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Bond behaviour between recycled aggregate concrete and glass fibre reinforced polymer bars

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HIGHLIGHTS

- Relation between use of RCA and variation in f_c does not respond to a common pattern.
- Using RCA causes no significance change in bond development and deterioration process.
- Substituting NA with a RCA causes no significant change in the bond-slip curves.
- Greater bond strengths are obtained in the RAC for the increasing concrete grades.
- Bond strength predictions using CEB-FIP model code compare well with experimental results.

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ABSTRACT

The use of recycled aggregate concrete (RAC) contributes to reducing energy and natural resource consumption in the construction industry. However, incorporating recycled concrete aggregates (RCA) into the concrete production process usually causes some difficulties in controlling fresh and hardened concrete properties. One of the properties susceptible to being affected is bond, which is a requirement for reinforced concrete (RC) structures. Besides, if more sustainable and durable structures are to be had, the benefits of fibre reinforced polymer (FRP) bars should be included to achieve this.

This study evaluates the effect on the bond behaviour between concrete and FRP bars when a percentage of natural coarse aggregates is replaced by recycled concrete coarse aggregates. To that end, a total of 48 pull-out tests were conducted. Three series of concrete mixes (i.e. three different concrete grades) were prepared, each containing four mixes, where the RCA were used at rates of 0%, 20%, 50% and 100% of the coarse aggregate total weight. The study also focuses on the influence of the rebar surface configuration (spirally wounded and ribbed) on FRP–RAC bond strength.

According to the experimental results, no unique pattern for concrete compressive strength variation after RCA has been included can be defined as being valid for all concrete grades. Furthermore, the experimental results showed that both bond development and the deterioration process between the RAC and FRP bars was similar to that between natural aggregate concrete (NAC) and FRP bars.

1. Introduction

The construction industry not only uses large quantities of natural resources, but also disposes of very large quantities of construction and demolition waste as well. The environmental and economic impacts of both these practices are considerable. Numerous policies aimed at increasing reuse and recycling are being promoted by many governments. The use of recycled aggregate concrete (RAC) is one way to reduce not only energy consumption, but also that of the available natural resources, thus solving some of the problems in construction engineering. However, there is a widespread reluctance to use recycled concrete as an aggregate in new concrete which results from the limited information available on the topic.

Employing demolition materials as a source of aggregates to produce new concrete may pose workability problems. The main problem with using recycled aggregates in structural concrete is their high water absorption capacity. The recycled aggregate (RA) is composed of natural aggregate (NA) bonded with cement mortar. This cementitious paste gives the recycled concrete aggregates (RCA) a rougher, lighter and more porous structure, thus decreasing their particles' density and increasing their water absorption capacity with respect to NA [1–4]. This leads to difficulties in

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controlling the properties of fresh concrete and consequently influences the strength and durability of hardened concrete [5]. One way to reduce the absorption capacity of RCA is to increase the amount of mixing water [6–8]. Alternatively, several authors pre-soaked RCA before use, keeping mixing water constant [9–12].

Several studies have looked into the impact using recycled aggregates has on the properties of hardened concrete. The differences in the sources and quality of the original concrete, their different crushing process and the RCA selection procedure, along with the variable percentage of NA being substituted by RCA used in the different studies are some of the reasons for the large variability in the experimental results obtained and which are not always consensual. Several studies report that when RCA is incorporated there is a decrease in the mechanical properties of concrete (in particular in the compressive strength, the splitting tensile strength and the Young's modulus) [13,14], while others obtained slight increases in the concrete strength when incorporating either recycled concrete coarse aggregate (RCCA) or recycled concrete fine aggregate (RCFA) [15,16]. Further studies define a replacement rate threshold value beyond which mechanical properties of hardened concrete decrease and below which mechanical properties increase [12,17,18]. In a closer analysis of the effect of substituting NA with RCA on the mechanical properties of hardened concrete, other studies differentiate between higher and lower compressive strength levels [9,19]; in these latter studies, the planes where failure takes place and the effect of the higher roughness of RCA are presented as determining factors.

One of the most important requirements in reinforced concrete (RC) constructions is the bond between the concrete and the reinforcement. Therefore, evaluating that bond behaviour between the reinforcement and the RAC is an essential requirement when employing RAC in RC structures. Investigations into the effect of RCA on bond strength with reinforcing steel are very limited [4,17,19–21], and the results and conclusions are not always consensual, even when confirmed and highly accepted aspects are checked. It is widely accepted, for instance, that the bond strength between natural aggregate concrete (NAC) and steel rebars is related to the square root of the concrete compressive strength ($f_c^{0.5}$). When this issue is studied in the case of RAC, different conclusions can be found in the literature. The now widely-accepted trend was confirmed in [4,17], where a decrease in the bond strength of RAC of differing percentages or RCA, that resembled the decrease in concrete compressive strength, was reported. Butler and co-workers [19] however, conclude that there is a weak relationship between the bond strength and the splitting tensile strength of concrete, and propose that bond strength is more dependent on the crushing resistance of RCA, thus highlighting the importance of knowing both the source and the characteristics of these RCA. Taking this one step further, results in [21] indicate that concrete compressive strength and the bond strength of RAC were affected by the aggregate size, with the smaller size of coarse aggregate gaining the advantage in the case of both mechanical properties. However, with the same maximum aggregate size, the compressive strength of the RAC decreased as the RCA replacement ratio increased, and the bond strength for 0% RCA replacement ratio was always higher than that of 100% RCA replacement ratio. In terms of normalized bond strength (i.e. bond strength divided by $f_c^{0.5}$), the authors observed reverse tendencies according to the maximum aggregate size: the normalized bond strength of RCA with a maximum aggregate size of 20 mm showed a tendency to increase in proportion to the RCA replacement ratio, while the normalized bond strength of RCA with a maximum aggregate size of 25 mm gradually decreased. This is in agreement with [22], where a 12.5 mm maximum aggregate size was used and the authors observed an increase in the normalized bond strength as the RCA replacement ratio was increased. However, the results in [21,22] contradict [4] where a 16 mm maximum aggregate size was used and the authors observed a decrease in the normalized bond strength as the replacement ratio of RCA was increased.

Another widely-accepted statement is that bond mechanisms acting between plain reinforcement and NAC differ from those acting between deformed rebars and NAC. As a result, the bond strength subsequently developed also varies. Xiao and Falkner [20] analysed the differences between the bond of plain and deformed steel bars when RAC was used, and confirmed that the bond strength of the deformed bars almost doubled that of the plain bars. According to the results reported, similar values of bond strength were obtained for deformed bars; irrespective of the RCA replacement percentage. However, a different trend was observed for plain bars, whose bond strength value decreased according to the rising RCA replacement percentage.

Given the inconsistencies in the experimental results, the database needs to be broadened so as to expand practical use of RAC in modern civil infrastructures. In addition, if more sustainable and durable structures are desired, the benefits of non-metallic reinforcement should be included, and therefore research into the combination of RAC and fibre reinforced polymer (FRP) rebars should be addressed. To the best of the authors' knowledge, no previous study on the bond behaviour between RAC and FRP reinforcement has ever been conducted. Therefore, within this new research field, it would seem reasonable to take the well-established knowledge on the combination of NAC and FRP as the starting point from which to evolve [23–26].

This paper investigates bond behaviour between FRP bars and concrete with different replacement ratios (0%, 20%, 50% and 100%) for the recycled coarse aggregates which were applied to three different concrete grades (low, medium and high). The study also focuses on the influence of the rebar surface configuration (spirally wounded and ribbed) on FRP–RAC bond strength. The replacement ratio of RCA was termed as the recycled aggregate replacement percentage to the total coarse aggregates by weight.

2. Experimental programme

2.1. Materials

The RAC mixes were made up of cement, water, a natural fine aggregate, a natural coarse aggregate, a recycled coarse aggregate and an additive. CEM I 52.5R cement, in accordance with the European standard EN 197-1: 2011 [27], was used in this study.

A commercial viscosity modifier and underwater admixture was used to improve workability and ensure compliance with the requirements set out by the Spanish Code on Structural Concrete (EHE-08) [28] for low water-to-cement ratio concretes.

The coarse aggregates used in this study are both natural aggregates (NA) and recycled concrete aggregates (RCA). The NA were obtained from a local quarry and one fraction size (5–15 mm) was used. The RCA were produced at a local construction and demolition waste treatment and recovery plant. The properties of the old concrete are unknown. The RCA size fraction used was also 5–15 mm. Two sizes of natural fine aggregates were used in this study: 0–2 and 0–4 mm. Table 1 summarizes the physical and mechanical properties, as well as standards used to determine the properties of the aggregates. At present, there is no standard test procedure for determining the amount of adhered mortar on recycled concrete aggregates. However, recycled aggregate was analysed in accordance with the European Standard EN 933-11:2009 [29] and Table 2 presents its constituents. The gradations and particle size distributions of the NA and RCA analysed in accordance with the European Standard EN 933-1:2012 [30] are presented in Table 3 and Fig. 1. The properties were all ascertained at the CECAM (Centre of Construction Studies and Materials Analysis) laboratories.

The size distribution curves of NA 5/15 and RCA are similar, indicating that the gradation/granulometry of the final mixture would not be greatly affected by the replacement with RCA. This is also depicted in the similar values for the fineness modulus of both the coarse aggregates (presented in Table 1). Not unexpectedly,