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The effect of multi-recycling on the mechanical performance of coarse recycled aggregates concrete

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HIGHLIGHTS

- Using coarse recycled aggregates (RA) from recycled aggregate concrete is viable.
- The properties of the RA tend to stabilize as the total recycling cycles increase.
- The mechanical properties RAC tend also to stabilize with the number of cycles.
- Three recycling cycles are required to achieve stable thresholds for most properties.

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ABSTRACT

This paper presents the mechanical performance results obtained to evaluate the effect of incorporating coarse recycled aggregates from various recycling cycles. These aggregates were obtained from crushing elements of concrete of controlled origin, which were mixed to have the same performance in each cycle. The specific purpose was to study the mechanical performance of concrete designed with incorporation of coarse recycled aggregates from three successive recycling cycles at two replacement ratios, 25% and 100%, comparing it with that of a reference concrete, a mix with the same composition but where all aggregates are natural.

An experimental campaign was carried out: to obtain all the necessary coarse recycled aggregates; to produce the concrete mixes that were the source of the recycled coarse aggregates; to produce the concrete mixes that were studied and; to perform all the necessary tests to evaluate the mechanical properties of these concrete mixes. Compressive strength, modulus of elasticity, tensile strength and abrasion resistance were tested.

The results prove that, with the increase of the number of recycling cycles of the coarse aggregates, there is a decrease of its quality that affects the mechanical performance of concrete. That mechanical performance decreases asymptotically with the number of recycling cycles, tending towards a final value representative of the property's stabilization, and linearly with the increase in the ratio of incorporation of recycled coarse aggregates. It is concluded that, by knowing the final value, concrete with incorporation of coarse recycled aggregates from any recycling cycle can be designed for the most diverse applications with a good safety level.

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1. Introduction

The awareness of the world population to the limits natural resources of the planet is raising an increasing concern with the maintenance of these resources for future generations. One of the sectors with greater responsibility in the consumption of natural resources and generation of waste is the construction industry. Construction and demolition waste (CDW) represents a large percentage of the total amount of waste produced in the European Union (from 25% to 30%). In the next few years, with the increase of demolitions and rehabilitations and the decrease of new constructions, the production of CDW will certainly rise. Nowadays, in the search for a sustainable construction and in response to the high levels of CDW production, the adoption, by this sector,

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of new practices and processes that reduce the negative impacts on the environment has been encouraged at a global level.

Within CDW, concrete is one of the most frequent materials [1], so the focus should be on its great recycling potential. In order to maximize this potential, the use of these materials as recycled aggregates in new concrete is seen as one of the most logical options. This enables to significantly reduce the amount of natural resources to be used, as well the amount of resources to be deposited in landfills. With the scarcity and increased cost of purchasing some raw materials, as well as landfilling CDW, the search for recycled materials will certainly increase [2].

The viability of using recycled aggregates in concrete production, especially coarse recycled aggregates, has been recurrently validated with very satisfactory results, in particular regarding the mechanical performance of recycled aggregates concrete (RAC) [3–5]. However, as new concrete structures are made with recycled aggregates, these will eventually reach the end of their service life, and consequently be demolished and new aggregates be produced. These new aggregates will eventually have different properties that need to be assessed. To the authors' best knowledge, the number of researches done to aggregates from multiple recycling, as well as to the concretes produced with those aggregates, has been scarce. Additionally, most of the existing literature has just tried RA from up to 2 recycling cycles [6–10] and very few went beyond that number [11,12], but not covering all properties tested here. Additionally, most of these researches have produced and tested RAC made with RA obtained from several origins and, consequently, with different properties. In this research, the RA were produced from crushing an original concrete with the same mix design and properties of the reference concrete, which was later used to measure performance changes through the recycling cycles. This strongly decreased the entropy of the influencing parameters.

The analysis of properties of coarse recycled concrete aggregates (CRCA) from multiple recycling cycles seems to point out that they worsen as the number of recycling cycles increases, because the amount of adhered mortar also increases [8,10–12]. As a consequence, the CRCA densities tend to reduce with the increasing number of recycling steps, eventually stabilizing. The water absorption of these aggregates follows the same trend as the remaining properties, since the magnitude of this property tends to reach a threshold beyond which it does not pass. De Brito et al. [11] state that CRCA can have water absorptions as high as 10%, depending on the recycling cycle reached. The same tendencies have been registered by Huda and Alam [12] and Salesa et al. [10]. In addition to the absolute water absorption of CRCA, its variation over time is fundamental to better correct the water requirements of the mixes. Previous researches by other authors [13,14] have shown that CRCA absorb a great deal of their full potential during the first 10 min (from 70% to 90%), after which the absorption rate tends to significantly decrease.

In terms of the mechanical performance of RAC made from multi-cycle CRCA, the results are somewhat divergent. Brito et al. [11] established that compressive strength of CRCA tends to stabilize at a given value, meaning that one can eventually proceed to recycle indefinitely without losing further performance. However, Feng et al. [7] and Huda and Alam [12] did not register such trend and kept losing performance as the recycling cycles increased. In a different direction, Salesa et al. [10] registered compressive strength increases for RAC using CRCA from 2 recycling stages, justifying the results with the high quality of the RA, which originated from pre-cast elements.

Regarding tensile strength, all consulted authors (Feng et al. [7]; Huda and Alam [12]; Zhu and Lei [9]) registered performance losses for this property, without pointing out any asymptotic tendencies. The same conclusions were drawn for the modulus of elasticity, where Feng et al. [7], Huda and Alam [12] and Salesa et al. [10] registered decreases in the modulus of elasticity for concrete using CRCA from an increasing number of recycling cycles, without detecting any asymptotic trends.

2. Research program

2.1. Materials

Two different grades of fine natural aggregates were used in all mixes: fine siliceous sand (0–2 mm) and coarse siliceous sand (0–4 mm). Three types of limestone coarse natural aggregates (CNA) were also used: fine gravel (4–8 mm), medium gravel (5.6–11.2 mm) and coarse gravel (11.2–22.4 mm). CRCA were obtained from crushed concrete elements made with a parent concrete. This parent concrete was produced in laboratory with a mix design similar to the one that was subsequently used for the remaining test mixes. The cement used was Portland type CEM I 42.5 R [15] and mixing water was provided by the public supply network.

2.2. Concrete composition

For this research program, a total of 7 concrete mixes were designed. All of these were based on the same composition, *i.e.* the constituent's contents were maintained, as well as the aggregates' size distribution. This way, it was possible to establish comparisons between the different recycling cycles, measuring the trends in performance. The reference concrete mix was made using a traditional design method, with no admixtures or mineral additions. The mixes were designed according to the procedures in NP EN 206-1 [16] and LNEC E 464 [17], using the Faury's method [18]. In order to eliminate any differences in size distribution between the mixes, all CNA and CRCA were sieved and separated by size fraction, and their fractions were adjusted to the theoretical grading curve. The grading curves of the fine natural aggregates were used and best fitted to the Faury's reference curve. The mixes' slump was kept constant in order to properly compare the mixes performance. The slump was set at 125 ± 15 mm and the adjustments to the water-cement ratio (w/c) were made to achieve such workability. For RAC, this was achieved by adding compensation water to the mix, which consists of providing an extra amount of water equivalent to the absorption of the CRCA during mixing, as suggested by Ferreira et al. [13].

Concrete production was separated into two different experimental stages, in which different mixes were produced, with different natural aggregates (CNA) by CRCA replacement ratios and different recycling cycles. The replacement of the aggregates was made in terms of volume, resulting in a lower mass of the incorporated CRCA relative to CNA. This mass reduction increased with the number of recycling cycles when CRCA were used (decrease of the density of the particles with the increase of the recycling cycles). The composition of all the mixes is presented in Table 1.

In the first stage, in order to obtain CRCA, three source concrete mixes were produced: SC1, concrete produced with CNA, from which the CRCA of the first cycle of recycling (CRCA1) were obtained; SC2, produced with CRCA1, from which the CRCA of the second cycle of recycling (CRCA2) were obtained; and SC3, produced with CRCA2, from which the CRCA of the third cycle of recycling (CRCA3) were obtained. The volume of SC1, SC2 and SC3 was defined considering the quantity needs of CRCA (CRCA1, CRCA2 and CRCA3, respectively) required to perform the second experimental stage.

The second stage corresponded to the production of the test mixes: one reference concrete produced with CNA (RC); two different mixes produced with CRCA1, one with 25% replacement ratio of NAC by CRCA1 (RAC125) and another with 100% replacement ratio of NAC by CRCA1 (RAC1); two different mixes produced with CRCA2, one with 25% replacement ration of NAC by CRCA2 (RAC225) and another with 100% replacement ratio of NAC by CRCA2 (RAC2); finally, two different mixes were produced with CRCA3, one with 25% replacement ration of NAC by CRCA3 (RAC325) and another with 100% replacement ratio of NAC by CRCA2 (RAC3).

2.3. Tests

The aggregates, both natural and recycled were tested for grading [19], particles density and water absorption [20], bulk density [21], *Los Angeles* wear [21], shape index [22] and water absorption for 24 h, using the methodology proposed by Rodrigues et al. [23]. Fresh state tests included slump tests [24] and fresh state density [25]. Hardened state tests included compressive strength at 7, 28 and 56 days [26], splitting tensile strength at 28 days [27], modulus of elasticity at 28 days [28] and abrasion wear resistance at 112 days [29].

3. Results and discussion

3.1. Aggregates properties

The results obtained for the tests on coarse natural and recycled aggregates can be seen in Table 2. The results show that, as

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