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Combining Reclaimed Asphalt Pavement (RAP) and Recycled Concrete Aggregate (RCA) from Cuba to Obtain a Coarse Aggregate Fraction

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Abstract: In Cuba, tons of construction and demolition waste (CDW) are generated during urban construction and reconstruction activities every year. The use of CDW, such as recycled concrete aggregates (RCA) and reclaimed asphalt pavement (RAP), in pavement construction is a viable solution to preserve the consumption of natural aggregates (NA), and to minimize the impact of landfill. The main objective of this work is to obtain a 5–10 mm aggregate fraction of RCA and RAP, to obtain an appropriate recycled coarse aggregate for manufacturing hot mix asphalt (HMA). Each source of RCA, RAP and NA, and the combinations RCA/RAP (0/100, 25/75, 50/50, 75/25 and 100/0) were characterized (moisture, asphalt content of RAP, specific gravity, water absorption, and flakiness index) for determining a better combination. The results showed that the combination (RCA/RAP) that best meets the NA aggregates specifications used for hot mix asphalt were RCA/RAP: 25/75 and 50/50. The results show the possibility of combining both wastes to obtain a coarse aggregate fraction with a high environmental benefit, by reducing the use of natural resources.

Keywords: recycled concrete aggregates; reclaimed asphalt pavement; bonded mortar; recycled materials; asphalt mixture; circular economy

1. Introduction

The indiscriminate use of natural resources is one of the causes of the gradual and progressive deterioration of the environment. The global production of construction and demolition waste (CDW) has significantly increased over the last few decades, causing environmental problems due to its uncontrolled disposal [1]. In recent years, the recycling and reuse of CDW has spread to practically all developed countries, together with a growing public awareness of the need to see how materials that have or have not reached the end of their useful life can be recycled. CDW is one of the heaviest and most voluminous waste streams generated in the European Union [2]. In general, CDW are all the wastes produced by the construction and demolition of buildings and infrastructure.

Recycled concrete aggregates (RCA) from CDW differ essentially from natural aggregates (NA), due to the mortar layer that remains adhered on the surface [3]. The adhered cement mortar on RCA is responsible for decreasing the particle density and increasing the water absorption and porosity of the RCA compared to NA [4–8]. Likewise, the crushing process affects the shape, the roughness, and the amount of fine and coarse recycled aggregate obtained [9]. In addition, the amount of flat and elongated particles and their wear resistance, among other properties, can also vary according to the crushing process [10]. Several possible RCAs' applications, such as the concrete [11] and pavement industry [1], have been extensively studied for the replacement of NA. The uses of this waste is currently restricted, because RCA exhibits higher porosity, higher water absorption and lower density, reducing the performance of concrete and pavement [12].

Reclaimed asphalt pavement (RAP) is a byproduct of asphalt pavement rehabilitation, and it has been used as an alternative material in hot mix asphalt (HMA) [13]. The use of RAP has become more widespread in recent decades, because using RAP has proven to be economical and environmentally sound [14]. The materials present in old asphalt pavements have residual value, even when the pavements have reached the ends of their service lives [15]. However, the characteristics of RAP vary greatly depending on the materials that make it up and the type of mixture from which it comes. When RAP is used in mixtures as a recycled aggregate, its quality is very important, since it depends on the initial deficiencies of the mixture design, the wear suffered by the aggregates, and the oxidation during its service life [16]. These RAP differences can result in significant variations in the aggregates characteristics, asphalt content and type of asphalt. The initial quality of the aggregates or after its use in pavement (polished particles) may limit their use in wearing courses, but they could be used for lower layers. To control the variability of the new HMA mixtures, most studies recommend using recycled material from a single source, characterizing, in detail, the reclaimed material [17].

For the use of RAP in mixtures as an aggregate fraction, the material must be characterized by determining moisture content, asphalt content and aggregate size distribution. In addition, the properties of the materials used should be determined. The RAP density obtained after the demolition process of pavements depends on the type of aggregate used and its moisture content, but in general, the values obtained are slightly lower than NA. Recently, the application of RCA in asphalt mixtures has been gaining more attention [18]. Acosta et al. demonstrated that the asphalt mixtures present good behavior, with up to 40% substitution of NA by RCA [19], and the results also corroborate that the stiffness modulus, even at high temperatures, was in line with the recommendations [20]. Al-Bayati et al. [21] studied asphalt mixtures with coarse RCA, treated and untreated. The results were highly successful in both cases and the findings encourage one to use RCA in HMA mixtures, using different percentages of RCA, RAP, and basalt as coarse aggregates in HMA. There are investigations where RCA has been used as aggregates in hot asphalt mixtures, obtaining satisfactory results [22–24], and other types of wastes such as sewage sludge ash [25], or mine tailings [26].

Nowadays, the possibility of using a combination of RCA and RAP in asphalt mixtures has also been demonstrated [27]. The possible use of an alternative aggregate to the NA should comply with the most important properties of the aggregate as size distribution, shape, angularity, texture, water absorption, density, hardness and cleanliness [27], because those properties directly affect the behavior of the asphalt mixture manufactured with them [28,29]. The characterization of residues for substituting natural resources is very important for the success of using them as an alternative. New methodologies have been developed by researchers to improve the approaches covered by the standards [30–32], but also, to date, it is spreading more and more innovative procedures for in situ characterization. An example of this is the extraction of micro coring of materials for performing a nano-identation test on very small samples, and to estimate its physical and mechanical properties [33,34], reducing the costs and time.

Therefore, it is necessary to investigate the use of RCA and RAP as a coarse aggregate in the manufacture of asphalt mixtures. RCA untreated and RAP aggregates have lower quality than NA, because they have higher water absorption, lower density, and lower wear resistance. Individually, the use of RCA or RAP aggregates as a coarse aggregate for manufacturing HMA could be difficult, and maybe one of them would not reach the minimum requirements according to the regulations. However, and with the objective that even with very low-quality, aggregates can be used as a coarse aggregate to manufacture HMA, the combination of different wastes is proposed. The combination of the two wastes could compensate for the defects that each of them have separately.

The characterization as an aggregate, and their possible combinations (RCA/RAP), result in a reduction of the negative environmental impact generated by these wastes and the improvement of Cuba's road network.

In Cuba, tons of CDW are generated during urban construction and reconstruction activities every year, and they occupy landfills—sometimes with hazardous materials that deteriorate the environmental condition [35]. Environmental policies in Cuba have been developed for managing CDW, because its natural resources are limited. Hence, several research studies have tried to reuse RCA for manufacturing HMA [19,20] in the place of NA, to reduce the negative impact generated by the wastes and the natural resources exploitation developing the Cuban sustainable construction.

In this research, properties such as particle density, water absorption and size distribution are analyzed. In addition, the asphalt and moisture content from the sources of RAP were also determined. For this purpose, three sources of RCA and three sources of RAP were analyzed and compared to a NA (5–10 mm fraction). The combinations RCA/RAP analyzed were: 0/100, 25/75, 50/50, 75/25, 100/0. This does not mean that the combination of both residues improves the properties of the NA, but it would allow one to obtain a recycled coarse aggregate with two sources of wastes, and whose final properties could be according to the minimum requirements demanded by the regulations.

2. Materials and Methods

2.1. Materials

In this work, three types of materials were analyzed: a NA from the Alacranes quarry—as a reference for the comparisons, three sources of RCA and three samples of RAP from different areas.

The NA fraction used was 5–10 mm (Figure 1). In all RAC and RAP samples, the fractions have remained constant (5–10 mm) to compare with NA.

Figure 1. Natural aggregate (NA) used as reference.

The three types of RCA used in this research come from two different sources. RCA from a sidewalk demolition (RCA-SW)—Figure 2c—and the other two types from Prefabricated Plant "José Martí" (Cuba). The prefabricated plant is specialized mainly in the manufacture of reinforced concrete precast core floor slabs of 15 to 20 cm thickness, and a concrete with 35 MPa of compressive strength. RCA from the slabs were discarded because they would break during transport from the manufacturing site to the storage place or did not meet with the minimum quality requirements (RCA-PCF)—Figure 2a. RCA from the remaining concrete was left in the mixer or from the slabs manufacturing process (RCA-PCFM)—Figure 2b. This waste presents a high degree of homogeneity due to its low contamination with other types of waste, such as steel, wood or plastics.

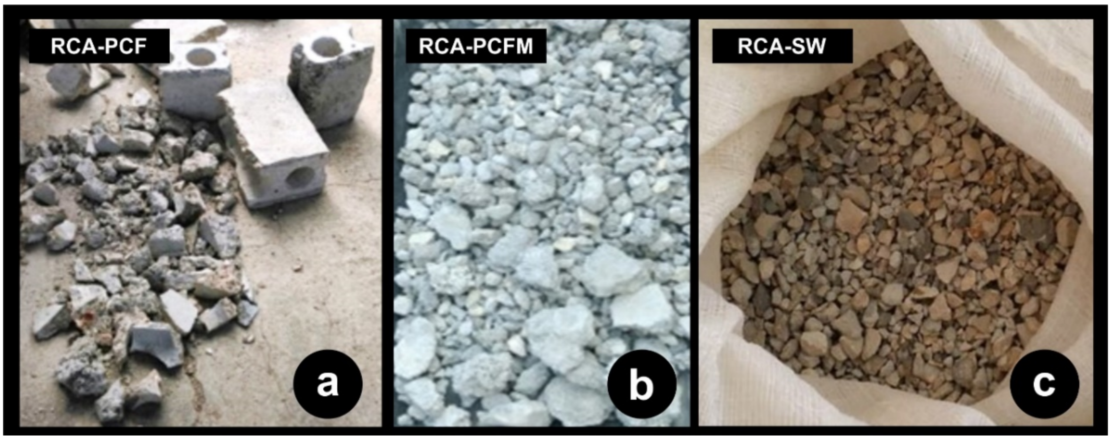

Figure 2. Recycled concrete aggregate (RCA). (**a**) Wastes from reinforced concrete precast core floor slabs (RCA-PCF); (**b**) remaining concrete from the manufacturing site (RCA-PCFM); and (**c**) sidewalk waste from crushing (RCA-SW).

Three sources of Cuban RAP were also analyzed (Figure 3); one from the milling of Primelles Avenue (RAP-P)—Figure 3a; another from Santa Catalina Avenue (RAP-SC)—Figure 3b; and the last from the collection of the Guanabacoa plant (RAP-G)—Figure 3c.

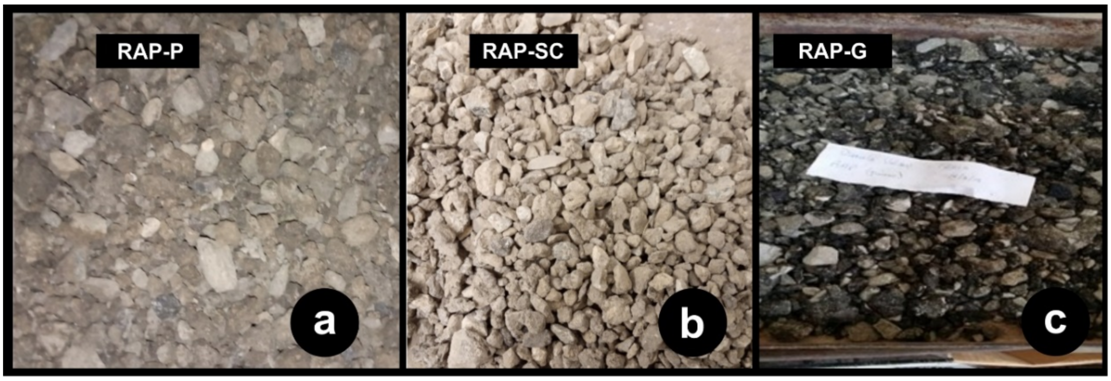

Figure 3. Reclaimed asphalt pavement (RAP). (**a**) From milling Primelles avenue (RAP-P); (**b**) from milling Santa Catalina Avenue (RAP-SC); and (**c**) from Guanabacoa plant (RAP-G).

As can be seen, Table 1 describes the selection process of the three sources of RCA, and three sources of RAP.

- RCA-PCFM1: from the loose material left in the concrete mixer, or spilled in the production process of the reinforced concrete precast core floor slabs, and then sieved in 5–10 mm fraction.
- RCA-PCFM2: from the loose material left in the concrete mixer or spilled in the production process of reinforced concrete precast core floor slabs larger than 10 mm; it was crushed in a jaw crusher and then sieved in 5–10 mm fraction.
- RCA-PCFM3: from the loose material left in the concrete mixer or spilled in the production process of reinforced concrete precast core floor slabs, which was crushed in a jaw crusher and sieved to obtain particles of 5–10 mm.
- RCA-PCF: coming from the crushing of reinforced concrete precast core floor slabs that have been broken in the storage process, or do not present the required quality. The waste was reduced to a size smaller than 30 cm with a rotary hammer, manually extracting the pre-stressed steel. Then, the blocks were crushed in a jaw crusher, the obtained material having a size of 5–10 mm.

- RCA-SW: the waste remaining of the demolition of the sidewalk was first crushed with a rotary hammer until obtaining a maximum size of 30 cm. Then, the blocks were introduced in a jaw crusher for obtaining particles with a size of 5–10 mm.

Table 1. Details of the RCA (recycled concrete aggregates) and RAP (reclaimed asphalt pavement) samples analyzed.

Sample	ID.	RCA (Recycled Concrete Aggregates) and RAP (Reclaimed Asphalt Pavement) Source	Process
1	RCA-PCFM1	Remaining concrete from the manufacturing site of the slabs	Sieved 5–10 mm
2	RCA-PCFM2		Crushed the remaining material > 10 mm and after sieved 5–10 mm
3	RCA-PCFM3		Crushed and sieved 5–10 mm
4	RCA-PCF	Waste from reinforced concrete precast core floor slabs	Crushed and sieved 5–10 mm
5	RCA-SW	Waste from sidewalk	Crushed and sieved 5–10 mm
6	RAP-P	Reclaimed asphalt pavement (RAP)	Milling of Primelles Avenue and sieved 5–10 mm
7	RAP-SC		Milling of Santa Catalina Avenue and sieved 5–10 mm
8	RAP-G		Pavement milling collected from Guanabacoa plant and sieved 5–10 mm

A microstructural analysis of the RCA was carried out through scanning electron microscopy (SEM), to appreciate their morphology and the amount of mortar adhered to the surface that influences their porosity, absorption and specific weight.

As an example of the RCA used in this research, Figure 4 shows the morphology of the RCA-PCF and RCA-SW. The small fissures observed in Figure 4a would have resulted from a shrinkage [36] or the crushing process. Most of the fissures are associated with the interface between cement paste and aggregate, as can be seen in Figure 4b, and responsible for the failure of the RCA. Different factors can affect the properties of RCA, but the adhered mortar has a strongly negative property because it increases the open porosity [37].

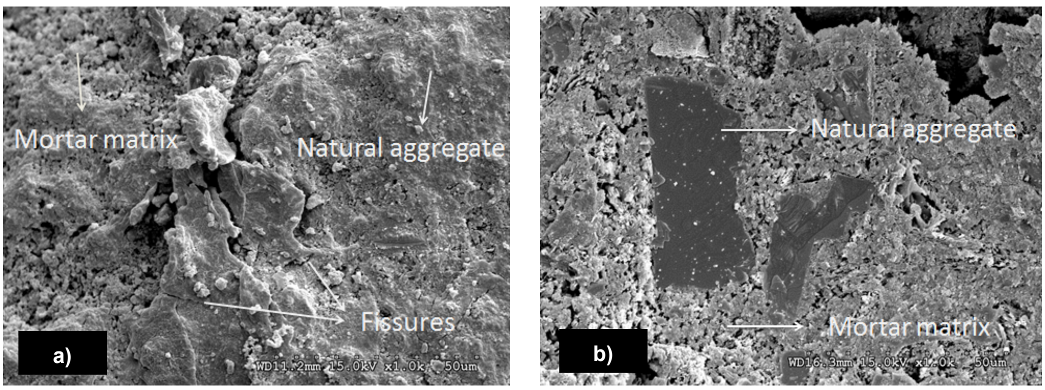

Figure 4. SEM micrographs at 1000× magnification of (**a**) RCA-PCF and (**b**) RCA-SW.

To verify the homogeneity of the RCA and the possible presence of polluting agents, the determination of their chemical components and mineralogical phases were also carried out.

Table 2 shows the results obtained in X-ray fluorescence (XRF). The main component of both samples was CaO (carbon oxide), with 39.09% and 42.29% for RCA-PCF and RCA-SW, respectively. This indicated that the NA used for manufacturing the concrete was predominantly limestone, so its adhesion to the binder is expected to be good, since limestone is one of the materials used worldwide to improve asphalt properties [38]. A high content of CaO in the aggregate used for asphalt mixtures increases the stiffening rate resulting in stiffer mastics, allowing strengthening of the aggregate-binder bond and the effective strength properties of the asphalt mixture manufactured with this aggregate [39,40].

Table 2. Chemical composition of the RCA from the reinforced concrete precast core floor slabs (RCA-PCF) and from the sidewalk (RCA-SW).

Oxides	RCA-PFC	RCA-SW
Na_2O	0.26	0.240
MgO	6.12	4.688
Al_2O_3	1.38	2.203
SiO_2	5.98	8.226
SO_3	0.50	0.085
K_2O	0.22	0.738
CaO	39.09	42.296
Fe_2O_3	0.76	1.332
TiO_2	–	0.184
SrO	–	0.187
BaO	–	0.604

"–"means that there is no evidence of this oxide in the analysis.

Figure 5 shows the X-ray diffractograms (XRD) of RCA-PFC and RCA-SW—values for the scattering angles and the peaks of the intensities for both samples. As can be seen, both samples contain calcite and dolomite, which promote good asphalt binder adhesion [41]. Calcite is also known to not contribute to stripping potential in asphalt mixtures [41]. There was no presence of Portlandite of the samples, indicating the carbonation of the concrete samples.

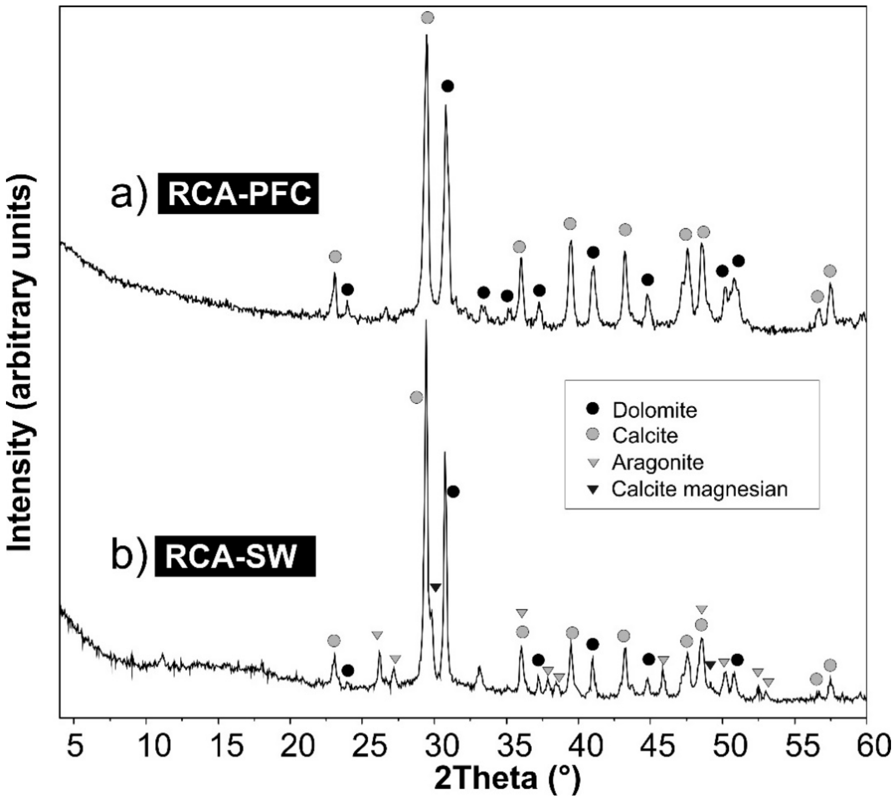

Figure 5. XRD diffraction for determining the mineralogical composition of the waste (**a**) RCA-PFC (**b**) RCA-SW.

The parameters chosen for previously characterizing the RAP samples were the moisture and asphalt content. The determination of moisture and asphalt content was performed according to NLT-359 [42] and NLT-164 [43], respectively. The RAP obtained from most wearing surface mixes will usually have an asphalt content in the 4.5 to 6 percent range. Information on the moisture content of RAP stockpiles is sparse, but the moisture content of the RAP increases while in storage. As can be seen in Table 3, both parameters determined are inside the typical range of values of RAP provided in [44].

Table 3. Moisture and asphalt content for the RAP sources studied: (a) from milling Primelles avenue (RAP-P); (b) from milling Santa Catalina Avenue (RAP-SC); and (c) from Guanabacoa plant (RAP-G).

Source	Moisture Content (%) According to NTL-359/87 [42]	Typical Range of Values According to [44]	Asphalt Content (%) According to NLT-164/90 [43]	Typical Range of Values According to [44]
RAP-P	5.93	Normal: 4.5–6% Maximum 3–7%	1.48	Normal: ≤ 5% Maximum 7–8%
RAP-SC	5.14		1.51	
RAP-G	4.63		1.86	

The RAP-G were obtained from the collection of the Guanabacoa asphalt plant. To homogenize the sample collected from the asphalt plant, it was processed by a secondary crushing and sieving of the material (5–10 mm). RAP-SC and RAP-P samples were directly obtained from the demolition of the avenues' pavement (Santa Catalina and Primelles, respectively), and sieved to obtain the size required.

2.2. Methodology

The standard test method used for the determination of specific gravity and water absorption of coarse aggregate is described in the NC 187 standard [45]. The sample used for determining the specific gravity was cleaned from powder or any other material adhered to the particle surface, and it was dried using an oven until constant mass. When the aggregate was dried and achieve the temperature room it was submerged in water for 24 h.

The particle shape of the product material was measured using the flakiness index method, according to NC 189 standard [46], which is valid for material in the size range 4.76–76.2 mm.

Finally, a statistical analysis was applied for establishing the structure of the variable dependence and their interrelationship, using the code SPSS 22.0 (from IBM Corp., Armonk, N.Y., USA). An analysis of variance (ANOVA) established the effect of each factor on the parameters. For each dependent variable, the Levene statistic test was applied. Its value was <0.05 indicating no equality of variances. Therefore, the Games-Howell test was applied, to compare the means finding differences between types of aggregates (RCA, RAP and combinations compared with NA).

3. Results and Discussion

The following are the results of tests carried out on recycled (RCA and RAP) and NA for comparing individually, and finally a combination of RCA and RAP. Six samples were tested to obtain the mean value represented in the figures, to achieve the repeatability and representativeness of the results. The results obtained were compared with requirements established for coarse aggregates according to Cuban specifications NC 253 [47] for manufacturing HMA. A minimum specific gravity (2500 kg/m^3), a maximum absorption (from 0.8 to 2%) and a maximum flakiness index (10%). However, depending on the country and the material to be manufactured from these coarse aggregates, the requirements will differ.

3.1. Recycled Concrete Aggregates (RCA) Characterization

3.1.1. Particle Density and Water Absorption

Figure 6 shows the specific gravity (a) and absorption (b) of the RCA and NA samples. The RCA samples present lower specific gravity (Figure 6a) values than the NA, and consequently a higher water absorption (Figure 6b). This finding is according to many researchers, and it is due to the existence of attached mortar [48,49], because of the lower density and higher porosity of cement paste attached to the RCA [9].

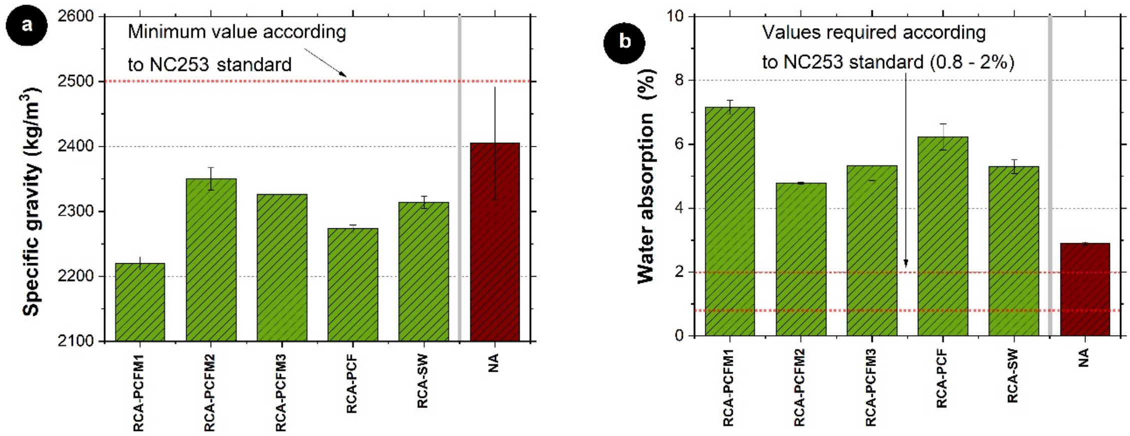

Figure 6. (**a**) Specific gravity and (**b**) water absorption at 24 h of the RCA samples studied compared with NA. Red-dot lines indicate the values required according to NC 253.

It can be seen (Figure 6a) that the samples RCA-PCFM2, RCA-PCFM3 and RCA-PCF and RCA-SW present higher specific gravity than those formed with loose material, without any process of crushing (RCA-PCFM1). The difference is that the samples RCA-PCFM2, RCA-PCFM3, RCA-PCF and RCA-SW were crushed, facilitating the detachment of the mortar adhered to the surface of the old natural aggregates.

It seems to be evident that there are differences between the samples crushed in a jaw crusher and the samples used directly from the sources and sieved to obtain the size 5–10 mm. In addition, it can be seen from the results in Figure 6a that the samples crushed (RCA-PCFM2, RCA-PCFM3, and RCA-SW) have slightly lower specific gravity than NA.

The lowest value in terms of specific gravity was found in the sample RCA-PCFM1. Those samples had origin in a concrete product crushed for reducing the size (other samples are waste material from the production). This implied adequate compaction during the origin, and they were more difficult to detach the mortar adhered to the natural aggregates during the RCA production, resulting in a less dense and more porous RCA obtained after the crushing process [50].

Analogous results were obtained for water absorption in RCA samples (Figure 6b). They were according to the specific gravity obtained. The lower specific gravity on the samples, the higher water absorption was observed, and vice versa. RCA-PCFM1 exhibited the lowest specific gravity and the highest water absorption. This is probably due to the inexistence of a process of compaction or treatment in origin, because they were collected directly from the material left in the concrete mixer, or spilled in the production process of the reinforced concrete precast core floor slabs. In general, the samples have lower specific weights and higher absorptions with respect to the value established in the NC 253 standard [47].

3.1.2. Elongated Particles

Figure 7 shows the flakiness index of the RCA samples compared with the NA sample. As can be seen, almost all of RCA samples presented higher quantity of flaky particles compared with NA.

The lower flakiness index was observed in RCA-SW. As previously mentioned, the origin of the RCA from a precast concrete results in a higher resistance to crushing for reducing the size. All samples have lower values than those established in the NC 253 standard (<10%) [47].

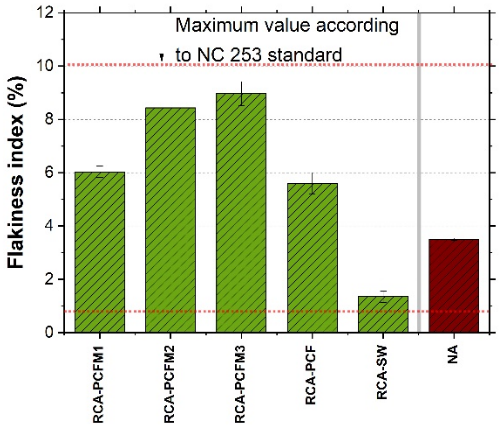

Figure 7. Flakiness index of the RCA samples compared with NA. Red line indicates the maximum value required according to NC 253.

3.2. Reclaimed Asphalt Pavement (RAP) Characterization

3.2.1. Particle Density and Water Absorption

As previously mentioned, the RAP used for this study was collected from three stockpiles from different roads projects in Cuba (RAP-P, RAP-SC and RAP-G). Figure 8 shows the results obtained of specific gravity and water absorption.

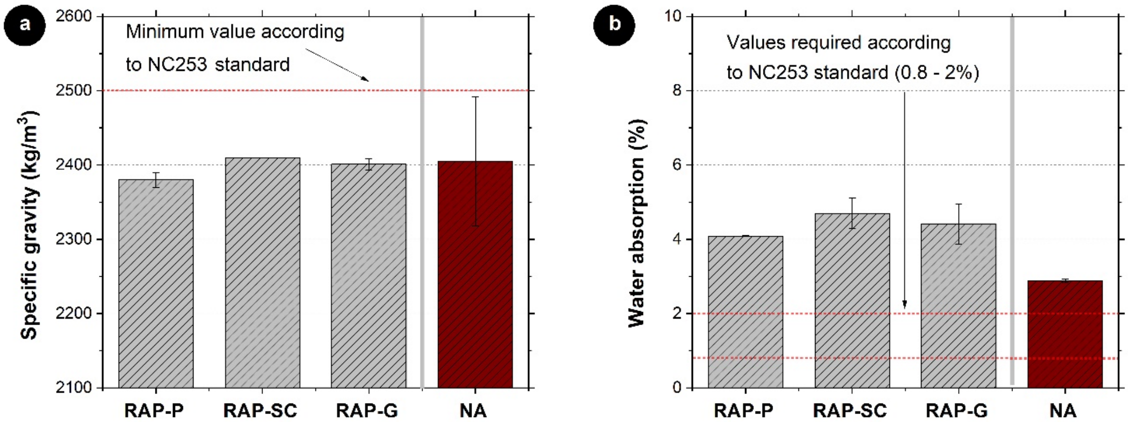

Figure 8. (**a**) Specific gravity and (**b**) water absorption of the RAP samples compared with NA. Red line indicates the value required according to NC 253.

As can be seen in Figure 8a, the specific gravity of the RAP samples was similar to the NA. This is due to the fact that the RAP aggregates obtained after the asphalt that were extracted were similar to the NA. The slight variation observed in the specific gravity was associated with the loss of aggregate quality when the asphalt mixture was in service. None of the samples comply with the minimum value established in standard NC 253 [47].

The water absorption measured in the recovered aggregates of the RAP samples compared with the natural ones (AN) are shown in Figure 8b. As can be observed, RAP samples exhibited much higher water absorption than the NA. All samples exceed the range established in the NC 253 standard [47] for asphalt mixtures.

3.2.2. Elongated Particles

When the asphalt was removed from the original RAP, the flakiness index was obtained and compared with NA (Figure 9).

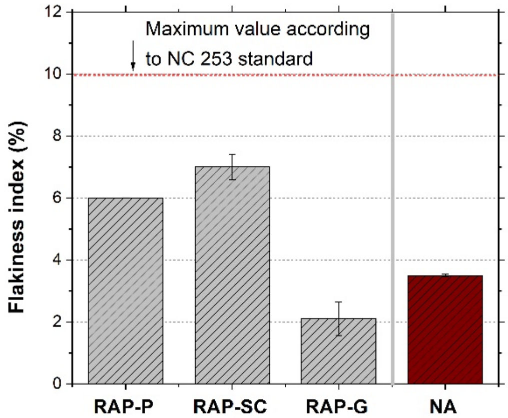

Figure 9. Flakiness index of RAP samples compared with NA.

Figure 9 shows that the RAP aggregate obtained after the extraction exhibited higher percentages of flaky particles than the NA, except for the sample RAP-G. All the samples presented values below the maximum value established in the NC 253 (<10%) [47]. It can be seen that the lowest value was obtained in RAP-G, and due to the classification process, provided a more homogeneous material.

3.3. RCA/RAP Combination

After analyzing the properties of RCA and RAP samples, it can be seen that they presented different properties compared to NA. To compensate the decrease in quality of the parameters studied (specific gravity, water absorption and flakiness index) in the waste aggregates compared with NA, a combination of RCA and RAP were considered, to observe how the combinations affects to the parameters studied in the aggregates separately. As previously mentioned, this does not mean that the combination of both residues improves the properties of the NA, but it would allow to obtain a coarse aggregate with two sources of wastes, with potential use as a coarse aggregate for HMA.

The RCA used in the combinations was RCA-SW and the RAP from Guanabacoa (RAP-G), as follows:

- 0/100: 0% RCA and 100% RAP.
- 25/75: 25% RCA and 75% RAP.
- 50/50: 50% RCA and 50% RAP.
- 75/25: 75% RCA and 25% RAP.
- 100/0: 100% RCA and 0% RAP.

3.3.1. Particle Density and Water Absorption

Figure 10 shows the specific gravity and water absorption obtained, and the limit established in the NC 253 standard [47].

The results presented in Figure 10a show that the combinations have values below the specifications of the NC 253 standard [47], as was also obtained in the RCA and RAP samples separately. As can be seen in Figure 10a, as the amount of RCA increased in the combination, the specific gravity decreased. This is due to the higher quantity of global mortar adhered to the surface of the particles in the samples. Figure 10b shows the water absorption results. All samples exceed the limit set in NC 253 standard [47]. As expected, when the RCA content increases, the water absorption also increases, due to the mortar adhered to the surface of the aggregates.

Despite having a lower density than natural aggregates, the combination 25/75 exhibited similar values of water absorption compared with the NA.

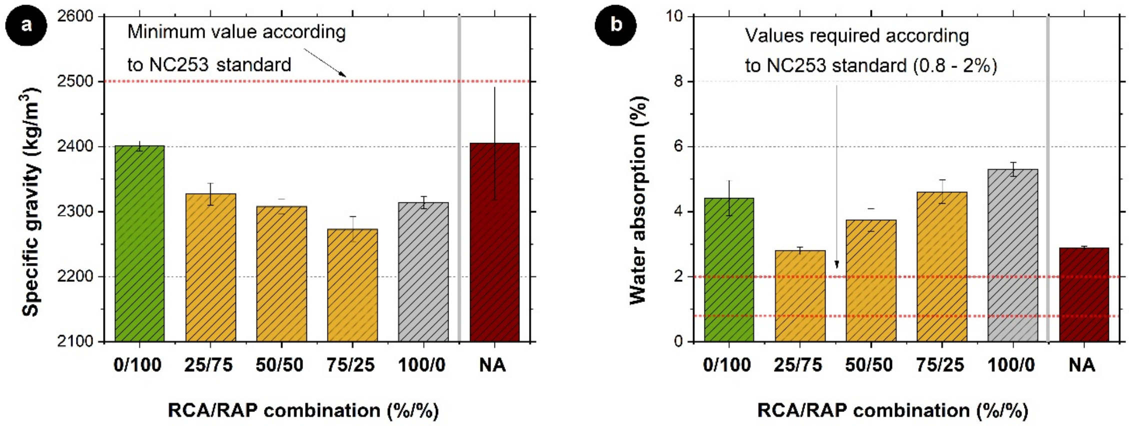

Figure 10. (**a**) Specific gravity and (**b**) water absorption of the combination of RCA/RAP compared with NA. Red line indicates the value required according to NC 253.

3.3.2. Elongated Particles

Figure 11 shows the flakiness index of the different combinations compared with the natural aggregates. As can be seen, the percentages of flaky particles are below the maximum value established in the NC 253 standard [47]. In all cases, the number of flaky particles was similar or lower than NA. In this case, the combination of both types of waste (RCA/RAP) significantly improved the value of flakiness index compared with the values obtained in the wastes individually, and the combinations also slightly improved compared with NA.

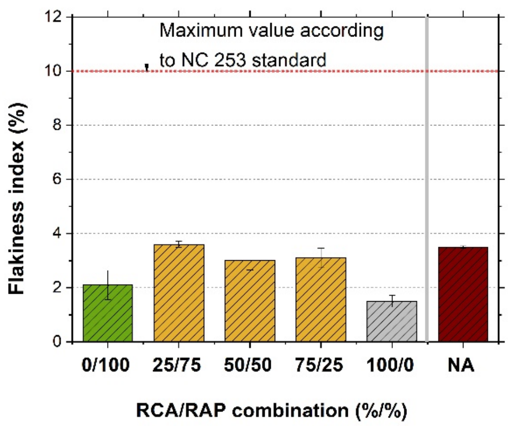

Figure 11. Flakiness index of RCA/RAP combination samples compared with NA.

3.4. Statistical Analysis

To formally determine if the properties of the RCA, RAP sources and combinations of both of them were statistically different from one another and the NA aggregates, an analysis of variance (ANOVA) test was performed for the specific gravity, water absorption and flakiness index.

In order to know if there are significant differences between the different types of samples tested (RCA, RAP and the different combinations) regarding the dependent variable (specific gravity, water absorption and flakiness index), a one-way ANOVA was performed using the code SPSS 22.0 (from SPSS Inc.), to identify which groups are significantly different from which other groups [51]. The test compared the means of all the samples calculating the F statistic and the level of significance. The level of significance obtained for the three dependent variables was lower than 0.05, rejecting the hypothesis of the equality of means—there were differences between the different samples studied.

Since the means are different, the post hoc tests indicate which samples were significantly different to others. To know which post hoc test can be applied in the dependent variables, the homogeneity of variances was studied with Levene. The Levene test indicates that the variances are different ($p < 0.05$) for the three properties studied. The Games-Howell post hoc test was applied, because this test does not assume equal variances. Consequently, significant differences between each of the groups were determined ($p < 0.05$).

The results of the ANOVA tests for all parameters showed that the probability value (p-value) was smaller than 0.05, meaning that, with a 95% confidence, this is indicated in Tables 4–6.

Table 4. Games-Howell test indicating significant difference results in specific gravity among all samples' pairs. Black dot in a cell (•) means significant differences among the two samples (column and row).

		NA	RCA					RAP			RCA/RAP				
			PCFM1	PCFM2	PCFM3	PCF	SW	P	SC	G	0/100	25/75	50/50	75/25	100/0
NA															
RCA	PCFM1			•		•	•	•	•	•	•	•	•		•
	PCFM2		•												
	PCFM3														
	PCF		•					•	•	•	•				
	SW		•					•	•	•	•				
RAP	P		•			•	•						•	•	•
	SC		•			•	•						•	•	•
	G		•			•	•						•	•	•
RCA/RAP	0/100		•			•	•						•	•	•
	25/75		•												
	50/50		•					•	•	•	•				
	75/25							•	•	•	•				
	100/0		•					•	•	•	•				

Table 5. Games-Howell test indicating significant difference results in water absorption among all samples' pairs. Black dot in a cell (•) means significant differences among the two samples (column and row).

		NA	RCA					RAP			RCA/RAP				
			PCFM1	PCFM2	PCFM3	PCF	SW	P	SC	G	0/100	25/75	50/50	75/25	100/0
NA			•	•		•	•	•							•
RCA	PCFM1	•		•			•	•	•			•	•	•	•
	PCFM2	•	•					•				•			
	PCFM3														
	PCF	•										•	•		
	SW	•	•									•			
RAP	P	•	•	•								•			
	SC		•												
	G														
RCA/RAP	0/100														
	25/75		•	•		•	•	•							•
	50/50		•			•									
	75/25		•												
	100/0	•	•									•			

Table 6. Games-Howell test indicating significant difference results in flakiness index among all samples' pairs. Black dot in a cell (•) means significant differences among the two samples (column and row).

		NA	RCA					RAP			RCA/RAP				
			PCFM1	PCFM2	PCFM3	PCF	SW	P	SC	G	0/100	25/75	50/50	75/25	100/0
	NA														
RCA	PCFM1														
	PCFM2														
	PCFM3														
	PCF														
	SW														
RAP	P									•	•	•	•	•	•
	SC									•	•	•	•		•
	G							•	•						
RCA/RAP	0/100							•	•						
	25/75							•	•						•
	50/50							•	•						
	75/25							•							•
	100/0							•	•			•		•	

As can be seen in Table 4, there is no significant differences in terms of the specific gravity of the NA with all the combinations studied. However, there are differences between the samples of RCA, RAP and the different combinations.

Table 4 shows that the source RCA-PCFM1, which was not subjected to any crushing process, presented significant differences to most of the other samples (RCA, RAP and those that combine both materials). There were also differences between the sources of RAP and those of RCA samples that come from manufactured concrete (RCA-PCF and RCA-SW); likewise, RAP presented differences with the RCA/RAP combinations, where a greater influence of RCA was observed. As for NA, there were no significant differences with any of the sources analyzed.

In summary, RAP sources presented significant differences to the rest of the sources and combinations studied. As can be seen, the specific gravity was influenced by the manufacture of concrete represented in RCA-PCF and RCA-SW samples, and by the crushing of the RCA sources.

As can be seen in Table 5, the statistical analysis showed that there were significant differences between the water absorption of NA and RCA sources, as explained above, due to the mortar adhered to the surface of the RCA responsible for its higher porosity. Regarding the RCA samples, as observed with the specific gravity, the significant differences with the rest of the RCA sources is the material that was not crushed (RCA-PCFM1). Therefore, it can be concluded that, for RAP/RCA combinations, the RAP materials had greater influence than RCA in the water absorption obtained.

In Table 6, the main statistical differences in terms of flakiness index were obtained in RAP-SC and RAP-P, with the combinations of both wastes. It can be concluded that the combination of RAP and RCA produced a statistical difference in the flakiness index of the aggregate generated.

4. Conclusions

The main objective of this study was to evaluate the specific gravity, water absorption and flakiness index of RCA, RAP, and a combination of both wastes, and compare with the same properties of NA in the fraction 5–10 mm, to use them as aggregate pavement projects.

- The detachment of the adhered mortar of the RCA samples crushed caused differences with the RCA samples without crushing.
- The samples RCA-PCF and RCA-SW were less dense and more porous aggregates, probably because they come from industrial wastes and they had a lower detachment of mortar.

- RAP samples exhibited results similar to those obtained in NA.
- RCA, RAP, and the different combinations studied, had lower specific gravity and higher water absorption than NA.
- The combinations of RCA and RAP influenced the values in the properties studied. The results obtained with a 25% of RCA and 75% of RAP combination were similar to NA.

Although, in the tests carried out, only the percentage of flat and elongated particles meet the Cuban specifications, it is necessary to go deeper into the influence of the RCA/RAP combinations, to use them as aggregates in asphalt mixtures. It opens up the possibility of using RCA in combination with RAP as a coarse aggregate, because the RAP aggregate compensates for its defects. Further studies are recommended for analyzing the wear and polishing the resistance of the combined wastes as coarse aggregates that affect the long-term behavior of the mixtures manufactured with these wastes; studies combining all the sources could be useful to identify the best aggregate for pavement purposes, and use innovative procedures to characterize the physical and mechanical properties on very small samples.

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Nomenclature

RCA	Recycled concrete aggregates
CDW	Construction and demolition waste
AC	Asphalt concrete
OAC	Optimum asphalt content
NA	Natural aggregate

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