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Anchorage of steel rebars to recycled aggregates concrete

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HIGHLIGHTS

- Concrete made with coarse recycled concrete aggregates.
- Anchorage strength of ribbed steel rebars with varying length and diameter.
- The anchorage strength decreases with the incorporation ratio of recycled aggregates.
- Numerical modelling of the experimental tests.

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ABSTRACT

This research aims at evaluating the effect of the replacement ratio of natural course aggregates (NCA) by recycled concrete coarse aggregates (RCCA) on the anchorage strength of ribbed steel rebars to concrete.

To accomplish this purpose, four concrete mixes were designed: a conventional NCA concrete (NCA by RCCA replacement ratio of 0%) to serve as reference and three recycled aggregates concrete (RAC) with 20%, 50% and 100% NCA by RCCA replacement ratios. Besides this parameter, all the remaining ones were kept constant. An effective water/cement ratio of 0.53 and a slump of 125 ± 10 mm were adopted.

The mechanical properties of the considered mixes were characterized in terms of compressive strength, splitting tensile strength, and Young's modulus. The anchorage strength of ribbed steel rebars to RAC was assessed for each of the four concrete mixes using pull-out tests. In addition to the NCA by RCCA replacement ratio, two other variables were evaluated: the diameter (12 and 16 mm) and the anchorage length (5ϕ, 10ϕ and 15ϕ) of the steel rebars. The combination of these three variables led to 24 different testing conditions. For each of these, three equal specimens were produced, corresponding to a total of 72 pull-out tests performed.

As main conclusions of this research study, it can be stated that NCA by RCCA replacement ratio has a negative impact on the mechanical properties of concrete, presenting an approximately linear correlation. Only for lower replacement ratios, namely 20%, there are not any clear changes in concrete mechanical properties, and a slight increase can even occur. Regarding the anchorage strength of ribbed steel rebars to concrete, the incorporation of RCCA has a similar effect: the increase of the NCA by RCCA replacement ratio leads to a decrease of this parameter. This effect can be well explained analysing the stress distribution inside the pull-out specimens using a finite-element model developed with this aim, also presented herein.

1. Introduction

1.1. Initial remarks

Construction represents an important pillar of most countries economy. The natural resources used by this sector are extracted from Nature at an extremely high rate, when compared to the one at which they are restored, being thus unsustainable. In what concerns the extraction of natural stone for construction, 90% of this activity within the European Union is concentrated in only five countries: Portugal, Spain, Greece, Italy and France [1]. Moreover, since these natural resources are available at low costs in these countries, the recycling rates of construction and demolition waste (CDW) are only marginal (less than 5%), significantly lower than the overall figure of 46% in the European Union [2]. Given the present scenario, all studies leading to use recycled aggregates concrete (RAC) in both new and existing structures is absolutely mandatory.

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However, most studies only deal with the material characteristics of RAC and do not address structural RAC.

1.2. Research significance

The main objective of the research study herein described is to characterize the influence of replacing natural course aggregates (NCA) by recycled concrete coarse aggregates (RCCA) on the anchorage of ribbed steel rebars, thus contributing to the use of structural RAC.

In this research study, except for the NCA by RCCA replacement ratio, all parameters of the adopted RCCA concrete mixes were kept constant, namely: cement dosage, aggregates' size distribution, and workability of concrete in the fresh state (calibrating the w/c ratio to take into account the higher permeability of RCCA relatively to NAC). Besides the NCA by RCCA replacement ratio, the influence of steel rebars' diameter and anchorage length was also investigated. In addition, numerical models were also considered to simulate pull-out tests, thus allowing in depth analysis of the stress distribution at the rebar-to-concrete interface before sliding.

The main conclusion, and innovative contribution of this study, is that regarding anchorage of ribbed steel rebars in RAC, it can be stated that, below a 50% NAC by RCCA replacement ratio, this type of RAC can be used in structures without any type of design and/or detailing specification change.

2. Literature review

In this section, a synthesis is made of the state of the art on the fields of knowledge relevant for this research study, namely recycled aggregates concrete and bonding between steel rebars and concrete.

Concerning the RCCA's properties, Matias et al. [3] highlight the influence of the cement paste bonded to the surface of the original natural aggregates, corroborating the study by Gonçalves and Neves [4] who stated that the optimization of both the size distribution and the shape of particles is achieved when the incorporated CDW is processed by primary and secondary crushing, allowing the effective removal of the most fragile parts of their mass. Matias et al. [3] also mention that the 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.

The RCA's characteristics, and particularly those of the RCCA, influence the properties of the concrete in which they are incorporated. The density of recycled concrete coarse aggregates concrete (RCCAC) is lower than that of the corresponding reference concrete (RC) (i.e. same composition but with NCA instead of RCCA), due to the lower density of RCCA. According to Kou and Poon [5], the incorporation of RCA decreases the mechanical properties of concrete (at 28 days), in particular the compressive strength, the splitting tensile strength and the Young's modulus. In this study [5], the loss of strength proved to be proportional to the replacement ratio of NCA by RCCA. The authors also showed that the differences in strength between RCCAC and RC decreased for longer curing ages. Fonseca et al. [6] studied the incorporation of RCCA in structural concrete and concluded that the splitting tensile strength is more sensitive to the replacement of NCA by RCCA than the compressive strength (at 28 days). In this study [6], the Young's modulus was also negatively affected by the RCCA incorporation. According to Coutinho and Gonçalves [7], the relationship between the Young's modulus of concrete and of its aggregates is different from that between the corresponding values for the compressive strength or the splitting tensile strength, because the former is mostly conditioned by the aggregates' stiffness, while the remaining depend mostly on the aggregates' mechanical strength. For this reason, since RCCA have lower stiffness than NCA, due to the bonded cement paste, the Young's modulus is expected to be closely related with the replacement ratio of NCA by RCCA, as Fonseca et al. [6] showed.

Some authors like Evangelista and de Brito [8] and Gomes and de Brito [9] obtained slight increases in strength in concrete incorporating recycled concrete fine aggregates (RCFA) and RCCA, respectively, justified by the presence of non-hydrated cement particles in the recycled aggregates that increased the absolute cement content in the mixes.

Regarding bonding of steel rebars to RCCAC, only few studies are published [10–12]. Furthermore, both results and conclusions are not consensual. This is one of the motivations for the study herein presented.

Xiao and Falkner [10] studied the bond of steel rebars to non-structural RCCAC. Ribbed steel rebars were used with a diameter of 10 mm. Three concrete mixes were adopted with the following NCA by RCCA replacement ratios: 0%, 5% and 100%. RCCA were pre-saturated in order to eliminate the influence of their higher water absorption capacity, thus allowing the effective water/cement ratio of all mixes to remain constant and equal to 0.43. Bond between steel rebars and RCCA was assessed using pull-out tests. This study [10] presented similar values of the bond stresses, independently of the replacement ratio of NCA by RCCA, contrarily of the compressive strength which values decreased proportionally to the replacement ratio. The authors concluded that, for reinforced RCCAC structures, the considered anchorage length can be the same as in conventional NCA concrete.

Kim and Yun [11] also conducted pull-out tests to study the bond between ribbed steel rebars with a diameter of 16 mm and RCCAC. The adopted RCCA resulted from processing CDW from a building demolition. Besides the replacement ratio of NCA by RCCA (0%, 30%, 60% and 100%), the authors also studied the effect of: (i) the maximum aggregates' size (20 mm and 25 mm), (ii) the direction of casting relatively to the steel rebars (parallel or perpendicular), and (iii) the distance of the steel rebars to the specimen's bottom.

For the specimens cast parallel to the steel rebars (as in the present study), the results showed different trends according to the maximum aggregates' size. The bond stress was higher in the specimens with smaller maximum aggregates' size (D_{max}) and it did not change significantly with the increase of the NCA by RCCA replacement ratio. Conversely, the bond stress of the specimens with higher D_{max} was negatively affected by the RCCA incorporation. In both concrete mixes, the compressive strength (at 28-days of age) dropped proportionally to the RCCA's incorporation ratio.

Butler et al. [12] also studied the influence of the incorporation of RCCA in concrete on the bond of (25.2 mm diameter) steel rebars to concrete. Beam-end tests were used aiming at simulating the pull out of steel rebars from current reinforced concrete elements, i.e. containing stirrups and longitudinal reinforcement. The authors studied the influence of the following three parameters: (i) the RCCA type, by selecting two sources of aggregates; (ii) the anchorage length (125 mm and 375 mm) of the steel rebar subjected to the pull-out force; and (iii) the concrete compressive strength (30 MPa and 50 MPa). The RCCA were subjected to several physical–chemical processes to remove the cement paste.

In this study [12] it is concluded that the incorporation of RCCA affects negatively the bond between steel rebars and concrete, even if the latter is produced to have the same compressive strength as the RC. According to Butler et al. [10], there is a weak correlation between the bond stress and the splitting tensile strength of concrete. On the other hand, the proposed correlation between the bond stress and the crushing resistance of RCCA adjusted well to measured values, highlighting the importance of knowing both the source and the characteristics of these