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EFFECTS OF THE USE OF RECYCLED CONCRETE AGGREGATES ON THE DRYING SHRINKAGE OF NORMAL AND HIGH STRENGTH CONCRETE

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Abstract

The main difference of the Recycled Concrete Aggregate (RCA), compared to the natural ones, is their greater porosity and, consequently, higher water absorption. Many researches have been carried out to investigate the influence of the use of RCA on the mechanical properties of concrete, but studies on the effects of RCA on the main concrete deformations is still very limited. The drying shrinkage is an important property, because it produces internal tensions and mass loss and, consequently, reduction in the concrete volume. This process can cause multiple cracking, damaging the durability of the material.

In this context, this study presents the results of an experimental campaign to evaluate the influence of RCAs on the drying shrinkage and the mechanical properties of different Recycled Aggregate Concrete (RAC) mixtures. RCAs from laboratory-produced waste were used in two size fractions (i.e., 4.8 mm to 9.5 mm and 9.5 mm to 19 mm). Normal and high strength concrete (35 and 60 MPa) with 100% of RCA in each size fraction were produced. The results showed that the smaller the modulus of elasticity, the greater the drying shrinkage. In addition, the drying shrinkage of the RACs was slightly higher than the strain of the reference mixtures.

1. Introduction

Concrete is one of the most used materials in construction because of the versatility and widely known properties of this material. Therefore, one way to promote sustainability in the construction industry is to use methods that minimize the environmental impacts of the use of concrete [1]. The recycling of Construction and Demolition Waste (CDW) in aggregate form is a potential alternative to improve this scenario, since most of these residues are composed of concrete, mortar and rocks [2]. The benefits of large-scale recycling of concrete waste are many, and two are highlighted: reducing the amount of concrete residues disposed in unsuitable locations and reducing the environmental impact generated by extraction of natural resources [3].

The main difference between the Recycled Concrete Aggregate (RCA) and the natural aggregate (NA) is the presence of an aged mortar, well-known as Attached Mortar (AM), on the surface of recycled aggregates. In general, this adhered mortar presents higher porosity than natural aggregates [4]. The properties of the RCAs are directly related to the characteristics and the amount of attached mortar in the grains. Thus, due to the higher porosity of RCAs, the Recycled Aggregate Concrete (RAC) is characterized by considerably higher water absorption and, consequently, a lower specific gravity [5].

The drying shrinkage is a phenomenon defined as the deformation of the concrete that occurs due to the evaporation of water from the capillary pores, caused by the low relative humidity of the environment. These conditions lead to the transport of water particles from the CSH to the capillary pores, which subsequently evaporate. The drying shrinkage produces internal stress, mass loss and, consequently, volume reduction in the concrete [6]. Studies have shown that the use of RCAs tends to increase the shrinkage of recycled concrete compared to natural concrete [7][8][9].

SILVA *et al.* [10] compared experimental data from different studies that evaluate the effect of recycled aggregates incorporation on concrete shrinkage. In this literature review, the authors concluded that as the recycled aggregate content increased in the mixtures, the shrinkage of recycled concrete was higher. However, this behavior may be more related to the quality of the original concrete waste, than to the amount of recycled aggregate present in the mixture. KOU & POON [11] evaluated the influence of the quality of the original concrete (compressive strength ranging from 30 to 100 MPa) of the RCAs in the shrinkage of concrete produced with these aggregates. The RAC that presented the highest drying shrinkage value was the mixture produced with aggregates from the concrete source with lower compressive strength (30 MPa). For the authors, this fact is associated with the higher water absorption presented by the aggregate produced from the original concrete with lower resistance. That is, recycled concrete produced with better quality aggregates have shrinkage values more similar to concrete with natural aggregates. GONZALEZ-COROMINAS & ETXEBERRIA [9] also investigated the influence of the original concrete quality (compressive strength of 40, 60 and 100 MPa) in the drying shrinkage of RACs. According to the results, the lower quality of the RCA together with the higher substitution rates of this material caused an increase in the drying shrinkage of the recycled concrete. For the authors, the drying shrinkage is related to the modulus of elasticity of the concrete, that is, the smaller the modulus of elasticity of the concrete, the higher the drying shrinkage. In the study of MEDJIGBODO *et al.* [12], the shrinkage deformation increased with the increase of the RCA. They attribute this fact to the increase in the amount of cement paste (old and new paste) and the distribution and connection between pores. In addition, the authors confirmed the conclusion of GONZALEZ-COROMINAS & ETXEBERRIA [9], that is, the lower modulus of elasticity of the RAC caused a smaller restraint of the drying shrinkage. ECKERT & OLIVEIRA [13] concluded that an adequate mixing process was able to reduce the negative effects of the high absorption of the recycled aggregates in the drying shrinkage test, reducing the susceptibility of cracking in a few ages. However, the internal cure was not able to compensate for the lower stiffness of the 100% RAC mixtures.

Therefore, the drying shrinkage of recycled concrete must be more evaluated to ensure that the material presents the performance required for practical applications. The objective of this study is to investigate the drying shrinkage of normal (35 MPa) and high strength (60 MPa) concrete including coarse RCAs.

2. Materials and methods

2.1 Materials

The cement used in this study was "high initial strength Portland cement" according to the National Brazilian Standard (NBR) 5733 [12] with a compressive strength of 40 MPa at 28 days and a specific gravity of 3181 kg/m³. A superplasticizer "MC Powerflow 1180", with a solid concentration content of 35% and specific mass of 1.070 g/cm³, was used in all mixes for workability control.

Fine quartz sand with nominal diameter smaller than 4.75 mm was used as natural fine aggregate and two types of granite stone with nominal diameter from 9.5 mm to 4.75 mm (coarse aggregate 0 – "Nat-C0") and 19 mm to 9.5 mm (coarse aggregate 1 – "Nat-C1") were used as natural coarse aggregates. The Recycled Concrete Aggregates (RCAs) with the same nominal diameters of natural aggregates (i.e. coarse aggregate 0 and coarse aggregate 1) were obtained from laboratory-produced concrete waste with average compressive strength of 30 MPa at 28 days, a water-to-cement ratio equal to 0.6 and a cement consumption equal to 353 kg/m³. This material has known properties and may be considered without contamination. The original concrete was maintained at 21°C temperature and 100% humidity until 28 days. At this age, the specimens were placed in mechanical press to be fragmented into smaller pieces before the crushing step. A jaw crusher was used to adjust the particle size to a similar granulometric range of the natural aggregates. After the crushing step, the particles were air-dried and separated in an industrial mechanical sieve. Finally, each fraction of recycled aggregate was homogenized by the longitudinal blending bed technique, which consists of alternately and in opposite directions spreading the same amount of material along a pile. The recycled material of nominal diameter between 4.75 mm and 9.5 mm was classified as coarse aggregate 0, "RCA-C0", and the material of nominal diameter between 9.5 mm and 19 mm was classified as coarse aggregate 1, "RCA-C1".

In order to characterize the natural and recycled aggregates, the specific gravity and water absorption was obtained in accordance with NBR NM 53 [15], NBR NM 52 [16] and NBR NM 30 [17]. The Los Angeles abrasion test was performed in accordance with NBR NM 51[18]. These physical properties of aggregates are reported in Table 1.

Table 1: Physical properties of aggregates

Aggregate	**Nominal diameter (mm)**	**Specific gravity (kg/m³)**	**Water absorption (%)**	**Los Angeles abrasion wear (%)**
Sand	0 - 4.75	2447	0.5	-
Nat-C0	4.75 - 9.5	2662	1.5	39.5
Nat-C1	9.5 - 19	2636	1.3	36.1
RCA-C0	4.75 - 9.5	2178	7.3	41.2
RCA-C1	9.5 - 19	2105	8.2	46.7

2.2 Concrete mixtures composition

Six concrete mixtures were developed according to the Compressive Packing Model (CPM) [19] by using the BetonLab Pro 3 software. The main advantage of CPM is the possibility to consider the intrinsic characteristics of each granular materials and determining the desired properties (both at fresh and hardened state) of the resulting concrete mixture. The mixture proportioning procedure was optimized by maximizing the compactness of the dry granular mixture with the aim of obtaining the desired compressive strength by minimizing the overall cement amount. It is worth mentioning that, in order to achieve the same compressive strength, the mixtures present different amounts of cement.

Two classes of compressive strength were considered: 35 and 60 MPa. For each class, a reference concrete mixture was composed with only natural aggregates, indicated as CX-Nat, where X indicates the strength class (35 or 60). Additionally, two recycled concrete mixtures for each strength class were designed: one composed by 100% of RCA in the coarse aggregate fraction C0, named as CX-RCA-C0, and one composed by 100% of RCA in the coarse aggregate fraction C1, named as CX-RCA-C1.

The RCAs were added in the dry condition to the mixture and the absorption of 50% of total water absorption obtained experimentally for each aggregate was considered in the composition of the mixtures. This value is based on the studies developed by Amario *et al.* [20] and Pepe *et al*. [21]. The authors concluded that both coarse fraction 0 and coarse fraction 1 of RCAs absorbs about 50% of their total absorption during the mixing process.

The superplasticizer content was 0.2% and 1.5% of solids in ratio to cement content for the concretes of 35 MPa and 60 MPa, respectively. The concrete mixture compositions are summarized in Table 2.

Table 2: Concrete mixtures compositions

Mixtures (kg/m³)	**Nat-C1**	**RCA-C1**	**Nat-C0**	**RCA-C0**	**Sand**	**Cement**	**Water**
C35-Nat	452	0	457	0	868	325	212
C35-RCA-C0	451	0	0	373	866	338	217
C35-RCA-C1	0	361	456	0	867	336	216
C60-Nat	448	0	452	0	860	448	150
C60-RCA-C0	448	0	0	371	861	458	152
C60-RCA-C1	0	356	450	0	856	461	151

2.3 Mixing and experimental procedures

Due to the higher water absorption of the RCA, the following concrete mixing procedure was used in this study: initially, the coarse and fine aggregates were mixed for 1 minute; then, 50% of total water was added and the materials were mixed for 1 minute; subsequently, the cement was added and the materials were mixed for more 1 minute; and, finally, the other half of the water and the superplasticizer were added and the mixing operation was continued for 8 minutes.

After the mixing process was completed, the slump test was performed according to NBR NM 67 [22]. In addition, the fresh concrete was compacted by the use of a vibration table in two layers for 30 seconds each for casting cylindrical samples of 75 mm diameter and 150 mm height and prismatic samples of 75 mm x 75 mm x 285 mm dimensions for all concrete mixtures. Samples were demoulded after 24 hours and cured at 21°C temperature and 100% humidity. All concrete samples were maintained under these conditions for 28 days.

The compressive strength tests were performed on cylindrical samples according to NBR 5739 [23]. Tensile splitting tests were performed on cylindrical specimens according to NBR 7222 [24]. The specimens were tested on a 1000 kN Shimadzu testing machine at a rate of axial displacement of 0.1 mm/min for the compressive tests and 0.3 mm/min for the tensile splitting tests. Drying shrinkage tests were performed on prismatic specimens for 180 days. The initial length reading and the initial mass were immediately recorded using a length comparator and a scale, respectively. Then the specimens were placed in an environmental room at a controlled temperature of 22 ± 2 ºC and 60 ± 5% relative humidity. The drying shrinkage was determined by taking measurements regularly and each result was the average obtained from the testing of three specimens per concrete mixture.

3. Analysis of the results

3.1 Workability and mechanical behaviour

The results of slump test, compressive strength at 28 days ($f_{c,28}$), strain at maximum stress measured during the compressive strength test ($\varepsilon_{c,28}$), elastic modulus ($E_{c,28}$) and splitting tensile strength at 28 days ($f_{t,28}$) of concrete mixtures are presented in Table 3. The slump test showed that all the mixtures present similar workability with slump values ranging between 165 and 180 mm. In addition, the mixtures with RCA-C0 (i.e. C35-RCA-C0 and C60-RCA-C0) presented the highest slump values. This fact may be associated with a more rounded shape of RCA-C0 in comparison with the others aggregates used in this experimental campaign.

Table 3: Rheological and mechanical properties of concrete mixtures

Mixture	Slump (mm)	$f_{c,28}$ (MPa)	$\varepsilon_{c,28}$ (με)	$E_{c,28}$ (GPa)	$f_{t,28}$ (MPa)
C35-Nat	175	34.2 (±2.4%)	2898 (±3.2%)	21.3 (±2.1%)	2.7 (±1.7%)
C35-RCA-C0	180	35.7 (±0.8%)	2941 (±5.6%)	22.1 (±2.4%)	2.7 (±3.7%)
C35-RCA-C1	165	35.3 (±0.9%)	2909 (±3.7%)	21.2 (±3.4%)	2.9 (±5.2%)
C60-Nat	165	60.1 (±1.5%)	2665 (±1.7%)	29.1 (±3.2%)	3.9 (±3.2%)
C60-RCA-C0	180	60.5 (±1.1%)	2602 (±1.5%)	29.8 (±1.5%)	4.0 (±3.7%)
C60-RCA-C1	170	61.9 (±1.3%)	2687 (±1.8%)	30.1 (±4.6%)	4.4 (±3.4%)

The mechanical results presented in Table 3 showed that all mixtures for both strength classes achieved the desired compressive strength, demonstrating that the methodology adopted in this study can be successful applied for designing structural RAC mixtures. Furthermore, the RCAs did not affect the compressive strength of RACs in comparison with natural mixtures, showing that an adequate mix-design allowed the production of RACs with the same strength as mixtures with only natural aggregates. The strain at maximum stress and the elastic modulus were also not influenced by the presence of RCA, in fact this values seems to be mainly affected by the concrete strength. Thus, the strain at maximum stress values were around 2900 με and 2650 με and the elastic modulus values were around 21 GPa and 30 GPa for C35 and C60 mixtures, respectively.

The typical stress-strain behaviour of all mixtures is presented in Figure 1. The C60 mixtures presented a more fragile fracture in comparison with the C35 mixtures. Moreover, the RAC mixtures presented the same stress-strain behaviour of the reference mixtures for both strength classes. Finally, the results of splitting tensile strength test (Table 3) were around 3 MPa and 4 MPa for C35 and C60, respectively. In fact, these values are related to the compressive strength values, but a lower $f_{t,28}/f_{c,28}$ ratio is registered as the compressive strength class increases.

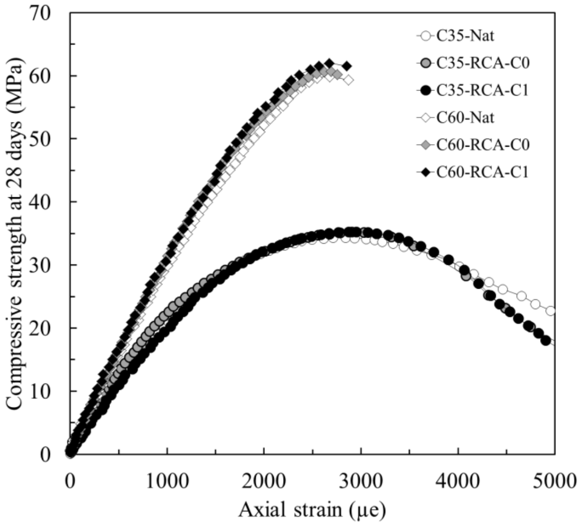

Figure 1: Typical stress-strain curves of compressive strength tests at 28 days

3.2 Drying shrinkage

Figure 2 show the results of drying shrinkage and mass loss during drying conditions obtained up to 180 days for all concrete mixtures. The strains caused by drying shrinkage ranged from -661 με to -700 με and -427 με to -490 με for the C35 and C60 mixtures, respectively. After 120 days of test, all mixtures showed a reduction in the shrinkage rate, tending to keep constant. The natural concrete presented the lowest drying shrinkage values for both normal strength and high strength mixtures. In fact, in concretes containing highly porous aggregates, such as RCAs, the water contained within these aggregates plays an important role in the amount of shrinkage increase. Furthermore, the RCA-C1 aggregate appeared to influence a little more in the strain than the RCA-C0 in the normal strength concretes, but this difference was not pronounced in the high strength mixtures.

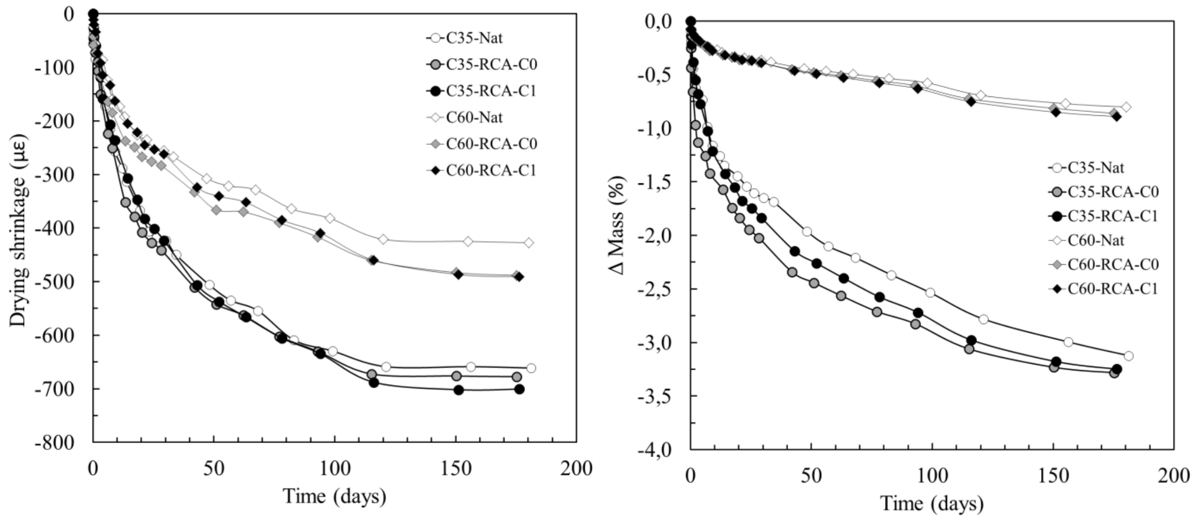

Figure 2: Experimental results: (a) drying shrinkage and (b) mass loss due to drying conditions

The results of mass loss indicate that the mixtures containing only natural aggregates presented a lower mass variation than RACs. These losses directly corresponding to the amount of water evaporated and the presence of RCAs increase the porosity of concrete mixtures. Finally, the recycled mixtures presented a similar mass loss during the test for both strength classes.

4. Conclusions

This study analysed the influence of RCAs in the drying shrinkage and mechanical properties of concretes with normal and high strength. The following consideration can be remarked:

- The RCAs did not affect the compressive strength of RACs in comparison with natural mixtures. In addition, the experimental results demonstrated that an adequate mix-design, particularly the CPM, can be successful applied for designing structural RAC with the same mechanical behaviour of natural concretes.
- The strain at maximum stress and the elastic modulus were also not influenced by the presence of RCA. Moreover, the results of splitting tensile strength test were also similar for recycled and natural mixtures for both C35 and C60 mixtures. In fact, these values are related to the compressive strength values, so as the compressive strength results are comparable between mixtures of the same class, these other mechanical properties are also similar.
- The natural concrete presented slightly lower drying shrinkage and mass loss than RACs for both normal and high strength mixtures. The presence of highly porous aggregates increase the shrinkage and mass loss of RACs, due to the large amount of water evaporated during the test.

Finally, the results are promising because they show that, as long as an appropriate mix-design methodology is used, RCAs could be effectively used to obtain concrete mixtures with performance comparable to that of mixtures containing only natural aggregates.

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