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Ultimate bond strength assessment of uncorroded and corroded reinforced recycled aggregate concretes

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HIGHLIGHTS

- Experimental study on the bond between recycled aggregate concrete (RAC) and steel.
- Effect of corrosion on bond behaviour using recycled aggregate concrete.
- Bond behaviour is strongly dependent on compressive strength values of concretes.
- RCA use leads to better bond strength performance at very low corrosion levels.
- The initial cracking of RAC occurred later than that of conventional concrete.

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ABSTRACT

This experimental study assesses the bond performance of recycled aggregate concretes (RAC) with embedded uncorroded and corroded steel bars. The RAC were produced using 20%, 50% and 100% of coarse recycled aggregates obtained from the crushing of waste 40 MPa compressive strength concrete. Three degrees of corrosion were reached on the steel bars. The uncorroded RAC specimens presented a comparable bond strength to that of conventional concrete (CC). Low corroded RAC specimens presented better bond performance and later superficial cracking when compared to those of CC. At a higher corrosion degree, all concretes presented a similar bond capacity. The ultimate bond strength estimation models used for CC were adequate for its prediction on RAC.

1. Introduction

Corrosion of the steel bars is one of today's most frequent and significant type of damage, in existing reinforced concrete structures. Therefore, the study of the structural effects of bars corrosion is crucial in determining the structural performance and residual strength of impaired structures. One of the most severe reinforcement corrosion effects is the change in bond properties between steel and concrete. Moreover, volumetric expansion of corrosion products causes serious problems by inducing splitting stresses along corroded reinforcement, with possible resulting damage to the surrounding material. Generally, the splitting stresses are not tolerated by concrete, resulting in cracking and eventually spalling of the cover. As the reinforcement becomes more exposed, the corrosion rate may increase and facilitate the deterioration process.

Steel reinforcement unconfinement due to cover cracking or spalling of concrete cover, as well as rust between both materials, quickly decreases the bond strength, thus changing the structural behaviour and inducing anchorage failures. Many researchers have extensively studied the effect of the corrosion process on bond deterioration extensively. Several studies have dealt with the investigation of the parameters that may influence the bond and anchorage capacity of corroded structures [1–5]. Models studying the interaction between both materials, and numerous experimental studies identifying and studying this phenomenon can be found in the literature on the subject [6–9]. Even though, the literature on works covering bond behaviour on recycled aggregates is very sparse [10–17].

The increasing amount of construction wastes coming from old and deteriorated structures at the end of their service life has a relevant environmental impact on the construction sector as the results of the economic benefits of using the wastes produced in the form of recycled concrete aggregates (RCA) in the concrete employed in reinforced concrete production. Wastes from older

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structures yield fragments in which the aggregate is contaminated with various different substances such as gypsum, asphalt, etc. A proper treatment of the recycled aggregate, as well as an accurate production process, results in recycled aggregate concrete (RAC) being a very suitable option to reduce the overall cost in the construction sector [18]. Over the past 50 years, the use of RCA has been profoundly studied for concrete production [18–27] and the resulting studies maintain that the primary weakness of RCA is its high porosity, which could directly influence a decrease in the compressive strength and durability of concretes produced with those aggregates.

Recent studies have tried to determine the bond between both the RAC and the steel with respect to that of conventional concrete (CC) and steel [13]. These studies manifest that a reduction of bond strength could be associated with the amount of recycled aggregate used in the mixture. Several authors [13,15,16] reported reductions of 6–8% up to 30% of bond capacity, nevertheless other researchers' work [10] noted differences of approximately 1% of the bond strength of recycled aggregate concrete with respect to that of CC concrete. Although the reduction in bond strength is strongly related to the concrete's compressive strength, it is also dependent on other parameters such as steel bar rib geometry and the position and orientation of the bars during casting. The amount of concrete cover also has an important influence on this phenomenon [10,28–33].

In this experimental study of the bond strength and bond behaviour between recycled aggregate concrete and reinforcement steel, either corroded or uncorroded, using the direct pull-out tests was presented. Two experimental phases were conducted, one with uncorroded and another with corroded steel bars embedded in RAC and CC concrete cube specimens. For that purpose, four different concrete mixtures were cast in each phase by replacing 0% (using 100% of natural aggregates, CC concrete), 20% (RAC-20), 50% (RAC-50) and 100% (RAC-100) of natural coarse aggregates for coarse recycled concrete aggregates. The obtained results for RAC concretes were compared with the results obtained from the CC concrete, before finally being compared to other models encountered in the literature referring to the bond strength capacity of reinforced conventional and recycled concrete.

2. Materials

2.1. Materials

Type I Portland cement, CEM I 42.5R, was used in concrete mixtures with rapid hardening and 42.5 MPa characteristic strength cement. The chemical properties of cement are given in Table 1.

Natural limestone, fine (FA, 0/4 mm) and coarse aggregates (two fractions; CA1 of 4/12 mm and CA2 fraction of 12/20 mm) were used for concrete production. Physical properties, density and absorption, and the grading distributions are described in Table 2 and Fig. 1, respectively. The properties of the fine and coarse aggregates were determined according to EN specifications. All fractions of natural aggregates satisfy the requirements specified by the Spanish Standard of Structural Concrete [34].

RCA aggregates were obtained by crushing rejected 40 MPa compressive strength concrete produced by a precast concrete company. The properties of RCA of density, absorption and grading size are shown in Table 2 and Fig. 1, respectively. It was found that the density of RCA was found to be lower than that of the natural aggregates and the absorption capacity was higher. The porosity of RCA determined by mercury Intrusion porosimetry (MIP) was 8.63% and its average pore diameter was 0.048 μm. The grading was defined by 4/20 mm, which complied with the Spanish Standard of Structural concrete regulations [34] in its employment for recycled concrete production and it was used in substitution of CA1 and CA2 natural coarse aggregates.

Table 2
Dry density and water absorption capacity of aggregates.

Properties	CA2 12/20 mm	CA1 4/12 mm	FA 0/4 mm	RCA
Dry density (kg/dm^3)	2.65	2.64	2.58	2.30
Water absorption (%)	0.67	0.87	1.68	5.91

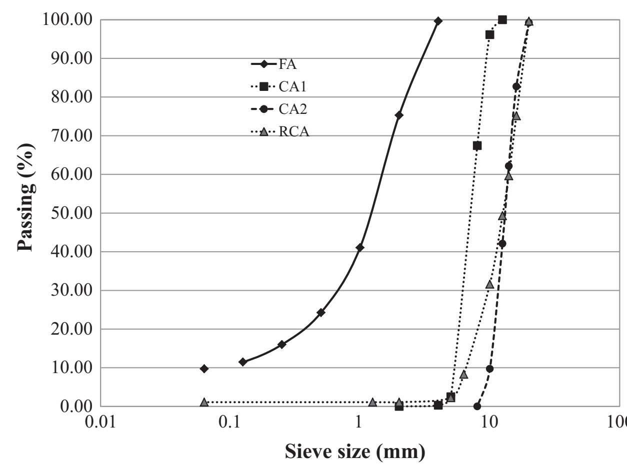

Fig. 1. Grading distribution of fine natural aggregates (FA) and coarse natural (CA1 and CA2) and recycled aggregates (RCA).

At concrete production 4% NaCl in weight of cement was added to the mixture; the aim of which was the depassivation of the steel inside the concrete and the causing of a conductive medium to facilitate the corrosion procedure. Superplasticizer was also used to provide the desired workability of the mixture.

2.2. Concrete mix proportions

The four mixtures (Conventional concrete, CC; concrete produced with 20% of RCA, RAC-20; concrete produced with 50% of RCA, RAC-50; concrete produced with 100% of RCA, RAC-100) were prepared and cast. The replacement of raw, coarse aggregates for recycled coarse aggregates was carried out according to the volume.

The mix proportion of CC concrete was defined with 300 kg of cement and a total water-cement ratio of 0.5 for concretes exposed to a marine and chloride environment as described by the Spanish Structural Concrete code [34]. The effective water-cement ratio of CC concrete was determined and maintained constant in all RAC concretes. The total w/c ratio of RAC was higher than for CC, due to higher absorption capacity of RCA [24].

It is taken as understood that the effective water/cement ratio of the concretes is the ratio between the effective water (free water which reacts with cement) and total cement weight. The effective water was determined by first calculating the total water used for concrete production and then subtracting both the water absorbed by the aggregates and the moisture present in RCA during concrete production. The previously mentioned water amount absorbed by aggregates at concrete production is termed as the effective water absorption capacity of aggregates and it was determined experimentally. The experiment consisted of submerging the aggregates in water for 20 min [24]. The effective water absorption capacity of natural coarse and fine aggregates was 20% and 80% of their total water absorption capacity, respectively. The recycled aggregates had an effective water absorption capacity of 70% of their total capacity. (The total water absorption capacity of the aggregates is described in Table 2.) The effective w/c ratio on CC concrete was approximately 0.45 and it maintained constant in all RAC concretes.

The control of the effective water/cement ratio in the production process of recycled aggregate concrete can only be obtained by using recycled aggregates with approximately a moisture level of between 80 and 90% of their total absorption capacity [24] (in order to reduce their total absorption capacity [26]). The coarse recycled concrete aggregates were wetted the day before use via a sprinkler system and then covered with a plastic sheet so as to maintain their humidity (approx. at 80% of their absorption capacity) until used in concrete production. During concrete production, recycled aggregates absorbed a certain amount of free water due to

Table 1
Chemical composition of cement.

Composition	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	LOI
%	19.16	3.56	5.04	62.9	1.66	0.75	0.15	3.54	3.25