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Self-Compacting Concrete with Recycled Concrete Aggregate: Resistance against Aggressive External Agents

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Abstract. *The use of waste in civil-engineering products, such as concrete and asphalt mixes, is a very effective strategy for reducing high consumption levels of Natural Aggregates (NA) in the construction sector. In this research, rejected precast concrete elements of high compressive strength are studied, following their crushing for use as a high quality Recycled Concrete Aggregate (RCA) in the manufacture of Self-Compacting Concrete (SCC). High volumes of this waste stream are employed in the mixture, completely replacing the coarse fraction of the natural aggregate (100% replacement rate) and half of the fine fraction (50% replacement rate). Once hardened, samples of the recycled SCC are exposed to several aggressive external agents, in order to evaluate their performance and durability in aggressive environments. Behavioral tests on the concrete in the presence of the most frequent aggressive agents in the surrounding environment demonstrated that the SCC containing RCA was resistant to freeze/thaw and moist/dry cycles, and sulphate attack, according to the results obtained in 4, 3 and 2 samples respectively, and of sufficient durability for use in structural concrete components.*

Keywords: *Self-Compacting Concrete, Recycled Concrete Aggregate, Freeze/Thaw Test, Moist/Dry Test, Sulphate Attack Test.*

1 Introduction

Modern-day society currently faces two immense environmental problems: climate change and the lack of natural resources (IPCC, 2014). Climate change is mainly due to the emission of greenhouse gases, resulting from a wide range of collective human actions related to manufacturing, transport, and energy production. High consumption in some areas of natural resources has led to shortages over recent years, as expanding populations need continual development of technology and infrastructure.

The construction sector is a major contributor to these problems (Sandanayake *et al.*, 2019): the cement industry emits high volumes of CO_2 (Maddalena *et al.*, 2018) and many other construction activities have a high carbon footprint (Noh *et al.*, 2018). Aggregate consumption in asphalt mixes, and concretes is also very high, in the order of 80% and 95% by volume. (CESCE, 2018). According to the Asociación Nacional de Empresarios Fabricantes de Áridos (ANEFA) [National Association of Aggregate Manufacturers of Spain], in 2017, 112 million tons of aggregates were consumed in Spain (ANEFA, 2018). The sector therefore has some responsibility to contribute to the reduction of these problems.

Aggregate substitution in several materials, including concrete, by different types of waste, such as rubber, slag, and even Recycled Concrete Aggregate (RCA), is an area of study that has opened several research lines (Busic *et al.*, 2018; Safiuddin *et al.*, 2013; Verian *et al.*, 2018). Hence, the use of RCA in this study is evaluated for the manufacture of concrete.

The mechanical performance of vibrated concrete with RCA is well-known: RCA, especially the fine fraction, decreases compressive strength (Evangelista *et al.*, 2014; Silva *et al.*, 2015). Durability is also affected, because of the high porosity of the attached mortar, which raises permeability levels and the entry of external agents (Guo *et al.*, 2018).

Self-Compacting Concrete (SCC) is of greater fluidity, so its porosity is lower. RCA can even improve its durability and enhance some other properties (Boudali *et al.*, 2016; Pereira-De-Oliveira *et al.*, 2014). The RCA effect on mechanical properties will not change due to self-compactability (Fiol *et al.*, 2018; Grdic *et al.*, 2010). Nevertheless, there is a scarcity of studies on precise definitions of the RCA effect.

In line with the above, the durability of an SCC design consisting of 100% coarse RCA and 50% by volume of fine RCA will be evaluated in this research. This concrete underwent three tests: behavior during freeze/thaw and moist/dry cycles, and resistance to sulphate attack, demonstrating its performance when exposed to highly aggressive environmental agents.

2 Materials

Three types of materials were employed: RCA, natural aggregates (NA), and non-aggregate.

CEM I 52.5 R with a density of 3.1 kg/dm^3 was employed as a non-aggregate material. Water was obtained from the mains water supply system of Burgos. Two admixtures were also used: a viscosity adjuster (called admixture 1) and a superplasticizer (called admixture 2). Previous studies showed that, if the amount of water is optimal, the quantity of these admixtures will range between 0.5-1.5% of the cement weight (Fiol *et al.*, 2018).

Only the fine NA fractions were used. Siliceous sand with a density of 2.58 kg/dm^3 and a 24h water absorption of 0.25% was used. In addition, SCC requires a large fines content for acceptable flowability, so limestone sand 0/1.2mm (density of 2.62 kg/dm^3 and a 24h water absorption of 2.08%) and limestone filler <0.063 mm (density of 2.77 kg/dm^3) were used.

The RCA consisted of rejected precast elements with a characteristic compressive strength of 40-45 MPa prior to crushing. The crushed RCA was sized between 0 and 30 mm, for which reason it was screened to obtain the desired fractions: the fine fraction 0/4 mm (density of 2.37 kg/dm^3 and 24h water absorption of 7.36%) and the coarse fraction 4/12.5 mm (density of 2.42 kg/dm^3 and 24h water absorption of 6.25%). Particles larger than 12.5 mm were discarded, because they were considered too large to make an SCC.

The appearance of the aggregate and their granulometry are shown in Figure 1 and Figure 2.

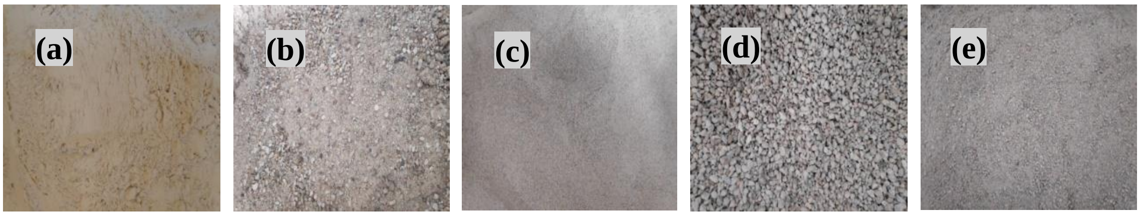

Figure 1. Appearance of the aggregates used for the manufacture of the SCC: a) Limestone filler <0.063 mm; b) Siliceous sand 0/4 mm; c) Limestone sand 0/1.2 mm; d) Coarse RCA 4/12.5 mm; e) Fine RCA 0/4 mm.

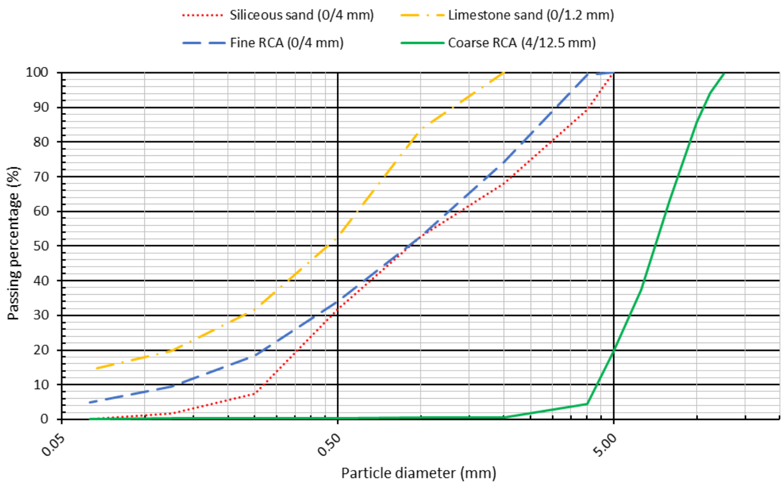

Figure 2. Aggregate granulometry.

3 Mix-Design

The SCC under evaluation was designed with the materials detailed in the preceding section and labelled SCC-I-50/100-D.

The dosage of the SCC was designed, so that neither segregation nor exudation would affect the final SCC and so that it would have an SF2 slump-flow class (maximum diameter between 650 and 750 mm). Design by trial and error began with a very common dosage in the precast cement component industry as the initial dosage. The results of a slump-flow test, norm EN 12350-8 (EN-Euronorm.), suggested adjustments to the proportions of the materials in a second stage. The process of trial and error was repeated several times (third dosage, forth one…) until the definitive optimal dosage was obtained: 296 kg/m^3 of cement, 122 kg/m^3 of filler, 183 kg/m^3 of water, 522 kg/m^3 of coarse RCA, 570 kg/m^3 of fine RCA, 343 kg/m^3 of siliceous sand 0/4 mm, 215 kg/m^3 of limestone sand 0/1.2 mm, 2.20 kg/m^3 of admixture 1, and 4.35 kg/m^3 of admixture 2. In Figure 3, some slump-flow trials during the design process can be observed.

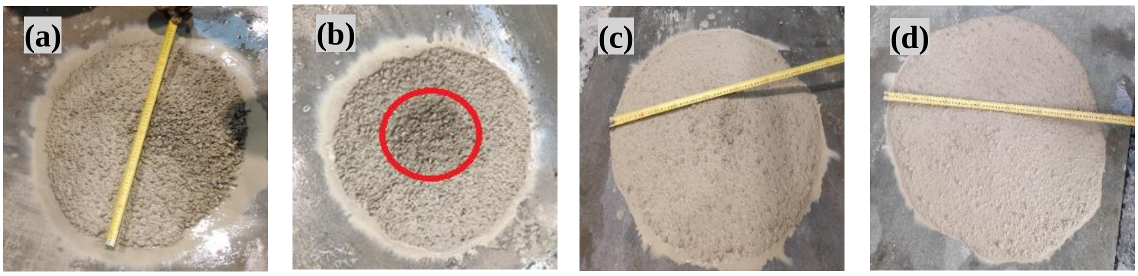

Figure 3. Dosages by trial and error during the development of the SCC: a) Initial dosage; b) Dosage with high segregation in the central area: c) Dosage with minimal segregation in the central area; d) Optimal dosage.

4 In-Fresh State Behavior

The slump flow test is insufficient in itself to ensure optimal SCC flowability and further characterization of the in-fresh state behavior is necessary (EFNARC, 2002).

- The slump flow test was performed first (EN 12350-8). A diameter of 500 mm was achieved in 4 s, being the maximum diameter 720 mm (SF2 slump-flow class).

- Viscosity was measured by the time it took the SCC mix to pass through a V-funnel (EN 12350-9), which took 7s (viscosity class VF1, time under 8s).
- The 2-bar L-box test (EN 12350-10) measured the passing ability of the SCC. The quotient between the maximum and the minimum height was 0.97 (passing-ability class PA1, quotient greater than 0.80 and 2-bar L-box).
- The sieve segregation test (EN 12350-11) assessed the segregation resistance. The result obtained was 0.41% (SR2 class, segregation lower than 15%).

5 Compressive Strength

Compressive strength at different ages was measured, to guarantee its structural suitability. Two specimens were tested at each age (1, 7 and 28 days),

At 1 day, the normalized sample already had a high compressive strength (28 MPa, 61.4% of 28-days strength). Increased strength over the first seven days was very fast (84.0% of the final strength was reached at 28 days, 38.3 MPa). After three weeks, the compressive strength increase slowed down, reaching 45.6 MPa at 28 days. The SCC could therefore be suitable for precast elements (compressive strength greater than 45MPa).

6 Durability

Three durability tests were performed as part of the analysis of the effects of aggressive external agents: freeze/thaw and moist/dry test cycles, and sulphate attack. All the tests began on the same day. 10 cm-side cubic samples cured over 30 days were used. On first day of the tests, the compressive strength, measured on two cubic samples, was 47.61 MPa on average, which subsequently became the reference for any quantifiable decrease in compressive strength.

6.1 Freeze/Thaw Test

Freeze/thaw tests were performed according to UNE-CEN/TS-12390-9-EX (2008) (CEN). Four 10 cm-side cubic samples were introduced into a container full of water with 3% by mass of NaCl and subjected to 56 freeze/thaw cycles. In each 24h cycle, the container was exposed to 16h of freezing at a temperature of -15ºC and to 8h of thawing in water at 20ºC. Any loose materials were removed every 10 cycles and the specimens were then dried and weighed. Figure 4 shows the loss of mass and, Figure 5, the initial and final state of the test specimens.

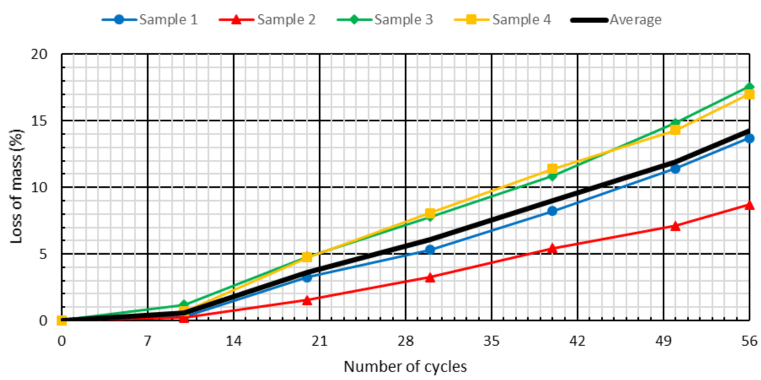

Figure 4. Loss of mass over freeze/thaw test. Average loss of mass at the end of the test: 14.23%.

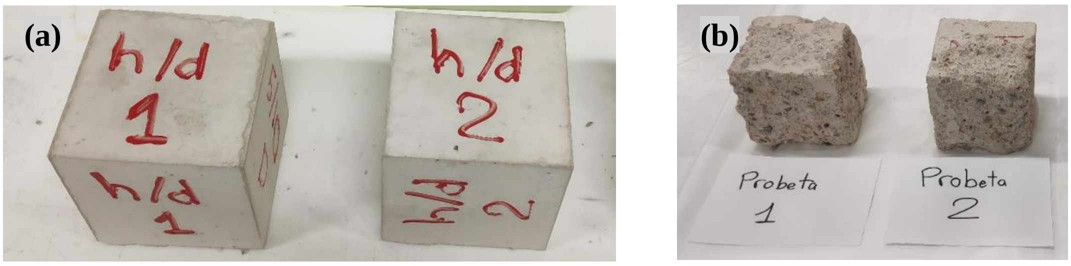

Figure 5. Freeze/thaw test: A) Initial state; B) Final state.

In addition to loss of mass, Ultrasonic Pulse Velocity (UPV), an indirect measure of compressive strength, was evaluated both before and after the test. The strength was also measured after the test. All the results are shown in Table 1.

Table 1. Freeze/thaw test. Results related to UPV and compressive strength.

Test/Sample	Sample 1	Sample 2	Sample 3	Sample 4	Average	Standard deviation
UPV before the test (km/s)	3.95	3.57	3.72	3.51	3.69	0.20
UPV after the test (km/s)	3.13	3.11	3.28	3.07	3.15	0.09
Comp. strength after the test (MPa)	37.06	20.94	32.62	34.46	31.27	7.12
UPV average variation (%): -14.67%	Comp. strength average variation (%): -34.32%					

The decrease in compressive strength was high, unlike the loss of mass. A decrease that could be due to the increased volume of water that expanded when frozen, opening internal micro-voids in the mortar that had adhered to the aggregate (a process that the mortar assists, because of its high porosity). It all caused a sharp decrease in compressive strength.

6.2 Moist/Dry Test

This test was performed by adapting the test in the ASTM D 559 standard (ASTM-International, 2008) that simulates the effects of rain and subsequent drying by solar radiation on concrete. Fundamentally, the thermal shock inflicted during the changeover from a wet to a dry situation. To do so, three 10 cm-side cubic specimens were subjected to 30 24-hour cycles, which consisted of full immersion in water at a temperature between 18ºC and 22ºC, over 16h, followed by oven drying for 8h at 60ºC.

The external appearance of each sample after the test is shown in Figure 6. Every 10 cycles, each specimen was weighed and its UPV was measured, a parameter that had also been measured before the beginning of the test. When the trial ended, the samples were tested to compressive strength. The results obtained can be seen in Table 2.

Figure 6. Moist/dry test. Final state of the samples.

Table 2. Results of moist/dry test.

Test/Sample	Sample 1	Sample 2	Sample 3	Average	Standard deviation
Initial mass (g)	2,068.8	2,189.1	2,094.1	2,117.33	63.42
Mass after 10 cycles (g)	2,043.5	2,152.0	2,047.1	2,080.87	61.63
Mass after 20 cycles (g)	2,022.2	2,146.3	2,044.8	2,071.10	66.10
Mass after the test, 30 cycles (g)	2015.8	2,140.0	2,043.9	2,066.57	65.13
UPV before the test (km/s)	3.72	3.79	3.64	3.71	0.08
UPV after the test (km/s)	2.60	2.65	2.56	2.60	0.04
Comp. strength after the test (MPa)	35.00	32.92	32.17	33.36	1.47
Mass average variation (%): -2.40%	UPV average variation (%): -29.87%				
Compressive strength average variation (%): -29.93%					

The external appearance (without appreciable changes except the increased number of external voids on sample Nª3) and the loss of mass showed no visible change in the concrete. However, the compressive strength and the UPV showed significant changes at a microscopic level. Both changes could be explained by the appearance of larger internal micro voids than in the freeze/thaw test. Nevertheless, the decrease in compressive strength was very similar in both the moist/dry test and the freeze/thaw test. It appears that the large number of micro voids in the moist/dry test was compensated by the negligible loss of mass.

6.3 Sulphate Attack Test

This test was performed according to the ASTM C 1012 standard (ASTM-International, 2008), in which the concrete is exposed to sodium sulphate decahydrate that crystallizes within the sample, thereby increasing its volume. Each of the 15 24-hours cycles consisted of a 5-hour immersion in water with 14% by mass of $Na_2SO_4 \cdot 10H_2O$, oven drying for 17h at 60ºC and cooling at room temperature (23ºC) for 2h.

The final appearance of the two specimens tested is shown in Figure 7. No visible change was detected, except discoloration in the form of darkening, due to sodium sulphate precipitation. Before and after the trial the samples were weighed, the length of their sides was measured (in order to determine the expansion of concrete by the absorption and crystallization of the salt) and the UPV was determined. In addition, both specimens were tested to compressive strength. All the results are indicated in Table 3.

Table 3. Sulphate attack test. Individual and average results.

Test/Sample	Sample 1	Sample 2	Average	Standard deviation
Initial mass (g)	2,098.8	2,199.2	2,149.0	70.99
Final mass (g)	2,083.9	2,193.3	2,138.6	77.36
Initial average side length (mm.)	100.11	100.33	100.22	0.16
Final average side length (mm.)	100.13	100.34	100.24	0.15
UPV before the test (km/s)	3.69	3.58	3.64	0.08
UPV after the test (km/s)	3.38	2.63	3.01	0.53
Compressive strength after the test (MPa)	41.44	35.68	38.56	4.07
Mass average variation (%): -0.48%	Side expansion (%): +0.02%			
UPV average variation (%): -16.62%	Comp. strength average variation (%): -19.01%			

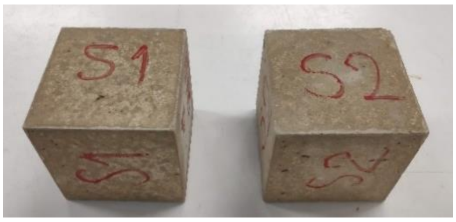

Figure 7. Sulphate attack test. Final state of the samples.

Neither the variation in either mass or length nor in the external appearance of the concrete samples showed relevant changes. The only noticeable effect was the reduction in compressive strength and the logical decrease in UPV. Nevertheless, compressive strength was less effected by the sulphates than by consequences of exposure to water in the moist/dry test. This difference can be explained by the high flowability of SCC, which implies that the concrete had a very low number of small-sized surface pores in the hardened state. Hence, the penetration of higher density solutions within the concrete was less likely, because water with no salt solutions penetrates with greater ease through surface pores than a sulphate solution, meaning that the sulphate effect would be lower towards the interior of the sample.

7 Conclusions

The following conclusions can be drawn from the study reported in this paper:

- Correct dosage design of an SCC with large amounts of both coarse and fine RCA will result in high flowability in the fresh state and a high compressive strength.
- A good design will mean that the SCC with RCA can be used in environments with aggressive external agents, with high precipitation and frequent frosts. These agents adversely affect the properties of the concrete, although the affections are not critical.
- The durability of the SCC exposed to aggressive external agents is linked to their external porosity. In other words, the greater the ease with which the external agent penetrates within the concrete, the worse the effect of those agents on the concrete.
- The concrete samples showed uniform behavior in all the tests, with similar results for all specimens, although those test results can vary depending on the surface finish. The homogeneity and workability of the mix was optimal when the specimens were manufactured, clearly demonstrating the uniform behavior and the durability of this SCC concrete for use in structural elements. This conclusion is based on the results obtained on four specimens in the freeze/thaw test, on three samples in the moist/dry test and two specimens in the sulphate attack test.

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