Construction and Building Materials 49 (2013) 852–862

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Bond behaviour of deformed steel bars embedded in recycled aggregate concrete

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HIGHLIGHTS

- Bond of deformed steel bars in NAC and RAC is investigated.
- Pullout tests were carried out on 12, 16, 20 and 25 mm bars.
- Bond failure mode in NAC and RAC has been compared.
- Measured bond strength has been calibrated with codal predictions.
- Empirical bond–slip relationship has been proposed for the RAC and the NAC.

ARTICLE INFO

Article history:
Received 4 December 2012
Received in revised form 13 April 2013
Accepted 25 August 2013
Available online 29 September 2013

Keywords:
Coarse recycled concrete aggregate
Replacement level
Natural coarse aggregate
Bond
Splitting failure
Relative bond strength

ABSTRACT

The results of sixty pullout tests carried out using 12 mm, 16 mm, 20 mm and 25 mm diameter deformed steel bars concentrically embedded in recycled aggregate concrete designed using equivalent mix proportions with coarse recycled concrete aggregate (RCA) replacement levels of 0%, 25%, 50%, 75% and 100% are reported towards investigation of bond behaviour of RCA concrete. It is postulated that due to internal curing action of the RCA particles, the relative bond strengths, obtained by normalising the measured bond stress with the respective compressive strength of concrete, across all the RCA replacement levels were higher for the RCA concrete compared to the NCA concrete. Further, the relative bond strengths increased with RCA replacement levels and the highest values were obtained for 100% replacement of natural coarse aggregate with RCA. On the basis of a regression analysis of the experimental data, an empirical bond stress-versus-slip relationship between RCA concrete and deformed steel bars has been proposed and it has been conservatively suggested that anchorage lengths of 12 mm, 16 mm, 20 mm and 25 mm diameter deformed steel bars embedded in RCA concrete may be taken to be the same as that in natural aggregate concrete.

1. Introduction

For the past several years, production of fresh concrete using recycled materials is being increasingly encouraged so as to reduce the environmental impact of concrete construction [1–3]. Of late, coarse recycled concrete aggregate (RCA), manufactured by processing of construction and demolition waste has received considerable attention as a potential substitute for natural coarse aggregate (NCA). However, structural application of RCA concrete has been slow primarily because of apprehensions that concrete containing RCA might be inferior to concrete made with NCA [4–7]. Findings of previous investigations on RCA concrete pertaining to processing of demolished concrete, mixture design, physical and mechanical properties and durability aspects, which have been extensively reviewed and discussed by Nixon [8], Hansen [9] and ACI Committee 555 [10], indicate that mechanical properties of RCA concrete are generally inferior to those of NCA concrete. Engineers considering structural use of RCA concrete for enhancing sustainability of concrete construction would be keen to know how the behaviour of this concrete under various actions compares to that of NCA concrete and to what extent recommendations in current design codes, originally intended for NCA concrete, can be used for conservatively predicting the strength and behaviour of RCA concrete members.

Bond is an important structural property of reinforced concrete and refers to the adhesion between reinforcing steel and surrounding concrete which is responsible for transfer of axial force between these two materials thereby ensuring strain compatibility and their composite action. Although bond behaviour between

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http://dx.doi.org/10.1016/j.conbuildmat.2013.08.031

Nomenclature

d	nominal rebar diameter
l	embedded length
f'_c	cylinder compressive strength of concrete
P_{max}	peak load
τ_{max}	peak bond stress
$\tau_{r,max}$	relative bond strength

NCA concrete and steel rebars has been extensively studied in the past [11–13], relatively few investigations have been reported on bond between RCA concrete and steel reinforcement [14–16] such that most of the recommendations in the literature related to bond strength of RCA concrete are tentative in nature, primarily because of the small experimental data base. Towards addressing this gap in the literature, this study presents part of the results of an ongoing experimental investigation of bond behaviour between recycled aggregate concrete and deformed steel bars with the main variables being the RCA replacement level and diameter of the deformed steel bars. The results of 60 pull-out tests performed according to IS: 2770 (Part 1) – 1967 [17] and RILEM [18] are presented and bond behaviour of RCA concrete has been compared to that of the control NCA concrete and anchorage lengths of deformed steel bars in RCA concrete have been suggested. The measured bond stress-slip response of the deformed steel bars has been used to propose an empirical bond stress-versus-slip relationship between the recycled aggregate concrete and the deformed steel rebars.

2. Experimental programme

2.1. Materials

The concrete mixtures used in the pull-out test specimens were made using ordinary Portland cement conforming to IS: 8112-1989 [19], NCA and RCA, clean river sand (fineness modulus = 2.68) and potable water. The physical properties of the natural coarse aggregates and the coarse recycled concrete aggregates used in this investigation are presented in Table 1. The aggregate crushing value and aggregate impact value of the NCA as well as the RCA was found per the procedure given in IS: 2386 (Part IV)-1963 [20]. The residual mortar content of the RCA particles mentioned in Table 1 was found using the hydrochloric acid dissolution method mentioned in Nagataki [21]. The natural coarse aggregates consisted of locally available crushed rock (fineness modulus = 6.38) and the coarse RCA was generated by processing with the help of a jaw crusher waste specimens obtained from the concrete laboratory of the authors' host institute. The nominal maximum size of the NCA and the RCA particles was kept at 12.5 mm and the size fractions of the RCA particles obtained from the jaw crusher were so blended that the grading curves of both the coarse aggregate types besides being similar to each other were also within the specified coarse aggregate grading limits of IS: 383-1970 [22], Fig. 1. Crescent-ribbed deformed steel bars (nominal tensile strength equal to 500 MPa) of diameters 12 mm, 16 mm, 20 mm and 25 mm were used in the pullout tests and their measured surface characteristics are given in Table 2.

2.2. Mixture proportion

The control concrete mixture consisting of only NCA was designed using the absolute volume method and the mixture design of RCA concrete was carried out using equivalent mix proportions wherein the mixture proportions for the NCA and the RCA concretes were nominally kept the same, except for direct weight-to-weight replacement of NCA with RCA, depending upon the desired RCA replacement level. The RCA replacement level is defined as the weight ratio of RCA to the total coarse aggregates in the concrete mixture and depending upon the desired replacement level, direct substitution of NCA with an equal weight of RCA particles was carried out. The following five weight combinations of NCA and RCA were adopted: 100% NCA (control mixture), 75% NCA + 25% RCA, 50% NCA + 50% RCA, 25% NCA + 75% RCA, 100% RCA, and the concrete mixture proportions are summarised in Table 3 wherein it may be noted that the water-cement ratio, w/c, across all the mixtures was nominally kept equal to 0.54. Since the RCA used in this investigation had water absorption values which were about 6 times

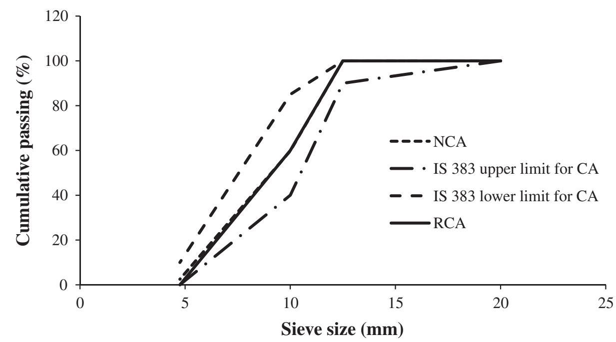

Fig. 1. Grading curve of the natural coarse aggregates and coarse recycled concrete aggregates.

Table 2
Surface characteristics of the rebars.

Property	12 mm ϕ	16 mm ϕ	20 mm ϕ	25 mm ϕ
Rib height	0.70 mm	0.83 mm	1.03 mm	1.50 mm
Rib width	1.43 mm	1.52 mm	2.10 mm	2.00 mm
Rib spacing	7.28 mm	8.30 mm	10.89 mm	12.53 mm
Rib face angle	45°	36°	41°	51°

Table 3
Concrete mixture proportions (kg/m^3).

Mix ID	RCA replacement level, r (%)	Cement	Sand	NCA	RCA	Mixing Water
AR0	0	369	854	912	0	199
AR25	25	369	854	684	228	199
AR50	50	369	854	456	456	199
AR75	75	369	854	228	684	199
AR100	100	369	854	0	912	199

Table 1
Physical properties of NCA and RCA.

Coarse aggregate type	Bulk density (kg/m^3)	Bulk specific gravity	Water absorption (%)	Crushing value (%)	Impact value (%)	Residual mortar content (%)
Natural	1630	2.7	1.0	21.2	17.3	–
Recycled	1385	2.5	6.00	21.7	22.2	32.2