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Effects of using recycled concrete aggregates on the shrinkage of high performance concrete

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HIGHLIGHTS

- The effect of RCA in the plastic, autogenous and drying shrinkage of HPC was studied.
- The quality of RCA and its replacement ratios of natural aggregates were assessed.
- Lower RCA quality and higher replacement increased the plastic and drying shrinkage.
- The autogenous shrinkage decreased by using lower RCA quality and higher RCA content.
- RCA showed internal curing effects which improved the mechanical properties of HPC.

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ABSTRACT

Over the past twenty years the use of Recycled Concrete Aggregate (RCA) has been mostly limited to normal-strength concretes. However, satisfactory properties have been found in previous studies dealing with the use of RCA sourced from medium to high strength concrete in the production of High Performance Concrete (HPC). In this study the effects of RCA were investigated in the plastic, autogenous and drying shrinkage of HPC. The quality of the RCA (sourced from concretes of 100, 60 and 40 MPa) and the replacement ratio (20, 50 and 100%) were assessed. The results revealed that the plastic and drying shrinkage became higher as the quality of the RCA decreased and the replacement ratio increased. However, a reduction in the autogenous shrinkage was proved to be possible by the employment of a higher content of lower quality RCA, as this, in fact, acted as internal curing agent. The effects of the internal curing explained the similar or higher compressive strength results of concretes containing RCA when compared to those obtained from the reference concrete.

1. Introduction

Over the last twenty years Recycling Construction and Demolition Waste (C&DW) has become a main economic and environmental concern for governments and public institutions. According to the Eurostat [1] C&DW represents the most voluminous waste stream in Europe. Consequently, standards and directive frameworks have been published in order to bring about the control and reduction of C&DW disposal in landfills, decrease the disposal site growth and promote the conservation of natural resources.

In general, when compared to natural aggregates, Recycled Concrete Aggregates (RCA) sourced from C&DW have the following differences in properties, lower density, crushing resistance and fragmentation resistance, and higher water absorption and porosity (the latter due to the old mortar attached to the aggregates) [2,3]. Many studies have focused on the physical, mechanical and durability properties of concrete employing recycled aggregates [4–15] and their findings have concluded that when compared with natural aggregates the lower properties of the recycled aggregates have a detrimental effect on the physical, mechanical and durability properties of the Recycled Aggregate Concrete (RAC). However, the use of RCA has successfully developed since its initial use via the strict following of minimum qualities, maximum replacement ratios, particular mixing methods or mixing designs using mineral admixtures [2,10,14,16–20].

Nevertheless, only a few studies have focused on the effects of using recycled aggregates in High Performance Concrete (HPC) [21–26]. HPC is designed to have more desired workability, higher compressive strength and improved durability properties than those of traditional concrete [27]. Gonzalez-Corominas and Etxeberria [25], Ajdukiewicz and Kliszczewicz [21] and Kou and Poon [23] found that coarse RCA sourced from parent HPC (>60 MPa)

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could be effectively used in the production of new HPC. These studies have also found similar or improved mechanical and durability properties of RAC when compared with Natural Aggregate Concrete (NAC), even using replacement ratios of up to 100%. Nonetheless, the particular behaviour of HPC implies that other factors, more determinant to those of traditional concretes, have to be taken into consideration, such as total shrinkage and, particularly, autogenous shrinkage [28,29].

The shrinkage phenomenon is defined as the volume reduction or strain due to the water loss by evaporation through the concrete surface or via the reactions of cement hydration [30,31]. Total shrinkage is made up of plastic shrinkage, autogenous shrinkage and drying-shrinkage and is the consequence of diverse factors such as temperature and relative humidity, size and shape of the concrete piece, components, water/binder ratios and age of concrete [18].

Plastic shrinkage occurs prior to the setting time of concrete as a result of water evaporation or suction, resulting mainly in the production of cracking on the surface layers [30]. Autogenous shrinkage, however, is caused by capillary depression during CSH formation as a result of the combination of water and binder. Autogenous shrinkage is especially important in HPC concrete due to the lower water-binder ratios and higher binder amounts, which lead to greater self-desiccation and higher internal stress [28]. Autogenous shrinkage can be significantly reduced or even eliminated via the use of lightweight aggregates and recycled ceramic/masonry aggregates [28,29,32,33].

The drying shrinkage occurs when the free water stored in the capillary pores evaporates due to a low relative-humidity environment. This circumstance leads to a humidity gradient which induces the transport of water particles from the calcium silicate hydrates (CSH) to the capillary pores after which it evaporates [30]. Drying shrinkage produces internal stress, mass loss and consequently volume reduction of the concrete.

The study of Silva et al. [34], which reviewed the influence of recycled aggregates on the drying shrinkage, found that RAC usually exhibits higher shrinkage than the corresponding NAC. However, low replacement levels of natural aggregates by RCA, up to 30%, showed similar or slightly higher shrinkage values than those of NAC [35–37]. According to the mentioned studies, the HPC produced employing any percentage of RCA suffered a greater drying shrinkage than those of concretes produced with natural aggregates [21–23].

In this research work, the influence of using recycled concrete aggregates (RCA) on the plastic, autogenous and drying shrinkage of High Performance concrete (HPC) was analysed. Three different types of RCA, in relation to their parent concrete's strength, were used. Three replacement ratios (20, 50 and 100%) were also chosen for each type of RCA to substitute the coarse natural aggregates in order to study the influence of the quality and amount of RCA in the HPC.

2. Experimental details

2.1. Materials

2.1.1. Cement and admixture

The cement used in the HPC production was a commercially available Portland cement (CEM I 52.5R) equivalent to ASTM Type I cement. The Blaine specific surface and density of the Portland cement were 4947.8 cm^2/g and 3.15 g/cm^3, respectively, and its chemical composition is given in Table 1. A rapid hardening Portland cement was employed in order to achieve 1-day compressive strengths higher than 50 MPa, thus fulfilling the minimum requirements to be used in precast and prestressed concrete [38,39].

The admixture selected for the concrete production was a high performance superplasticizer based on modified polycarboxylate-ether (PCE). The specific gravity of the admixture was 1.08.

2.1.2. Aggregates

The source and type of the natural aggregates used in the production of the concrete were the same as those used in previous studies [24,25] and are those presently used in the production of a commercial High Performance Concrete in a Spanish precast concrete company. The natural fine aggregates employed were two river sands which were mainly composed of silicates divided into two different particle size fractions (0–2 mm and 0–4 mm) in order to achieve higher compaction. Two types of coarse natural aggregates were used to improve the workability and the mechanical behaviour of the concrete, rounded river gravel (siliceous composition) and crushed dolomitic coarse aggregate. The physical and mechanical properties of the natural aggregates are given in Table 2.

The three coarse RCAs were sourced from crushing parent concretes of different qualities, whose characteristic compressive strengths after 28 days were 100, 60 and 40 MPa. The RCAs were crushed and sieved to achieve similar particle size distributions to those of the coarse natural aggregates. The physical properties of the RCAs are also shown in Table 2 (coded as RCA-X, X according to their compressive strength).

In comparison with coarse recycled concrete aggregates, natural aggregates have a higher density and lower water-absorption capacity, a fact which has been reported in several studies [2,3,40]. However, it has been found that when the quality of the original concrete increased, the physical properties of the RCA also improved [8,41,42]. Likewise, the mechanical properties of the RCA were directly related to the compressive strength of the parent concrete [41,43]. The crushing resistance values obtained by RCA were lower than those obtained by both natural aggregates. The fragmentation coefficients were consistent to those presented by Silva et al. [2]. As was expected, their considerably low values were a result of the high qualities of the parent concretes.

The soluble sulphate (0.43–0.52%) and the chloride content (0.01–0.02) of the RCAs fulfilled the maximum requirements of 0.8 and 0.03%, respectively, established by the Spanish structural concrete code [44] for prestressed elements.

2.2. Concrete mixtures

All concrete mixtures were prepared and produced in the laboratory. As shown in the concretes proportioning in Table 3. The 380 kg cement quantity and effective water/cement ratio of 0.29 were kept constant in all concrete productions (considering effective water as that amount water reacting with the binder or not stored in the aggregates [30]). The recycled aggregates were used as 0, 20, 50 and 100% by volume replacement of both coarse natural aggregates.

The NAC proportioning, which was provided by a Spanish precast concrete company, was based on the Fuller dosage method [45]. The concrete proportioning parabola was in accordance with the Gessner parabola provided by the Fuller method in both cases, whether using NA or RCA aggregates. The recycled aggregate concretes, referenced as R-X-Y (X indicating the quality of the RCA and Y indicating the replacement ratio) had a constant cement amount and admixture content (1.5% of the cement weight).

The results from the concrete slump test (UNE-EN 12350-2:2009) using the Abrams cone were dry consistencies of 0–20 mm (S1 class following the BS-EN 206-1:2000). The natural aggregate concrete mixture, which was considered as the reference concrete, replicated the High Performance Concrete mixture used by an existing precast concrete manufacturer. The reference HPC had low water-cement ratio and very low workability in accordance with the design requirements stipulated for the technical requirements of prestressed concrete sleepers [38]. With regards to prestressed concrete elements the main requirement for those mixtures is the high early compressive strength (minimum of 50 MPa after 24 h [38,39]), in order to bear the tension release from the prestressing wires. However the workability of the concretes mixtures is a minor concern for prestressed concrete manufacturer due to the automated process of concrete pouring and high-intensity vibrating-table for compaction.

All RCAs were used at 80–90% saturation at the moment of concrete production. Additional water was added at mixing time to compensate for the remaining water absorption of the RCAs, thus maintaining constant the effective water-cement ratio. Results revealed that the total water amount of the recycled aggregate concretes increased with the reduced quality of the RCA employed, the reason for this being

Table 1
Chemical composition of the Portland cement.

Composition (%)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Cl	SO_3	LOI
Cement CEM I 52.5R	21.75	3.38	4.55	64.65	1.63	0.64	0.01	2.66	0.91