Characterization of Recycled Concrete Aggregate as Potential Replacement of Natural Aggregate in Asphalt Pavement

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Abstract. The Construction Industry around the world generates the largest amount of waste and uses generally tons of non-renewable natural resources. Recently, the use of Construction Waste and Demolition (C&WD) in different construction fields has been reported by different authors as its composition includes a wide range of materials. One example of C&WD with potential use in Pavement Infrastructure is Recycled Concrete Aggregate (RCA). RCA have been studied as suitable replacement to Natural Aggregates (NA) in asphalt pavement, results have shown good performance and important environmental and economic benefits from the use of RCA with respect to conventional aggregates. This paper aims to evaluate the feasibility of using RCA obtained from different resources as a replacement material to NA in asphalt concrete mixtures. NA from regional representative quarries were used in this investigation. Instead, RCA was obtained from two different sources; one source, was obtained from a concrete pavement demolition project (Recycled Concrete Aggregate Pavement source – RCAP), and the second source was obtained from the demolition of some concrete structures in a baseball stadium in Barranquilla’s city (Recycled Concrete Aggregate Building source – RCAB). Characterization of both RCA and NA includes determination of physical, mechanical and chemical properties according to Colombian Standards. Laboratory test results indicates that RCA could be a viable option as potential replacement of natural aggregate in asphalt pavement and to reduce the carbon footprint during the production of asphalt mixtures. Nevertheless, some intrinsic properties of the material must be considered with special care, e.g. absorption, gradation, abrasion resistance, pH, among others. Finally, scanning electron microscope (SEM) techniques were used to provide images on RCA’s surface morphology and its composition, giving significant differences between RCA and NA.

1. Introduction
Construction is one of the industries that consumes the most non-renewable resources around the world. In U.S. at least 200 million tons of demolition wastes are produced every year from aging infrastructure and almost 50% are Portland Cement Concrete (PCC) debris [1]. Since aggregates are the most used material in civil engineering projects, any strategy that involves reusing aggregates from demolition of concrete structures, should reduce construction environmental impacts and costs [1][2]. Including different types of solid waste in hot mix asphalt (HMA) is not a new practice. In fact, end-of-life tires, reclaimed asphalt pavement, asphalt shingles and demolition wastes are some of the
recycled materials being incorporated in producing HMA [2,3,4]. Construction and Demolition Waste (C&DW) is defined as those pieces(debris) coming from the construction, rehabilitation and demolition of any type of infrastructure or building, whose varied composition is associated with materials and technologies used during construction phase at the end-of-life buildings; architectural and structural elements. Therefore, C&DW are composed mainly of different amounts of concrete, masonry, wood, metal, plastics and other materials [2]. Among these wastes, recycled concrete aggregate (RCA) are identified as the aggregates produced by the process of crushing demolished concrete elements at the end-of-life, and recently there is an increased interest on their use based on the greater benefits from a practical and eco-friendly standpoint. Many tons of RCA may be obtained by generating large amounts of hardened concrete waste that can be sorted from the source or eventually obtained from the demolition of concrete roads or concrete buildings [4]. Limited disposal sites (landfills) added to depletion of NA sources, prompt researchers and practitioners to assess mechanical and technical issues of RCA in order to re-use this type of aggregates in a cost-effective way.

In order to properly use the RCA, physical, mechanical and chemical properties must be known. As reported by different researchers, the RCA provides particular properties that can influence both negatively or beneficially on the performance of a cement or asphalt mixture [4, 5]. It should be noticed, that RCA differs from NA in that cement paste that remains on the surface of the recycled concrete aggregates after the crushing process [1]. Basically, the presence of this cement paste (adhered mortar) is the characteristic influencing several RCA properties. Chemically, the adhered mortar is more reactive than a NA and therefore, more susceptible to bond and interact with other binding materials [5, 6]. Suitable aggregates for HMA production must fulfill minimum physical and mechanical requirements [7], which in Colombia are defined in the National Standards for Highways Construction-INVIAS (INV) [8] and corresponding quality control is also required. Hence, RCA should be assessed in light of technical standards related with its final application.

Among others, RCA physical properties such as high porosity and absorption have been reported in the literature as critical parameters in fact, the bulk specific gravity (Gsb) is usually lower than for the NA, while absorption values can be high to very high comparing to those for the NA. Table 1 reports basic physical properties from previous studies on RCA. From Table 1, it can be seen that Gsb shows values between 2.1 and 2.4, while absorption values are reported from 2 up to 7%. This lower Gsb and higher absorption are attributed to an adhered mortar layer, which in turn depend on the quantity of adhered mortar in any particular particle and the strength of the original concrete [5,9]. Table 1, also shows Los Angeles (LA) abrasion test, Aggregate Crushing Value (ACV) and percentage of fractured faces. Overall, these properties present fair to very good qualities, fostering the research and interest in this promising material. This paper aims to evaluate the feasibility of using RCA obtained from different resources as a replacement material to NA in asphalt concrete mixtures, so that, physical, mechanical and chemical properties were studied on RCA’s coming from a pavement and structural elements on PCC.

2. Experimental Procedure

2.1. Materials

In this study three types of aggregates were considered; one Natural Aggregate (NA) and two RCA. The NA was chosen to represent a typical material used in pavement construction in Atlántico-Colombia. One of the RCA comes from a demolition of PCC from a high traffic road (Hamburg Avenue) in Barranquilla-Colombia (Recycled Concrete Aggregate Pavement- RCAP). Another RCA comes from the concrete building demolition of the Baseball Stadium “Tomas Arrieta” in Barranquilla, (Recycled Concrete Aggregate Building – RCAB). RCA was then obtained by crushing waste concrete from this two sources to obtain around one cubic meter of each. Figure 1 illustrate the crushing process to obtain RCA in the field, and Figure 2 shows the typical components of RCA, where the crushed stone represents the original aggregate with attached mortar.
Table 1. Literature review summary of RCA tests results

| Researcher                        | Aggregate size (mm) | Bulk specific gravity | LA Abrasion (%) | Water absorption (%) | Fractured faces (1 foam) (%) | Aggregate Crushing value (%) |
|-----------------------------------|---------------------|-----------------------|------------------|----------------------|-------------------------------|------------------------------|
| Paranavitana and Mohajerani, 2006 [10] | 4.75 - 20           | 2.333                 | -                | 5.9                  | -                             | -                            |
| Bhushal et al., 2011 [1]          | >4.75               | 2.412                 | 22               | -                    | 100                           | -                            |
| Al-Bayati et al., 2018 [5]        | <4.75               | 2.052                 | -                | -                    | -                             | -                            |
| Zhang et al., 2016 [6]            | >4.75               | 2.295                 | -                | 5.91                 | 89.9                          | 27.42                        |
| Motter et al., 2015 [4]           | >9.5                | 2.415                 | 27               | 4.3                  | -                             | -                            |
| Gomez-Majiide et al., 2015 [11]   | 24/12               | 2.2                   | -                | 7                    | -                             | 89                           |
| Mills-Beale and You, 2010 [7]     | -                   | 2.43                  | 48               | 2.34                 | 98.8                          | -                            |

Note: - means no information available.

Figure 1. Crushing process to obtain the RCA

Figure 2. Typical components of RCA

2.2. Testing methods
In order to characterize the NA and two sources of RCA, several physical, mechanical and chemical tests have been conducted. Specific gravity and water absorption of coarse and fine aggregate were determined according to Colombian Standards INV E 222-13 and INV E 223-13 respectively. Usually, high values of water absorption are expected for the recycled aggregates as compared to NA, due to the mortar adhered to these aggregates [4,6]. Sieve analysis of fine and coarse aggregates and quantification of coarse aggregates angularity were performed in accordance with the Colombian Standards INV E 213-13 and INV E 227-13 respectively. Aggregates gradation and coarse aggregate
angularity are important issues in asphalt pavement applications [5]. For the angularity examination, the aggregates are separated considering the angular, rough or broken surfaces and the weight percentage of the different groups are calculated. The results are important given that more angular coarse aggregates can increase the stone-on-stone interlocking and consequently increase mechanical properties. These parameters are used to assure aggregates quality and have been correlated to the performance of asphalt concrete mixtures [2,5].

Los Angeles abrasion test (LA coefficient), Micro-Deval tests and Aggregate Crushing Value test (ACV) were performed according to INV E 218-1, INV E 238-13 and INV E 224-13 respectively. The LA abrasion test uses impact load and grinding to quantify degradation by using a rotating steel drum and steel balls and after 500 revolutions, the aggregate mass is reported in percent loss. The Micro-Deval test is an abrasion and durability test that induces aggregate wear by rotating a sample of aggregate, steel balls and water in a smooth drum and after two hours the percent loss is calculated. The ACV test was performed to assess the relative mechanical resistance of an aggregate sample to crushing when subjected to an applied compressive load until a 10% of fine fraction (passing sieve No.8) is obtained, then the load necessary for this condition is recorded and used in calculation the ACV index.

In general, abrasion resistance of RCAs can be related to the relative strength of the original concrete (from demolition) and the particle size of the crushed aggregates, and it is usually higher than for the NA [2,5]. Also, Los Angeles coefficient has been identified as one of the most critical properties of recycled aggregates from mixed debris [2]. Weaker aggregates will give lower ACV as an indication of the smaller load to produce a crushed fraction of 10% passing the sieve No.8. Abrasion resistance and relative strength index are important properties of the RCA and can be seen as the ability to resist wear, friction and impact under handling, mixing or loading, three activities usually related to asphalt pavement applications and road construction [5].

The pH test was performed in accordance with Colombian Standard NTC 5264–08. The pH of RCA depends on the degree of carbonation which is associated to the service life exposure of the demolished concrete structures used to obtain them [12]; in this investigation pH measurements will be related to two types of concrete waste: pavement (RCAP) and building structures (RCAB). Finally, the microstructure surface morphology of NA and both RCAs were investigated using the Scanning Electron Microscopy (SEM) technique and the specimen was coated with a 40 nm carbon layer for testing purposes. The specimens were examined in a JSM 6490-LV equipment at an accelerating voltage of 20 kV at various working distances and magnification factors for SEM analysis.

3. Experimental results and discussion

3.1. Aggregates Characterization

The particle size distribution of the coarse and fine aggregate materials plays an important role in the asphalt mixture design and performance. RCAs are granular materials in various sizes but usually gradation limits for asphalt mixtures are not meet in as-received condition, then additional crushing process is required to adjust the sizes of the RCA material. On the other hand, sieve analysis can be used to assess the relative amount of material of each sizes, which is an indication of the gradation type, being even, continuous or discontinuous, depending on the crushed stones size distribution.

The selected gradation for this investigation corresponds to a MDC-25 according to the Colombia's National highway authority (INVIAS), considering that this type of mix can be useful as a wearing and binder course in pavement applications. Figure 3 shows the particle size distribution of the NA, RCAP and RCAB and also includes the gradation limits established by INVIAS for an MDC-25 asphalt mixture. The particle size distributions of the three materials were not between the low and high gradient limits, indicating that, in general, the NA and RCA need to be combined to fulfil the specifications. Based on the gradation curves, the optimal gradation ratios corresponding to the coarse to fine aggregate percentage for the three aggregates studied were selected. Results indicate that 55% -
45%, 55%-45% and 50%-50% were the optimal ratios of coarse to fine aggregates for the NA, RCAP and RCAB respectively.

Figure 3. Particle size distribution fine and coarse of the NA, RCAP and RCAB

A summary of the physical properties for the three types of aggregates used in this investigation is presented in Table 2. In order to understand the requirements column in Table 2 is important to mention that the traffic level (NT) corresponds to the design traffic of the road where NT1 corresponds to less than $0.5 \times 10^6$ equivalent axes of 80 kN, NT2 for design traffic between $0.5 \times 10^6$ and $5 \times 10^6$ equivalent axes and NT3 for traffic greater than $5 \times 10^6$ equivalent axes. The bulk specific gravity for the three types of aggregates considering both coarse and fine fraction are shown. The three materials exhibited bulk specific gravity values ranging from 2.6-2.2. However, as observed in Table 2, bulk specific gravity values for the RCA (fine fraction) are slightly lower than those reported for NA, confirming the presence of an adhered mortar layer covering the RCA material. In the case of RCA coarse fraction, differences with NA are bigger, RCAB performed with the lower bulk specific gravity. This factor may be considered of interest in designing HMA mixtures as the RCA presents an irregular and porous surface that can be highly absorbent and in consequence tends to increase the Optimal Binder Content (OBC) in an asphalt mixture [4,5]. The absorption values of the RCA as illustrated in Table 2 were in all cases higher than 5%, while for the NA absorption values were lower than 2%. Many researchers have explained that the high absorption in the RCA is due to the mortar content or cement paste on the crushed aggregates, and as the RCA content increases the OBC in the asphalt mixture also increase [2,4,5].

Regarding angularity, values as reported in Table 2 indicate that the three sources of aggregates meet the requirements in terms of the percentage of fractured faces for the traffic levels specified by INVIA. The percentage of fractured particles for both RCA was in the order of 95-97%, while for the NA was 77-86%. In general, higher values of angularity were found for both RCA compared to NA. In general, literature reports high percentage of fractured particles for RCA [1,5,7].

The pH test revealed that the aggregates are in the basic - alkaline range, which is important for RCA being used in asphalt mixtures as the adhesion in the aggregate-asphalt interface is greatly enhanced at this pH values as reported elsewhere [13]. For RCA the pH values are in the range between 10.07 and 12.26 as shown if Figure 4, and there is a slight tendency to decrease for the fine fraction of RCA. However, in the natural aggregate this tendency is more marked as the pH falls between 7.29 - 7.55, representative of values very close to neutral pH.
Table 2. Physical Properties of NA and RCAs

| Test                          | Standards          | Results NA | RCAP | RCAB | Requirements |
|-------------------------------|--------------------|------------|------|------|--------------|
| Fractured particles one face(%)| INVE 227-2013      | 86         | 97   | 97   | NT1 (60)     |
|                              |                    |            |      |      | NT2 (75)     |
|                              |                    |            |      |      | NT3 (70)     |
| Fractured particles two faces(%)| INVE 227-2013      | 77         | 95   | 95   | NR           |
|                              |                    |            |      |      | NR           |
| Bulk specific gravity, fine aggregate| INVE 222-2013 | 2.56       | 2.41 | 2.41 | -            |
| Bulk specific gravity, coarse aggregate| INVE 222-2013 | 2.59       | 2.32 | 2.24 | -            |
| Water absorption (%), fine aggregate| INVE 222-2013 | 1.91       | 6.59 | 7.14 | -            |
| Water absorption (%), coarse aggregate| INVE 223-2013 | 1.16       | 5.28 | 6.17 | -            |

Requirements are based on binder layer
NR: Not required for binder layers

Note: NT stands for Traffic Level based on Colombian National Standards for Highways Construction.

Figure 4. pH results for RCAP, RCAB and NA

The mechanical properties for the three types of aggregates evaluated in this investigation are presented in Table 3. It has been observed that both RCAs evidence higher LA abrasion coefficient (27.3 -31.6 %) than the NA (21.5%), nevertheless values are usually within specified limits for this parameter as stipulated by INVIAS and reported by other authors [1,4,7]. The lower abrasion resistance of RCA has been attributed to the presence of adherent mortar on the crushed aggregate particles, which typically has a lower toughness compared to a conventional NA; also the abrasion resistance of RCA decreases proportionally with an increase in the mortar content and/or cement paste as reported elsewhere [2]. Results from mechanical resistance test or ACV indicate lower resistance for the RCAs than for the NA as expected, with better performance of the RCAP than the RCAB; additionally, values in the dry condition were significantly better than in the wet condition. It is important to mention that the crushing value as reported here corresponds to a modified procedure as established by Colombian Standards and will not be directly comparable to ACV as reported for RCA by other researchers. However, results as presented in Table 3 represents the expected behaviour for NA exhibiting the highest crushing strength among the three sources studied in this investigation.
Table 3. Mechanical Properties of Natural and RCA Aggregates

| Test                        | Standards | Requirements               |
|-----------------------------|-----------|----------------------------|
| LA wear (%) (100 revolutions) | INV E 218-13 | Wearing course (5%)         |
|                             |           | Base course (7%)           |
| LA wear (%) (500 revolutions) |           | Wearing course (20%) (NT3) |
|                             |           | Wearing course and Base course (25%) (NT2) |
|                             |           | Base course (30%)         |
| Micro-Deval                 | INV E 238-13 | Wearing course (110)       |
| Aggregate Crushing Value    | Dry       | Base course (75)           |
|                             | Moist     |                            |

Note: NT stands for Traffic Level based on Colombian National Standards for Highways Construction.

Figure 5. SEM micrographs of (a) NA; (b) RCAP, and composition estimated by EDS; (c) NA; (d) RCAP

The RCAB (Recycled Concrete Aggregate from building) is the aggregate source exhibiting the lower performance of the group based on the mechanical parameters are presented in Table 3.
Although, lower quality has been attributed to RCA in comparison to the NA, RCA can be used as a partial replacement of NA in order to obtain an economic, sustainable and high quality material in asphalt pavement applications [1, 2].

SEM analysis was performed to characterize the microstructure of the different aggregates sources. Figure 5a-b) shows the SEM images and the composition estimated by EDS for NA and RCAP. The results indicated that both samples contained similar components but there are marked differences. In particular, the quantity of Si, Al, appears to be higher in the RCA than in the NA because the former contains adherent cement paste or mortar. The main difference between the two spectra is the presence of Ca, Na in the RCA sample but not in the NA sample, which represents typical elements such as alkalis and calcium components in the cement matrix as well. Regarding particle morphology using SEM image analysis, both NA and RCAP have an irregular surface with the RCAP as a mixture of original aggregates and bonded hydrated cement paste or mortar, and the interface between them is well defined as shown in Figure 5c-d).

4. Conclusions

The physical, mechanical and chemical properties of three aggregates (NA, RCAP, RCAB) were analysed in this investigation. On the basis of our comparative analysis of test results the conclusions are as follows:

It was noted that RCA materials are more absorbent in comparison to a natural aggregate. For RCA materials the water absorption increases when the particles size decreases. The mortar content adhered to the aggregate on the RCA tends to decrease the density for the coarse fraction and water absorption depends on the porosity of cement matrix attached to the recycled concrete. The fine particles of the RCA are composed mostly of disintegrated mortar or cement paste and in smaller amounts, by coarse aggregate after the crushing process. Therefore, the lower the amount of mortar presents in the aggregate, lower absorption capacity and in consequence better quality of the coarse fraction of RCA.

According to the results of abrasion resistance (LA coefficient) and Aggregate Crushing Value (ACV) the RCAB is the material that exhibits the lowest mechanical resistance and also there is a tendency in all three materials to decrease their mechanical resistance in a moist condition as expected. It is important to mention that a reason of better mechanical performance of the RCAP compared to RCAB can be related to the properties of the waste concrete, which for roads projects could be similar (obtained by crushing same strength class concrete and same thickness), while the concrete waste from building demolition may not be the same (depends on the structural elements), so properties can differ substantially.

In general, RCA properties differ between fine fraction (Particle size < 4.0mm) and coarse fraction (Particle size > 4.0mm). For NA this characteristic is relevant because coarse and fine fraction are obtained from different quarrying sites.

Coarse RCA is composed of a natural coarse aggregate and an adhered mortar layer or cement paste, while fine RCA is composed in a higher amount of a crushed mortar. This difference in composition determines the properties in the fine and coarse fractions of the RCA.

Based on the results from physical, mechanical and chemical analysis, the RCAP demonstrated the best behaviour and could be used as a potential replacement of NA in asphalt pavement applications. Further investigation is needed to evaluate the performance in HMA with partial replacement of RCAP.

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