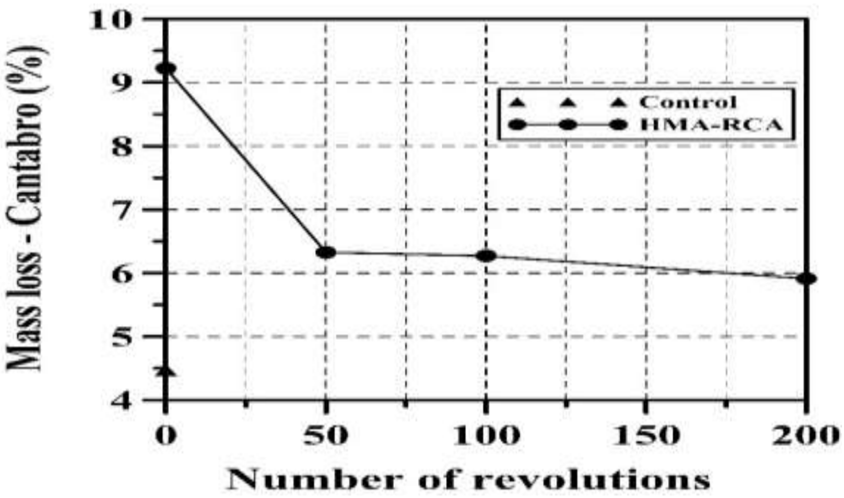

Figure 14 Cantabro mass loss evolution

4. CONCLUSIONS

This paper evaluates mechanical behavior when using RCA aggregates in HMA mixes. For this purpose, part of the coarse fraction of natural origin aggregate NA (particles that pass-through sieve 3/4" and that are withheld in sieve 3/8"; 21% replacement of the total NA in mass) was replaced with RCA material which was mechanically treated in the Los Angeles Machine with 50, 100 and 200 revolutions in order to mainly reduce the coating mortar, and as consequence asphalt absorption as well. Based on the results obtained, it is possible to conclude the following:

- When replacing NA with non-mechanically treated RCA, the mix notoriously reduced its resistance to monotonic load under Marshall and ITS tests, as well as Cantabro resistance.
- In general terms, treating RCA in the Los Angeles Machine in order to replace the coarse fraction of NA was beneficial, given that physical characterization results indicate that subjecting the material to mechanical treatment generates the reduction of adhered mortar, particle absorption and the indexes of flattening and elongation. Likewise, it helps to reduce the probability of adhered mortar detachment during mechanical load, and it increases SG and abrasion wear resistance. All of these properties are more evident when the number of revolutions applied to RCA during mechanical treatment is greater (this study used 200 revolutions).
- The changes previously reported in the Los Angeles Machine mechanically treated RCA allow to reduce *Va* in the mix, increase *VFA* and in consequence, increase resistance under monotonic load in the Marshall Test measured through *S/F* ratio. The above mainly occurs when RCA is subjected to 100 and 200 revolutions of mechanical treatment (HMA-RCA-100 and HMA-RCA-200, respectively). These (HMA-RCA-100 and HMA-RCA-200) also underwent an increase in ITS_W and *TSR* parameters with relation to the control mix, which is an indicator of increase in moisture damage resistance. It is important to highlight that all of these resistance increases were obtained without having to increase the asphalt content within the mix.
- On the contrary, a slight reduction in Cantabro resistance was observed for HMA-RCA-100 and HMA-RCA-200 mixes with relation to the control mix, however, said reduction was not statistically significant. This slight reduction was mainly due to the greater *Va* content of RCA

mixes and the remaining presence of adhered mortar, which could facilitate its detachment during the testing process.

- Application of RCA in the proposed manner (replacing part of the coarse fraction of NA in a conventional mix) is viable from a technical and environmental standpoint, because it allows for a form of safe final disposal that will contribute to the preservation of the environment, promoting sustainable practices in civil engineering.
- In practice, mechanically treating RCA in the form which this study proposes may increase production costs. Future research must be conducted in order to assess economic feasibility of mechanical treatment proposed on a real scale. Likewise, other mechanical properties must be assessed in the mix, such as stiffness under cyclic load, resistance to permanent deformation and fatigue.

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