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Shear transfer strength of normal and high-strength recycled aggregate concrete – An experimental investigation

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HIGHLIGHTS

- The first study on shear friction behaviour in high-strength recycled aggregate.
- The shear friction of RCA concrete improved due to the internal curing of RCAs.
- An analytical procedure for shear strength prediction of RCA concrete was proposed.

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ABSTRACT

Initially uncracked push-off specimens were tested to investigate shear transfer in recycled aggregate concrete with concrete grade, normal force and the replacement level of recycled aggregates being the variables. A marginal increase in normalized shear strength was noted when the natural coarse aggregates were replaced with the recycled aggregates. Normal force and concrete grade had the most significant effect on the measured strengths and predictions obtained from modified Zia failure criterion were in good agreement with the experimental results of the natural as well as the recycled aggregate concretes. Selected shear strength models in the literature have been reviewed for their predictive efficacy and in the context of design, the PCI code gave reasonably accurate and conservative predictions of the measured shear strengths of both the concrete types.

1. Introduction

In many cases, shear may have to be transferred across planes of existing or potential cracks or interfaces between elements of a beam such as flanges and webs or across interfaces between concretes placed at different times. In such cases, shear failure may involve sliding along a plane of weakness rather than the diagonal tension failure which is more common for example in a beam-like element under one-way shear. In general, shear strength developed along the plane on which sliding occurs consists of frictional resistance, resistance to shearing off of the aggregate protrusions on the irregular crack surface (aggregate interlock) and the dowel force developed in the transverse reinforcement bridging the plane. The aforesaid shear resisting mechanisms are variously known as interface shear or shear friction. It is reckoned that similar to one-way shear strength in beams for example, in shear friction also, aggregate interlock is one of the principal mechanisms of shear transfer across cracks [1–6]. However, the mechanics of shear transfer through aggregate interlock is complex because several phenomena are involved in which normal and shear stresses interact [7]. Never-the-less, it is well established that at the global level, aggregate interlock is primarily affected by crack width, concrete strength and the normal force across the crack whereas at the local level it is influenced by the nature of contact between the coarse aggregate particles projecting from one face of the crack and the cement mortar into which these particles interlock in the opposite face [8]. Hence, volume and characteristics of coarse aggregates and strength of the mortar in concrete are likely to have a significant influence on aggregate interlock.

Extensive investigations of shear friction in Natural Aggregate Concrete (NAC) have lead for example, to the development of design equations in the ACI [9] and the PCI codes [10]. If out of environmental concerns and in order to advance the sustainability agenda, it is proposed to replace Natural Coarse Aggregate (NCA) in concrete with coarse Recycled Concrete Aggregate (RCA) derived from processing of construction and demolition wastes, then designers and engineers would be keen to know the implication (s) of this choice on shear friction. Aggregate interlock is one of

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the important mechanisms of shear resistance in plain and in reinforced concrete [10,11]. This mechanism is dependent on properties of the coarse aggregates, the cement mortar and the cement-aggregate interface. Presence of the relatively soft and porous layer of residual mortar on typical Recycled Concrete Aggregate (RCA) particles may make them weaker relative to Natural Coarse Aggregates (NCA). This situation is further compounded by the uncertain quality of the waste concrete from which RCAs may be produced. Due to the aforesaid reasons, mechanical properties of RCA concrete are generally inferior to those of concrete made with natural aggregates. Further, it is reckoned that the use of weaker aggregates (such as RCAs) can be especially critical in the resisting mechanisms that rely on the properties of the coarse aggregates. Amongst these mechanisms is the shear strength in one-way and two-way shear and in shear transfer which comes into play when force must be transferred across an interface between two members that can slip relative to one another. It is in this context that the present investigation has been undertaken in order to study shear transfer in RCA concrete and promote safe structural use of this concrete.

Relatively few investigations have been carried out on shear transfer in Recycled Aggregate Concrete (RAC). On the basis of tests on 32 initially cracked push-off specimens, (Refer Section 2.3), Xiao et al. [8] reported similar shear friction behaviour between his NAC and RAC specimens. According to them, the ultimate shear strength was most significantly influenced by the normal force and RCA replacement level. Pending availability of more experimental data towards development of RCA specific predictive equations, Xiao et al. [8] have recommended the use of the shear friction design equations given in the ACI [9] and the PCI [10] codes. The investigation of the effect of internal curing provided by saturated recycled concrete aggregates on shear friction in high-strength self-consolidating concrete carried out by Fakitsas et al. [12] shows improved frictional and compressive strength characteristics in the concrete made with the recycled aggregates compared to that made with the natural aggregates. The test results of 20 initially uncracked push-off specimens have been used by Fakitsas et al. [12] to present shear strength predictive equations in the form of Mohr-Coulomb failure criterion. On the basis of tests on initially uncracked push-off specimens, Rahal and Al-Khaleefi [13] have concluded that partial replacement with recycled aggregates resulted in a significant reduction in ultimate shearing strength whereas full replacement only had a limited effect. They have reported overly conservative shear strength predictions from the shear friction model in the ACI code [9].

In actual construction, shear may have to be transferred across the planes of existing cracks. An example of a pre-existing crack in the case of construction joint between the web and flange of a T-girder or cracks which may arise as a result of restraint to deformation because of shrinkage, creep or temperature. However, shear transfer also occurs along planes not previously cracked, such as the bearing region of a simple girder or the vertical plane between a corbel and the supporting column. Since, the bulk of the experimental data in the literature deals with pre-cracked shear planes, the focus of the present investigation was on uncracked shear planes.

Except for the limited investigation of Rahal and Al-Khaleefi [13,14], there is a lack of information in the literature on shear transfer in uncracked (*as constructed*) recycled aggregate concrete. This investigation seeks to address this gap and has been carried out by testing 48 initially uncracked push-off specimens (wherein shear must be transferred across a definite plane) considering concrete grade (normal-strength and high-strength), RCA replacement level (50%, and 100%) and the normal force (three levels of normal force) as the variables. Salient characteristics of shear friction behaviour have been noted, measured strengths have been compared with predictions from modified Zia failure criterion, selected current design codes, shear-friction predictive models in the literature and selected previous test data of various researchers and relevant recommendations have been made.

2. Experimental program

2.1. Materials

Concrete used in the push-off specimens was made using Portland cement conforming to IS: 8112-1989 [15], coarse aggregates, clean river sand and potable water. Physical properties of the aggregates are presented in Table 1. The aggregate crushing and impact values reported in Table 1 were measured per the procedure given in IS: 2386 (Part IV) – 1963 [16] and the residual mortar content of the RCA particles was found using the hydrochloric acid dissolution method of Nagataki [17]. The natural coarse aggregates consisted of locally available crushed rock 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 20 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 [18]. Reinforcement in the push-off specimens, provided either to prevent flexural failure (the main reinforcement) or to act as transverse (or normal) reinforcement across the shear plane, consisted of steel bars having a yield strength of 525 MPa and an ultimate tensile strength of 598 MPa respectively. The rebars were ribbed and the surface characteristics of the rebars are presented in Table 2.

2.2. Concrete mixtures

The normal- (N) and the high-strength (H) control concretes (made using NCA as the coarse aggregates) having 28-day target cylinder compressive strengths of 30 MPa and 70 MPa respectively were designed using the absolute volume method. The design of the RCA concrete was carried out using equivalent mix proportions wherein the mixture proportions of the NCA and the RCA concretes were nominally kept the same, except for substitution of NCA with RCA per the desired RCA replacement level. The RCA replacement

Table 1
Physical properties of the aggregates.

Physical property	Natural coarse aggregates (NCA)	Recycled concrete aggregates (RCA)	Fine aggregates (FA)
Maximum size (mm)	20	20	4.75
Relative density	2.69	2.58	2.65
Water absorption (%)	1.27	6.30	1.15
Fineness modulus	6.90	7.05	2.62
Impact value (%)	16.7	21.5	–
Crushing value (%)	21.7	27.4	–
Residual mortar (%)	N.A	26.5	–

Table 2
Surface characteristics of the rebars.

Property	Rebar diameter	
	8 mm	12 mm
Rib height, h_r (mm)	0.48	0.71
Rib width, w_r (mm)	1.17	1.40
Rib spacing, s_r (mm)	5.30	7.35
Rib face angle, α (°)	46°	47°