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GRANULAR SUBBASE IMPROVEMENT WITH RECYCLED CONCRETE AGGREGATES IN TROPICAL AREAS

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ABSTRACT: Use of Recycled Concrete Aggregate (RCA) for Granular Subbase (GSB) in the tropical area is evaluated in this work. Among the materials widely studied as replacements in granular and surface layers is RCA. Its mechanical behavior in granular layers has mainly been evaluated with tests such as California Bearing Ratio (CBR). However, abrasion is also a determining property in the strength of these materials. In this study, the performance of Natural Aggregates (NA) with replacement of RCA was evaluated for use as GSB in a tropical area. Even though several laboratory tests were performed, the focus of the article lies on the performance in the Los Angeles (LA) abrasion test. Two replacement percentages of coarse RCA were considered: 10 and 15 % by weight of aggregates. The RCA and NA were characterized according to different laboratory tests: Granulometry, Absorption, Atterberg Limits test, Plasticity, Specific Gravity, and LA abrasion. In turn, all results were compared with Colombian specifications for a typical GSB in the area. In addition, a simple Life Cycle Assessment (LCA) was included to evaluate the environmental impacts of the base and alternative scenarios. The results show that GSB with 10% RCA present a higher abrasion resistance than the GSB with 15% RCA. Even better results are obtained with 10% RCA than with natural GSB. Specifically, average LA abrasion test losses of 30.86, 29.80 and 32.07% were obtained for NA, 10% RCA and 15% RCA, respectively. The LCA results show an increase of 50% and 75% in energy consumption by comparing the base scenario with 10 and 15% RCA replacement, respectively. This leads to an increase of 40 and 80% in carbon monoxide (CO) emissions for 10 and 15% RCA replacement respectively, and 100% in carbon dioxide (CO_2) emissions for both alternative scenarios.

ABSTRAK: Penggunaan Agregat Konkrit Kitar Semula (RCA) bagi Subtapak Butiran (GSB) bagi kawasan tropika telah dikaji dalam kajian ini. Antara bahan yang banyak dikaji sebagai bahan ganti dalam butiran dan lapisan permukaan adalah RCA. Ciri-ciri mekanikal dalam lapisan butiran telah diuji, terutamanya dengan ujian seperti Nisbah Bearing California (CBR). Walau bagaimanapun, pelelasan juga merupakan ciri penting dalam menentukan ketahanan material. Kajian ini merupakan prestasi Agregasi Semulajadi (NA) dengan ganti RCA yang diuji bagi penggunaan GSB di kawasan tropika. Walaupun pelbagai ujian makmal telah dijalankan, fokus artikel ini terletak pada prestasi ujian pelelasan Los Angeles (LA). Dua gantian bagi peratus RCA kasar telah diambil kira: iaitu pada agregat berat 10% dan 15%. Ciri-ciri RCA dan NA dikategori berdasarkan pelbagai ujian lab yang pelbagai: Granulometri, Penyerapan, ujian Had Atterberg, Keplastikan, Graviti Tertentu dan Pelelasan LA. Kemudian, kesemua dapatan kajian dibandingkan dengan ciri-ciri Kolombia bagi ciri tipikal GSB di kawasan itu. Tambahan, Pentaksiran Kitar Hidup (LCA) yang ringkas dimasukkan bagi menilai impak terhadap alam terhadap penggunaanya pada pangkal bijirin dan pada senario alternatif. Dapatan kajian menunjukkan GSB yang menggunakan RCA 10% mempunyai rintangan lelasan tertinggi berbanding GSB dengan RCA 15%. Tambahan, dapatan kajian yang lebih baik didapati daripada RCA 10% berbanding GSB semula jadi. Terutama pada purata ujian lelasan LA telah mengalami penyusutan sebanyak 30.86, 29.80 dan 32.07% bagi NA, RCA 10% dan RCA 15%, masing-masing. Dapatan LCA menunjukkan peningkatan sebanyak 50% dan 75% pada penggunaan tenaga dengan perbandingan senario Subtapak Butiran dengan gantian RCA 10% dan 15%, masing-masing. Ini membawa kepada peningkatan sebanyak 40% dan 80% emisi karbon monoksida (CO) bagi gantian RCA 10% dan 15% masing-masing, dan emisi karbon dioksida (CO_2) 100% bagi kedua-dua senario alternatif.

KEYWORDS: *recycled concrete aggregate (RCA); natural aggregates (NA); granular subbase (GSB); Los Angeles (LA) abrasion test; tropical area*

1. INTRODUCTION

In recent years, the use of Recycled Concrete Aggregate (RCA) has been widely recognized worldwide, as it contributes to the preservation of the environment and has several economic and social benefits that make this alternative sustainable. In civil engineering projects, this material has been widely studied as a replacement for natural aggregates in asphalt mixtures [1]–[3], concrete mixtures [4]–[6] and as granular base improvement, just to mention a few [7]–[9].

RCA is a material composed of virgin aggregates covered by a layer of cement mortar [8], these wastes are part of the composition of Construction and Demolition (C&D) waste. Bonded cement mortar is related to different undesirable characteristics of RCA behavior, such as higher absorption, lower durability, and lower mechanical behavior; compared to natural aggregates [3], [10]. However, as a replacement of the Natural Aggregates (NA) in road structures in certain percentages, RCA have shown a relatively good performance [10]. In general, studies show that RCA replacements in pavement structure is an alternative to controlling C&D waste, since it reduces the consumption of natural aggregates and protects the environment [8], [11], [12]. Its use on pavements has been categorized worldwide as a viable, cost-effective, and sustainability-friendly alternative [10], [13].

The stiff and durable structure of the RCAs allows them to be used in the Granular Subbase (GSB) and Granular Base (GB) instead of conventionally used materials [9]. Some studies have been carried out to evaluate and compare the properties of natural granular layers vs. granular layers with RCA replacements. From the results reported in the literature regarding mechanical properties such as the California Bearing Ratio (CBR) and the LA abrasion test, it has been determined that RCAs are comparable to NA [14], highlighting that lower strengths and higher abrasions are observed but they fulfill the standards for GSB. In terms of resilient modulus, it has been established that GB with RCA show higher results than natural aggregates [14]. In addition, they found that RCA had better mechanical properties than NA but had higher permanent deformation. In general, RCAs meet the desired criteria for granular layers, showing satisfactory performance in mechanical behavior [9], [15].

In addition, the environmental effects of the use of RCA in road construction must be considered. It has been established that the use of RCA as a replacement in highway structures reduces greenhouse gas emissions and energy use [10], [14]. The environmental savings that can be achieved with this alternative are mainly related to the production of the materials [14], [16]. A saving of about 16% in CO_2 generation has been established, when comparing the production of NA versus a 70% NA and 30% RCA mix [17].

On the other hand, another important variable in the environmental analysis of the use of RCA in pavement structures is the transportation of the material [14], [18]. Thus, when transportation is not included in the scope of the analysis, large environmental advantages are observed [19], [20]. However, when transportation of materials is considered, it can be concluded that there are savings in energy use only if the recycling facilities are close to the construction sites [10], [21]. In general, it has been established that, under certain replacement percentages and hauling distances, the use of RCA in highway structures is an innovative and ecofriendly solution [10], [14], [17].

The influence of RCA on properties such as CBR, resilient modulus, granulometry and others, has been extensively evaluated in the literature, but few studies have focused on abrasion [14], [22]. This resistance characteristic can be influenced by RCA replacements, so it is studied in detail in this research.

Considering the evidence, the present research has been proposed to evaluate the improvement of a GSB with RCA substitutions. Two percentages of coarse RCA replacement were considered: 10 and 15%. The RCA and GSB were characterized according to different laboratory tests: Granulometry, Absorption, Atterberg Limits test, Plasticity, Specific Gravity, and LA abrasion test. The main comparison of the alternative scenarios versus the natural one was based on the resistance of the samples in the LA abrasion test. In addition, environmental impacts were calculated by a LCA, using the PaLATE 2.0 tool. The analysis was carried out considering a base scenario of the construction of a pavement with a 100% natural GSB, and as alternative scenarios, substitutions of 10% and 15% in the same granular layer were evaluated.

2. METHODOLOGY

For the laboratory tests, samples of the granular materials (natural and recycled) were evaluated individually and then mixed with 10 and 15% replacements of coarse Recycled Concrete Aggregate (RCA). The recycled material was obtained from the demolition of a three-story house, located in the Campo Alegre neighborhood, Barranquilla - Colombia. A portion of a concrete beam was extracted from the area, which was initially subjected to crushing processes in the laboratory. The crushing was carried out using a Bico Brarun jaw crusher (Fig. 1) with a V-Belt Drive system, with a jaws capacity of 2¼ x 3" which allows a reduction of the material from 3/8 to 1/16”. To obtain smaller sizes, manual crushing was performed in the laboratory.

Physical and mechanical properties were evaluated on Natural Aggregates (NA) and RCA, as described below. In order to obtain results that can be comparable with other studies, American Society for Testing and Materials (ASTM) standards were used for the development of the tests [23]–[27]. At the same time, these standards are the basis for many standards in different countries such as Colombia. Thus, having them as a basis can guarantee internationally comparable and representative results for the study area.

In addition, all tests performed satisfy Granular Subbase (GSB) Colombian standards [28]. Specifically, the results were compared with the standards for a GSB with 37.5 mm (GSB38) as nominal maximum size.

Fig. 1: Laboratory Scale Jaw Crusher used for the crushing of recycled material [29].

Finally, each laboratory test was performed on at least three different samples of the material. It is important to mention that with the number of samples evaluated for each test, a clear trend in the results was observed. The tests carried out and their respective standards are mentioned in Table 1.

Table 1: Test, tested material and standard considered

Test	Tested material	Standard
Granulometry	NA, RCA, 10 and 15% RCA replacements	ASTM D6913 [26]
Density, Relative density and Absorption	RCA	ASTM C127 [24]
Atterberg Limits and Plasticity	NA and RCA 10 and 15% RCA replacements	ASTM D4318 [25]
Specific gravity	RCA	ASTM D854 [23]
LA abrasion	NA, RCA, 10 and 15% RCA replacements	ASTM C131 [27]

3. RESULTS AND DISCUSSION

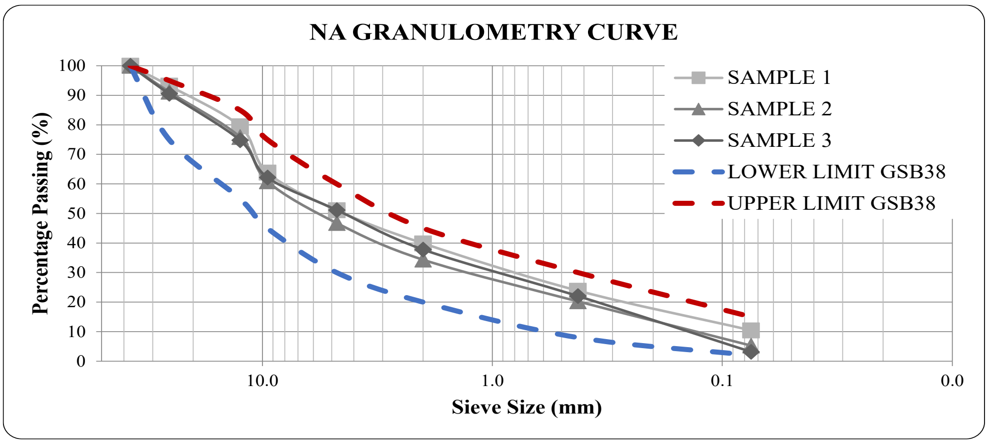
The section is divided into two parts: The first corresponds to the characterization of the samples of the granular subbase and recycled aggregates and the second part corresponds to the characterization of the Granular Subbase (GSB) mixed with coarse Recycled Concrete Aggregate (RCA) at 10 and 15% with respect to their dry mass.

3.1 Characterization Tests on Natural and Recycled Aggregates

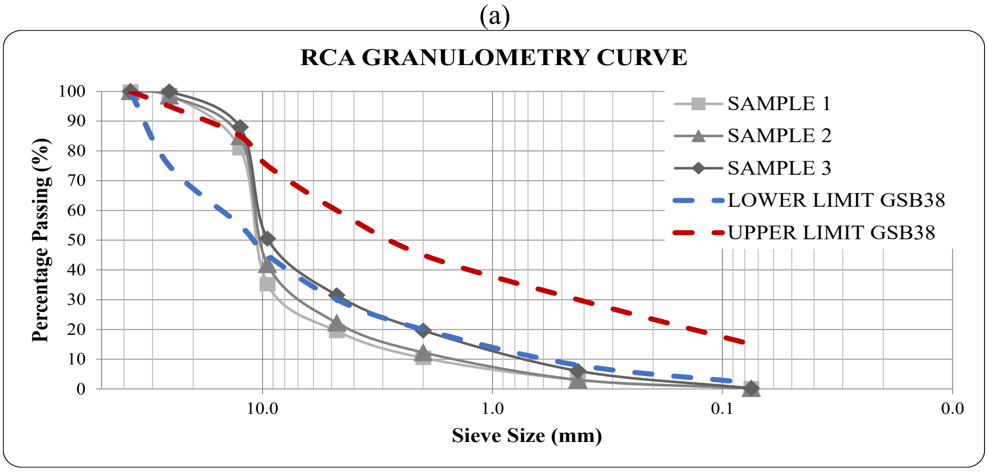
(A) Granulometry Test

The granulometry test was carried out including sieves from 1 1/2" to No. 200. Fig. 2 presents the granulometry curve of the three samples evaluated for (a) Natural Aggregates (NA) and (b) RCA, including the limits established for GSB with 37.5 mm (GSB38) as nominal maximum size [28].

The natural aggregate complies with the granulometry parameter for GSB38 (dashed red and blue lines), showing a curve within the range established by the standard. Considering the crushing method used for the RCA, it was to be expected that its granulometry would not comply with the parameters established for GSB38. Therefore, the RCA should be blended with the necessary sizes so that its particle size complies with the range established by the standard [28] or it can be used as a partial replacement in granular layers as analyzed in this work. In addition, Fig. 3 shows the particle size distribution of one of the RCA samples evaluated.



(a)



(b)

Fig. 2: Granulometry curve of (a) NA and (b) RCA.

Fig. 3: Particle size distribution of one of the RCA samples evaluated.

(B) Density, Relative density and Absorption Test

Considering that absorption is one of the properties that most affects the behavior of the RCA and therefore of the mixtures where they are replaced [10]; density, relative density and absorption tests were carried out on the coarse fraction of the RCA.

Table 2: Density, Relative density, and Absorption results of coarse RCA. A = mass of oven-dry test sample in air; B = mass of saturated-surface-dry test sample in air; C = apparent mass of saturated test sample in water

Specimen	**A [g]**	**B [g]**	**C [g]**	**Relative Density (OD)**	**Relative Density (SSD)**	**Apparent Relative Density**	**Absorption [%]**
				$\frac{A}{(B-C)}$	$\frac{B}{(B-C)}$	$\frac{A}{(A-C)}$	$\left[\frac{(B-A)}{A}\right]x100$
1	5072	5253	3035	2.29	2.37	2.49	3.57
2	5050	5251	3101	2.35	2.44	2.59	3.98
3	5010	5201	3089	2.37	2.46	2.61	3.81

The oven-dry (OD), saturated-surface-dry (SSD), apparent relative density, and absorption results of the three samples evaluated are shown in Table 2. These agree with those reported in the literature. Where OD is in the range of 2.20 to 2.40, SSD between 2.31 and 2.68, apparent between 2.42 and 2.70, and absorption between 1.43 and 8.05 for the coarse fraction of RCA [14], [22], [30], [31].

(C) Atterberg Limits and Plasticity Test

Atterberg limits and plasticity index tests were performed on three samples of NA and RCA. The results show a non-plastic behavior for the NA and slightly plastic for the RCA. Specifically, the RCA results show a Liquid Limit (LL) of 33.54% and a Plastic Limit (PL) of 2.24% on average, complying with GSB38 standards [28].

(D) Specific Gravity Test

The specific gravity of three samples of fine RCA were evaluated and the results show an average of 2.64. This agrees with the literature which shows a range of 2.14 to 2.65 for this property in fine RCA [14].

(E) LA Abrasion Test

LA abrasion tests were performed on three samples of NA and RCA. The results were compared as a measure of resistance and are shown in Fig. 4. The figure shows the requirements for low (NT1), medium (NT2) and high (NT3) traffic levels for GSB38 [28], and both materials fulfill it. Specifically, the limit for the different transit levels is a loss in abrasion of 50%. An average of 30.86 and 35.72% in abrasion loss were obtained for the NA and RCA, respectively.

The results agree with those reported in the literature. It is stated that the RCA has lower resistance in LA abrasion test than the NA [17], [22] and shows weight loss between 27.3 and 39.0% [14].

3.2 Characterization Tests on GSB with RCA Replacements

Once the materials (natural and recycled) were characterized by the physical and mechanical properties tests described above, the evaluation of the alternative scenarios continued. The mechanical evaluation of the alternatives and their comparison with the base scenario was carried out based mainly on the results of the LA abrasion test. Properties such as granulometry and plasticity were also evaluated and compared according to GSB38 standards [28].

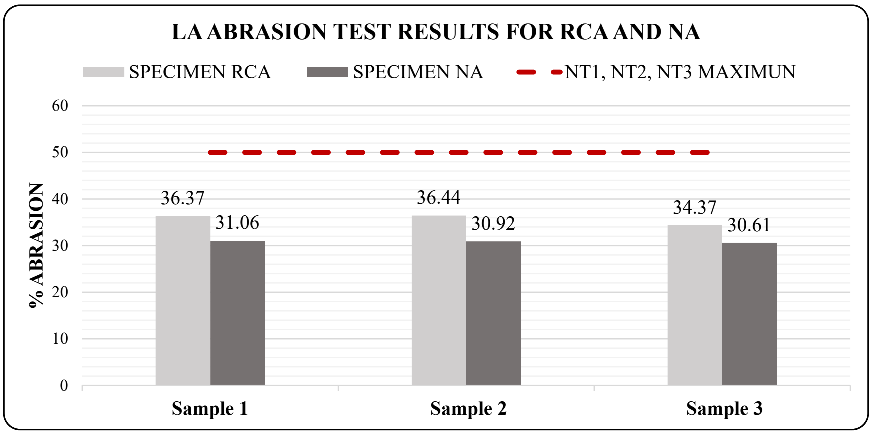
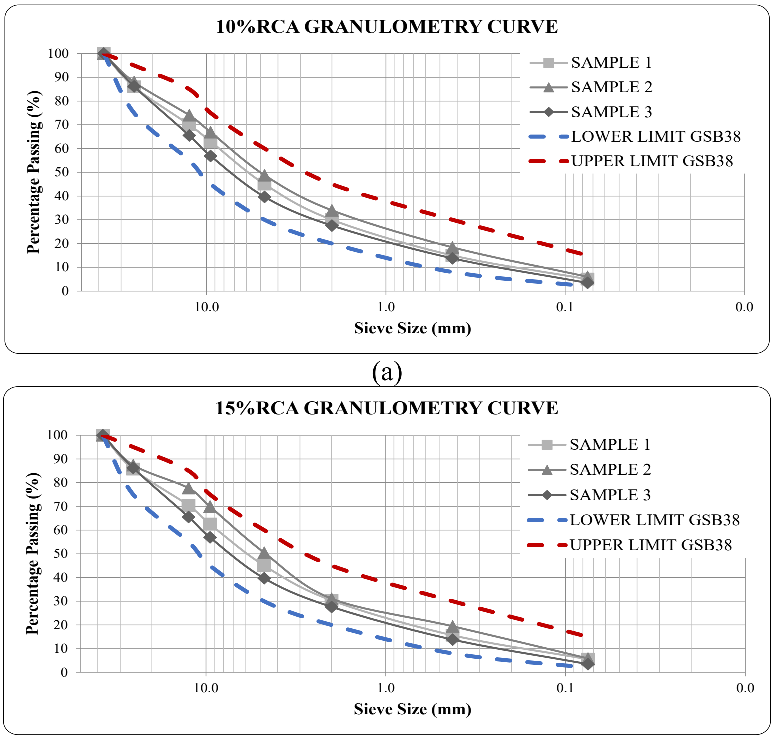


Fig. 4: LA abrasion test results for NA and RCA.

The alternative scenarios correspond to 10 and 15% coarse RCA replacements. It should be noted that these percentages were determined considering the literature [14], [17], [22]. For both replacements, 10 and 15% coarse RCA, three samples were evaluated for the granulometry test.

As shown in Fig. 5, the granulometry curve of both alternatives of RCA replacement comply with GSB38 standards (dashed red and blue lines) [28]. A similarity in the granulometric curves was observed, as the size distributions remained similar, varying mainly in the percentage of RCA substitution.



(a)

(b)

Fig. 5: Granulometry curve of NA with (a) 10% and (b) 15% coarse RCA.

For plasticity, no significant changes were observed due to the influence of the RCA replacements. For both alternatives, slightly plastic behavior is found, with PL of around 2.5% on average. This satisfies the standards for GSB38, established as a maximum of 6% [28].

Comparing the results of the LA abrasion test (Fig. 6), it is observed that the 15% RCA mixes show a weight loss 2.27% higher than the 10% RCA mixes, on average. On average, values of 29.80 and 32.07% in abrasion loss were obtained for 10 and 15% RCA replacement, respectively. In addition, the replacement of 15% RCA decreases the LA abrasion resistance when compared to the natural sample. Whereas, with the 10% RCA replacement, a small increase in this property is observed.

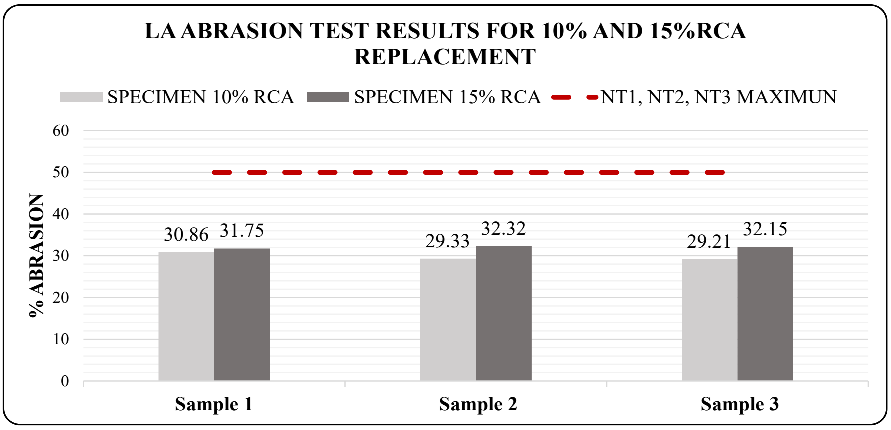


Fig. 6: LA abrasion test results for 10% and 15% RCA replacement.

It is observed in Fig. 6 that the highest value obtained for abrasion with 10% RCA is 30.86% while the lowest value is 29.21%. When analyzing the 15% RCA replacement, it is observed that the highest value is 32.32% compared to the minimum which is 31.75%. These values are very similar in the literature, which are less than 35% [14], [22]. However, both alternatives comply with the requirement for GSB38 [28] established as a maximum of 50% for the different levels of traffic (Low: NT1, Medium: NT2, High: NT3).

Subsequently, Table 3 contains the average percentage results of LA abrasion loss and differences found when comparing the results of the alternative scenarios versus the NA. This indicates that, for replacements higher than 10% RCA, the abrasion resistance of the granular layer decreases. Wider replacement rates should be evaluated to determine an optimal replacement range.

Table 3: Average percentage results of LA abrasion loss and differences between NA and alternative scenarios

Average results (%)	Difference (%)
NA 30.86	-
10%RCA 29.80	1.06
15%RCA 32.07	-1.21

Finally, Fig. 7 presents the ratio between LA abrasion tests with 10% and 15% RCA replacements with respect to the result obtained for NA (i.e., LA abrasion with replacement with RCA/LA abrasion with NA). Therefore, greater values than 1 represent negative influence; lower than 1 suggests a positive influence, and a value equal to 1 represents null influence.

The results show that with a replacement of 10% RCA, values lower than the reference value (1) are obtained, which are related to a reduction in the abrasion. On the other hand, a replacement with a 15% RCA suggests values higher than 1, demonstrating an increase in abrasion.

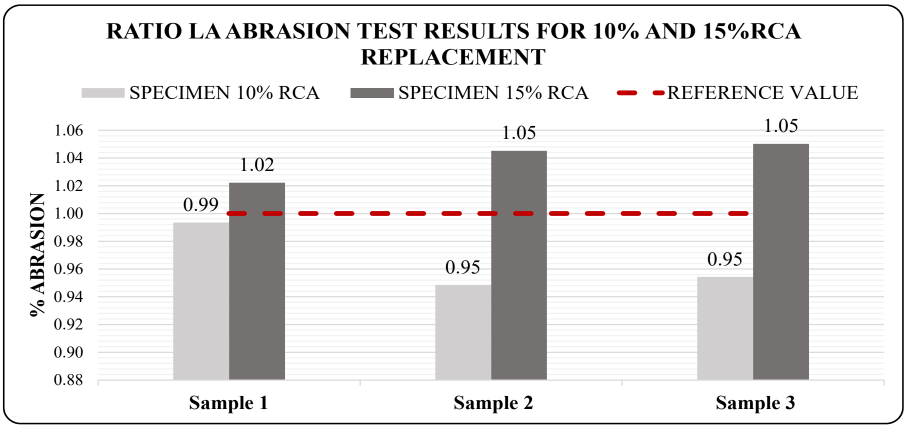


Fig. 7: Ratio LA abrasion test results for 10% and 15% coarse RCA replacement.

Analyzing the values presented in Fig. 7, it is observed that for 10% RCA a maximum ratio of 0.99 and a minimum of 0.95 was obtained, while for 15% RCA the maximum value was 1.05 and the minimum was 1.02. This shows that there is a trend of decreasing abrasion when GSB is replaced with 10% RCA. When analyzed with 15% RCA replacement, an upward trend in abrasion loss is obtained. Consequently, the abrasion values increase when 15% RCA replacement is reached and decreases for 10% RCA. Thus, an optimum value can be found between the percentage of RCA and the maximum decrease of abrasion as evidenced in the literature [14], [22].

3.3 Environmental Results

Environmental impacts were calculated by a life cycle analysis (LCA) using the PaLATE 2.0 tool. It was carried out considering as a base scenario the construction of a pavement with a 100% natural GSB, and as alternative scenarios substitutions of 10% and 15% in the same granular layer were evaluated.

In this study, the functional unit was defined as the construction of the GSB of a typical Colombian road section: 1 km in length and 1 lane of 3.5 m wide. Considering the typical conditions of the area and the regulations [28], the following design characteristics were established: (1) a traffic value of 5×10^6 Equivalent Single Axle Load (ESAL) of 80 kN; (2) CBR of 30%; (3) service life of 10 years; (4) a GSB modulus of 200 MPa. Considering the above, 22 cm was considered as the GSB thickness. Therefore, the construction of 770 m^3 of GSB was evaluated for both the base and alternative scenarios.

The PaLATE 2.0 tool evaluates 12 environmental impacts, considering the stages of Materials Production, Materials Transportations and Processes (Equipment). It is important to highlight that in this study hauling distances were not considered, with the purpose of only considering the replacement of the RCA as a variable. Thus, the environmental impacts are related to Materials Production and Processes (Equipment). In addition, of the 12 impacts, the following impacts were considered: energy (MJ), water consumption (kg), CO_2 (kg), particulate matter with a diameter of 10 microns or less PM_{10} (kg), and CO (kg).

The results presented in Table 4 suggest that the use of RCA as a replacement in GSB implies a significant increase in energy consumption and water consumption. This would be related to the activities involved in the RCA production process [10], [17]. In turn, this represents an increase in emissions of the different impacts evaluated.

Specifically, the LCA results show an increase of 50% and 75% in energy consumption by comparing the base scenario with 10 and 15% RCA replacement, respectively. This leads to an increase of 40 and 80% in CO emissions for 10 and 15% RCA replacement respectively, and 100% in CO_2 emissions for both alternative scenarios. In terms of PM_{10} emissions, a 50% increase was observed when comparing the base scenario with 15% RCA replacement.

Table 4: Environmental results of base and alternatives scenarios

	Energy [MJ]	**Water Consumption [kg]**	**CO_2 [kg]**	**PM_{10} [kg]**	**CO [kg]**
100% NA	13669	1	1000	2	5
10%RCA	20504	1	2000	2	7
15%RCA	23922	1	2000	3	9

The environmental results contrast with those reported in the literature. It has been established that the use of RCA tends to represent a saving in emissions of different pollutants. Savings of 16% in CO_2 generation are reported when comparing the production of NA versus a mixture of 70% NA and 30% RCA [17]. In addition, significant savings in CO emissions and energy consumption have also been found when evaluating the use of RCA replacements in pavement structures [13].

However, when high percentages of RCA (45% replacement) are analyzed, increases of 20% in CO_2 generation and 10% in emissions of Particulate Matter with a diameter of 2.5 microns or fewer of $PM_{2.5}$ have been found [10]. Also, increases in impacts such as climate change and eutrophication have been reported by including RCA in concrete [21]. In general, environmental impacts are sensitive to the percentage of replacement and hauling distances of RCA, so the use of RCA does not necessarily imply environmental savings [10], [21]. Thus, the environmental results are a function of the case study conditions and characteristics such as the functional unit evaluated.

4. CONCLUSIONS

The performance of natural aggregates with 10 and 15% replacement of coarse Recycled Concrete Aggregate (RCA) was evaluated for use as Granular Subbase (GSB) in Colombia as a tropical area. Initially, the physical and mechanical characterization of both materials (natural and recycled) was carried out considering Granulometry, Absorption, Atterberg Limits test, Plasticity, Specific Gravity, and Los Angeles LA abrasion test. At least three samples of each material were considered for each test. Noting that with the number of samples evaluated for each test, a clear trend in the results was observed.

Then, results of Natural Aggregates (NA) versus 10 and 15% RCA replacement as alternative scenarios were evaluated and compared. The main comparison was based on the resistance of the samples in the LA abrasion test. This is because abrasion is a determining property in the strength of these materials, however few studies have focused on its influence [14], [22]. Therefore, the objective of the research is to evaluate how aggregate abrasion varies when a significant percentage of RCA is added.

All results were compared with the GSB with 37.5 mm (GSB38) as nominal maximum size standards according to Colombian regulations. This is because GSB38 is the typical GSB in the area. In addition, a simple Life Cycle Assessment (LCA) was included to evaluate the environmental impacts of the base and alternative scenarios. The LCA was conducted considering Materials Production and Processes (Equipment) stages and including 5 environmental impacts: energy (MJ), water consumption (kg), CO_2 (kg), particulate matter with a diameter of 10 microns or less PM_{10} (kg) and CO (kg).

Based on the conditions and results of the study, the following can be concluded:

- The granulometry of the NA complies with GSB38 standards, while the RCA shows a curve outside the range stipulated by the standard [28]. Therefore, the RCA would have to be mixed with other aggregates to achieve an acceptable granulometry curve.
- The densities and absorption of the fine RCA agree with those reported in the literature [14], [22], [30], [31]. With averages of 2.34, 2.42, 2.56 and 3.79% for OD, SSD, apparent, and absorption, respectively.
- The plasticity of the RCA complies with GSB38 standards, showing an average result of 2.24%. For the NA, a Plastic Limit (PL) showing non-plastic behavior was obtained.
- The specific gravity of the fine RCA agrees with the literature [14], showing an average value of 2.64.
- The results of the LA abrasion test comply with the standards for both materials. As expected, a higher loss is observed in the RCA. Specifically, an average weight loss of 30.86% was found for the NA and 35.72% for the RCA.
- When evaluating the 10 and 15% RCA replacements, the granulometry curves complied with GSB38 standards; the plasticity did not show major changes and complies with the requirement for this property in GSB38 too [28].
- The results of the LA abrasion test show that GSB with 15% RCA has higher losses than that with 10% RCA. Specifically, it is observed that the 15% RCA mixes show a weight loss 2.27% higher than the 10% RCA mixes, on average.
- On average, values of 29.80 and 32.07% abrasion loss were obtained for 10 and 15% RCA replacement, respectively.
- The replacement of 15% RCA decreases the LA abrasion resistance compared to the natural sample. Whereas, with 10% RCA substitution, a small increase in this property is observed compared to the natural sample.
- For replacements higher than 10% RCA, the abrasion resistance of the granular layer decreases. Wider replacement rates should be evaluated to determine an optimal replacement range.
- The environmental results show that the use of RCA as a replacement in GSB implies a significant increase in energy consumption and water consumption. In turn, this represents an increase in emissions of the different impacts evaluated. This would be related to the activities involved in the RCA production process [10], [17].
- Specifically, the LCA results show an increase of 50% and 75% in energy consumption by comparing the base scenario with 10 and 15% RCA replacement, respectively. This leads to an increase of 40 and 80% in CO emissions for 10 and 15% RCA replacement respectively, and 100% in CO_2 emissions for both alternative scenarios.

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