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ORIGINAL ARTICLE

Effect of natural coarse aggregate type on the physical and mechanical properties of recycled coarse aggregates

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Abstract Many environmental problems caused by the large volumes of construction and demolition waste (C&DW), the lack of adequate deposition sites and the shortage of natural resources have led to the use of C&DW as replacement of natural aggregates in the production of new concrete. As in the case of natural aggregates, when recycled aggregates are used to manufacture structural concrete, the assessment of their physical, mechanical and durable characteristics is a key issue. The different physical and mechanical properties of the recycled coarse aggregate (RCA) are evaluated. RCA was obtained by crushing conventional concretes with different strength levels (different w/c ratios) containing four different types of natural coarse aggregates (three crushed stones and a siliceous gravel), which differ in shape, composition and surface texture. There is a significant influence of the natural coarse aggregate (NCA) on the properties of RCA, which in many cases is greater than that of the w/c ratio of the source concrete.

Keywords Natural aggregate · Recycled aggregate · Absorption · Los Angeles abrasion · Flakiness index · Mortar content

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1 Introduction

All sectors of society are responsible for environmental pollution problems, but the incidence of the construction industry is particularly high, owing to both waste generation and the exploitation of natural resources. However, there are many possibilities and alternatives to contribute to environmental protection.

Although in Argentina there still are vast areas where suitable aggregates for concrete manufacture can be obtained, it is certainly true that in many cases large distances have to be travelled to obtain good-quality natural aggregates. Besides, because of their composition, certain types of natural rocks may cause different durability-related problems such as the alkali-aggregate reaction in rocks containing reactive minerals or the occurrence of expansive clays in the microstructure of some basalts, which would further add to the damage caused by the use of natural aggregates.

Large urban centres are also facing the problem of not having adequate deposition sites, which leads to large accumulations of construction waste material.

One of the ways of mitigating such problems is related to the use of recycled aggregates, obtained by crushing waste concrete, as replacement of natural aggregates in the production of new concrete. This would obviously reduce the amount of deposited waste.

Owing to their composition, where the mortar and the rock form mixed particles with varying proportions of each of them, recycled aggregates have different characteristics than natural aggregates, such as lower specific gravity and higher water absorption and Los Angeles abrasion [1–3]. However, to our knowledge there are no studies about the influence of the type of natural coarse aggregate (NCA) on the properties of recycled aggregates obtained from crushed concrete. Some studies on this subject have analysed how the quality of the crushed original concrete influences the properties of the recycled coarse aggregate (RCA), arriving at various conclusions [3–5].

It is well known that the shape and surface roughness of NCA have some influence during concrete production since they can change concrete proportions (w/c ratio, cement content, fine aggregate/coarse aggregate ratio, etc.) as well as some of its fresh state characteristics. Moreover, the above-mentioned characteristics of NCA exert a great influence on hardened concrete properties because of the change in the aggregate-matrix interface [6–9].

The first part of an extensive study regarding the behaviour of recycled concretes is presented in this paper. The purpose is to evaluate the effect of the type of NCA used in the manufacture of conventional concretes with different strength levels on the physical and mechanical properties of the recycled aggregates obtained by crushing them. Four natural coarse aggregates that are usually employed in the central region of Argentina were selected. They have different characteristics related to their origin, composition, shape and surface texture that change both their properties and those of the concretes made with them [10].

For each type of NCA used, concretes with w/c ratios of 0.45 and 0.65 were made, which were then crushed to obtain eight different types of RCA. Different physical and mechanical properties of the NCA and of the resulting RCA are presented, such as specific gravity, water absorption in 24 h, Los Angeles abrasion, unit weight, void content, material finer than 75 μm, flakiness index and mortar content.

2 Experimental

The NCA consisted of three crushed stones and a rounded aggregate, all of them with a nominal size of 6–20 mm. The NCA has differences in composition, particle shape and surface texture, which makes its physical, mechanical and durable characteristics also different. The crushed stones consisted of one of igneous plutonic origin (granitic—G), one of igneous volcanic origin (basaltic—B) and the other of sedimentary origin (quartzitic—Q), whereas the fourth NCA was a siliceous gravel from the Uruguay River (siliceous gravel—S).

Concretes with w/c ratios of 0.45 and 0.65 were made with each one of the four NCAs, keeping the volume content of the concrete coarse aggregate constant. Each of these concretes was cured for 28 days, crushed in a jaw crusher and subsequently sieved to obtain eight RCAs 6–20 mm in nominal size. The recycled aggregates are designated by the letter R followed by a second letter that indicates the type of NCA they contain, and by a number that refers to the w/c ratio of the source concrete. Thus, aggregates RG45 and RG65 denote the RCA obtained by crushing conventional concretes, made with granitic aggregate (G), with a w/c ratio of 0.45 and 0.65, respectively.

On each coarse aggregate sample (four natural and eight recycled coarse aggregates) different physical and mechanical properties were determined, such as specific gravity at saturated and surface-dry state, water absorption in 24 h, weight loss by the Los Angeles abrasion test, percentage of material finer than 75 μm, unit weight measured by the shovelling procedure, void content, flakiness index, weight loss after immersion in ethylene glycol for 30 days (only in the case of aggregate B) and loss on acid digestion in order to estimate the RCA mortar content. The standards used for each test performed are included in Table 1.

The basaltic aggregates (B) may be contaminated with secondary minerals such as clays of the montmorillonite group, which exhibit a laminar structure and may undergo significant increases in volume and cause aggregate fracture when they are subjected to

Table 1 Test standards used

Properties	Test standard
Specific gravity and absorption	ASTM C 127-01
Los Angeles abrasion	ASTM C 131-03
Material finer than 75 μm	ASTM C 117-03
Unit weight	ASTM C 29-03
Voids	ASTM C 29-03
Flakiness index	BS 812-105.1:1985
Durability in ethylene glycol	IRAM 1519:1982

drying and wetting cycles. The durability test in ethylene glycol is carried out to evaluate whether these aggregates have these characteristics, and they will be considered as acceptable whenever their weight loss is not over 10%.

In order to determine the RCA mortar content, samples of a 10–20 mm fraction of each of them were taken and covered with a known volume of water to which the same volume of hydrochloric acid was added, obtaining a 1:1 dilution. Heating to incipient boiling was then performed and the samples were stored for 24 h. Finally, the remaining aggregates were washed, dried to constant weight and then sieved through a sieve # 4 to obtain the rock particles of the original NCA. The weight losses of NCAs were also determined by the same procedure. The reported values correspond to the net percent of mortar loss for each RCA since each NCA loss has been deducted.

2.1 Characteristics of NCA

The aggregate G consists of a medium-grained, very compact and unweathered granitic migmatite, containing 30–40% quartz with cataclastic structure and undulatory extinction. The aggregate B is composed of alkaline basaltic rocks originated from fracture outflow that are petrographically classified as fine-grained, massive and slightly altered nepheline basanites. The aggregate Q consists of orthoquartzite of sedimentary origin, containing 97–99% quartz forming subrounded, subangular and even angular grains bonded by siliceous cement. They have a fine-grained structure with grains ranging between 0.5 and 0.8 mm, which are yellow to dark brown because of iron hydrolysis. The fourth NCA is a siliceous gravel (S) from deposits of the Uruguay River, which is composed of rounded clasts containing quartz (∼30%), chalcedony (∼50%) and sandstones-siltstones (∼20%).

The physical characteristics of shape, surface texture and grain size of each of the four NCAs selected are summarised in Table 2.

2.2 Results and analysis

Figure 1 shows the grading of the four NCAs together with the limits set by the Argentine CIRSOC regulations [11], and Table 3 reports the different properties determined on each of them.

Table 2 Characteristics of natural coarse aggregates

Characteristics	G	Q	B	S
Shape	Angular			Rounded
Surface texture	Rough		Smooth	
Grain size	Medium		Fine	

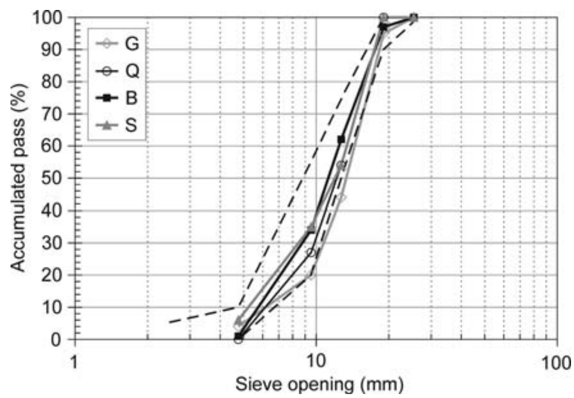

Fig. 1 Grading of natural coarse aggregates

Table 3 Properties of natural coarse aggregates

Properties	G	Q	B	S
Specific gravity (kg/dm^3)	2.72	2.48	3.03	2.60
Absorption (%)	0.3	2.0	0.8	0.5
Los Angeles abrasion (%)	25.0	59.8	9.1	18.8
Material finer than 75 μm (%)	0.6	0.9	0.3	0.2
Unit weight (kg/m^3)	1410	1310	1530	1580
Voids (%)	48.0	46.2	49.3	38.4
Flakiness index (%)	19.2	25.3	26.7	9.9
Weight loss in ethylene glycol (%)	–	–	2.5	–

It can be observed that aggregate Q has the highest absorption and Los Angeles abrasion values, as well as lower specific gravity, which is directly related to its origin. Aggregate S has the highest unit weight value, although its specific gravity is not the highest, and the lowest flakiness index, which is directly associated with its shape that gives it a lower void content.

The grading determined on each of the eight RCAs is shown in Fig. 2, together with the above-mentioned limits set by the CIRSOC regulations for natural aggregates of the same maximum nominal size.

It can be noted that the eight RCAs have similar particle-size distribution, regardless of the type of

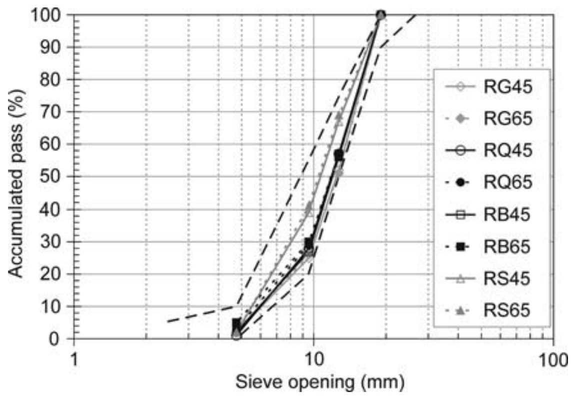

Fig. 2 Grading of recycled coarse aggregates

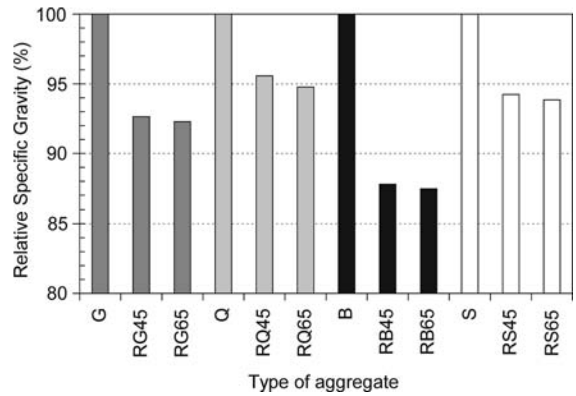

Fig. 3 Relative specific gravities of recycled coarse aggregates

NCA and the w/c ratio of the source concrete. The results obtained agree with some other results reported in the literature, where the grading of RCAs is independent of the w/c ratio of the original concrete [3, 5] and meets the limits prescribed for NCAs. It is also clear that the grading of RCA is not influenced by the different characteristics of shape and texture of the NCAs in the source concrete.

The physical and mechanical properties determined on each of the eight RCAs under study are given in Table 4, as in the case of natural aggregates, but including their mortar content.

The relative specific gravities at saturated and surface-dry state of each RCA with respect to the specific gravity of the corresponding NCA are indicated in Fig. 3.

It is worth noting that for each type of NCA, the specific gravity of the corresponding RCA is lower and that there is no significant difference depending on the source concrete quality, which is in agreement with literature reports on this subject [5, 12]. The specific gravity values of RCAs decreased by approximately 7, 4, 12 and 6% in relation to those of the natural aggregates G, Q, B and S, respectively.

Besides, as expected, the higher the specific gravity of the NCA used in concrete production, the greater the influence of the mortar present in RCA particles. This implies a larger decrease in specific gravity, which is more clearly shown in the case of aggregate B. Although the specific gravity of RCAs decreases in relation to that of NCAs, the specific gravity of an RCA from a concrete made with a certain type of NCA may be greater than that of another type of natural aggregate. This is the case of recycled aggregates RB45 and RB65 as compared to the natural aggregates S and Q. So, recycled concrete would not always present a lower unit weight than conventional concrete.

As expected, 24 h water absorption of RCAs shows a significant increase with respect to that of NCAs for each type of natural aggregate used (see Table 4), which is directly related to the presence of mortar as a constituent part of these aggregates. RCA absorption

Table 4 Properties of recycled coarse aggregates

Properties	RG45	RG65	RQ45	RQ65	RB45	RB65	RS45	RS65
Specific gravity (kg/dm^3)	2.52	2.51	2.37	2.35	2.66	2.65	2.45	2.44
Absorption (%)	4.0	4.1	5.9	6.0	3.9	4.5	3.9	4.4
Los Angeles abrasion (%)	34.8	37.4	52.2	55.4	25.3	30.3	31.6	37.0
Material finer than 75 μm (%)	0.6	0.1	0.2	0.2	0.2	0.4	0.1	0.1
Unit weight (kg/m^3)	1220	1190	1100	1140	1260	1290	1190	1210
Voids (%)	49.4	50.9	50.9	48.5	50.9	49.2	49.5	48.1
Flakiness index (%)	12.9	10.1	14.9	12.7	11.3	9.9	11.2	10.4
Mortar content (%)	45.6	41.8	64.4	57.6	48.4	42.0	49.3	44.2

values were approximately 14, 3, 5 and 8 times higher than those of aggregates G, Q, B and S, respectively. In contrast to what happens with the specific gravity, the RCAs from concretes of lower quality (0.65 w/c ratio) have absorption values higher than those of the RCAs from concretes with a w/c ratio of 0.45. These results agree with the findings of some studies [13, 14] but completely disagree with others [3, 4, 12].

Figure 4 shows the weight loss values from the Los Angeles abrasion test for each RCA in relation to those of natural aggregates, using gradation "B" as defined in the standard (see Table 1).

From the tests conducted so far, it follows that the porosity of RCAs, estimated by the absorption and specific gravity tests, increases in relation to that of each of the four NCAs. This behaviour is different in the Los Angeles abrasion test, where increases in abrasion values are observed for recycled aggregates RG, RB and RS in relation to those of the corresponding NCAs, with average values of 45, 200 and 82%, respectively. The greatest abrasion in RCAs occurs in concretes with a weaker matrix (w/c of 0.65), which is expected and agrees with what has been reported in the literature [5, 13].

A particular case is that of the quartzitic aggregate where RQ showed less abrasion than Q (of the order of 5%). This is a clear indication of the lower quality of the natural aggregate, since even the RCA from a concrete with a w/c ratio of 0.65 showed less abrasion than the NCA.

Figure 5 shows the unit weights of RCAs in relation to those of the corresponding NCAs, determined by the shovelling procedure.

Unit weight values are lower for RCAs because of their lower specific gravity; there are no significant

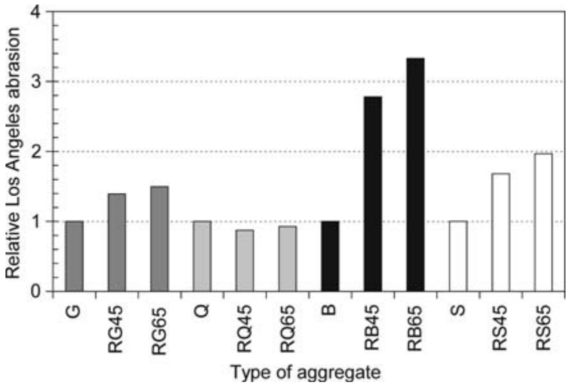

Fig. 4 Relative weight losses by the Los Angeles abrasion test

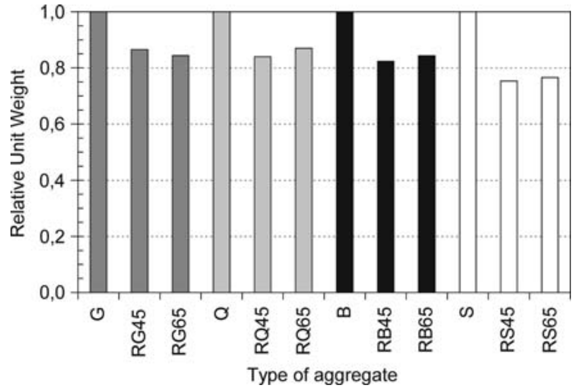

Fig. 5 Relative unit weight of recycled coarse aggregates

differences among those from concretes with a w/c ratio of 0.45 and 0.65. The average decreases were 15, 15, 17 and 25% for the aggregates RG, RQ, RB and RS, respectively. The larger decrease in the case of aggregates RS must be attributed to the additional effect of the change in shape of the recycled aggregate particles. This is evidenced by the higher void content of both aggregates RS in relation to that of S.

The flakiness indexes of RCAs in relation to those of the corresponding NCAs are presented in Fig. 6.

The RCAs from concretes containing aggregates of angular shape (G, Q and B) have a lower flakiness index than the corresponding NCAs. Because of the presence of oriented weak planes in the natural rocks, the crushing process will lead to a larger fracture on these planes forming a larger number of flaky particles in the NCAs [15]. In the case of crushed concretes, weakness planes (interfaces) are distributed without a defined orientation, which makes the RCA particles have similar sizes in the three

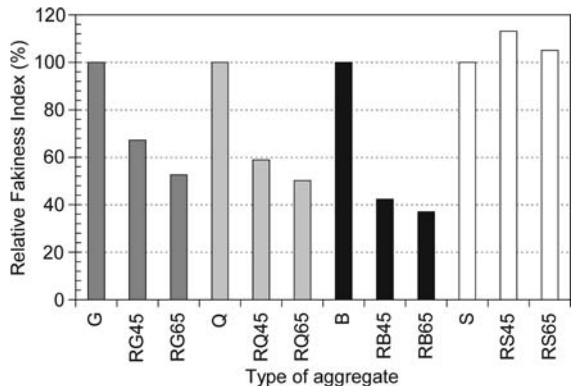

Fig. 6 Relative flakiness index of recycled coarse aggregates

directions. However, the type of crusher used will have a strong influence on the shape of the particles formed [15, 16].

Another peculiarity shown in Fig. 6, for the four types of NCA used, is that the recycled aggregates produced from concretes with a higher w/c ratio are less flaky. The lower matrix strength of concretes with a w/c ratio of 0.65 would lead to a larger mortar loss during their crushing, making these RCA particles less flaky than those from concretes with a w/c ratio of 0.45. This can be confirmed with the results from other tests, as shown below.

In Table 4, it can be seen that the RCAs from concretes with a w/c ratio of 0.65 show lower mortar content values than those from concretes with a w/c ratio of 0.45, which occurs for the four types of NCA selected.

As mentioned above, this can be attributed to a greater mortar loss during the crushing of concretes with a high w/c ratio, because their matrix is weaker than that of concretes with a w/c ratio of 0.45. The grading of recycled samples after the hydrochloric acid attack confirms these results. As an example, the particle-size distribution of the original natural basalt (B) and those of the natural aggregate extracted by means of the diluted hydrochloric acid attack to aggregates RB45 and RB65 (named B in RB45 and B in RB65, respectively) are shown in Fig. 7.

The grading of B in RB45 is the one that differs more from that of the natural aggregate B. This clearly shows that in the case of RB45, the fracture process occurs mainly through the natural aggregate because of the higher matrix strength. Whereas in RB65, because of the lower matrix strength the fracture preferably occurs through the mortar, leading to a coarser particle size than in the former case although finer than that of B.

The relationships between Los Angeles abrasion loss and the mortar content of the RCAs under study, for both RCAs from concrete with w/c ratios of 0.45 and 0.65 (R45 and R65, respectively), are shown in Fig. 8.

For both w/c ratios the abrasion loss tends to increase with the mortar content of the aggregates. For a given mortar content, aggregates R65 attain higher Los Angeles abrasion values than R45, which is in agreement with the lower quality of the mortar.

Owing to the characteristics of aggregate Q, the abrasion loss values are high in the corresponding RCA (the upper points in Fig. 8), indicating the strong influence that the properties of the original natural aggregates may have on those of the resulting recycled aggregates. So a recycled aggregate obtained from a concrete with a w/c ratio of 0.45 may exhibit a higher abrasion value than another one from a concrete with a w/c ratio of 0.65, which is the case of the aggregate RQ45 with respect to RB65. This allows confirming that the w/c ratio of the original concrete is relatively less important than the abrasion loss value of the NCAs it contains.

Figure 9 shows the relative differences between aggregates R65 and R45 in the absorption, Los Angeles abrasion and mortar content tests, for the four types of natural aggregates used. It must be remembered that the mortar contents of aggregates R65 were lower than those of R45, so in the figure the axis corresponding to this determination is on a negative scale.

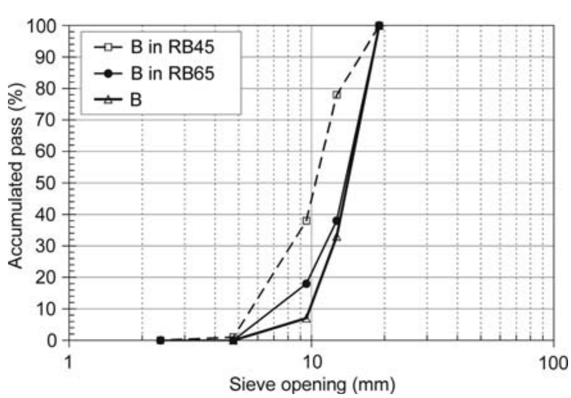

Fig. 7 Grading of aggregates B, B in RB45 and B in RB65

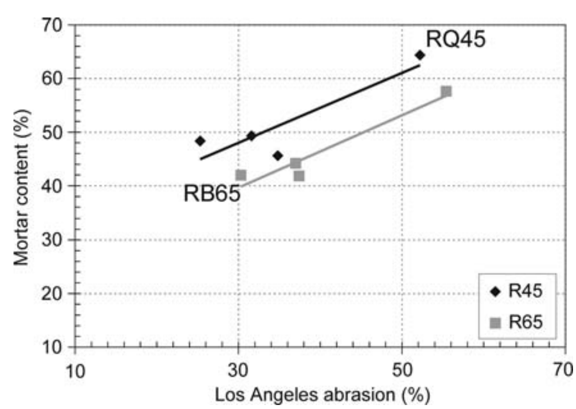

Fig. 8 Relationships between Los Angeles abrasion and the mortar content

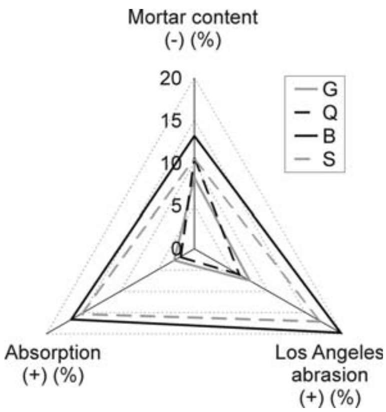

Fig. 9 Relative differences between aggregates R65 and R45 for the absorption

There is a marked difference in absorption and abrasion between the recycled aggregates that contain the natural aggregates G and Q and those that contain the aggregates S and B; the differences in mortar content are lower but still show the same tendency.

The behaviour observed must be analysed taking into account the matrix strength together with the surface texture of the NCA, which are known to change the characteristics of the aggregate-matrix interface [10, 17]. If the matrix is weak (w/c ratio of 0.65), the smooth surface texture of natural aggregates B and S negatively affects adherence. This facilitates mortar separation from NCAs during crushing and the formation of particles made up of only mortar in aggregates RB65 and RS65. In the case of natural aggregates G and Q, owing to their rough surface textures, the improved aggregate-matrix interface led to higher fracture of NCAs and the formation of a larger number of mixed particles (rock-mortar).

3 Conclusions

Based on the physical and mechanical characteristics determined on different RCAs (6–20 mm in nominal size) from crushed conventional concretes with different w/c ratios and made with NCAs of the same nominal size, having different surface roughness, shape, and physical and mechanical behaviour, the following conclusions can be drawn:

– The grading and the unit weight of RCAs are not influenced by any of the two variables studied (type of NCA and w/c ratio). The specific gravity, water absorption and Los Angeles abrasion clearly indicate that RCAs are of lower quality than NCAs because of the mortar they contain.
– The natural quartzitic aggregate is a particular case because in the Los Angeles abrasion test the recycled aggregates have lower weight loss than NCA, which is directly related to its low quality.
– The mortar content is lower in RCAs from concrete with a higher w/c ratio, which must be attributed to a higher mortar loss during the concrete crushing process owing to the weaker matrix.
– For the NCAs used and the w/c ratios studied, the properties evaluated for RCAs are more affected by the type of NCAs than by the w/c ratio of the source concrete from which the recycled aggregates were obtained.

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