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Shear strength of longitudinally reinforced recycled aggregate concrete beams

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ABSTRACT

The inferior qualities of recycled concrete coarse aggregates (RCA) relative to natural coarse aggregates (NCA) can unfavorably affect the properties of concrete made using RCA. The detrimental effects can be more pronounced in the resistance mechanisms which rely significantly on the properties of the coarse aggregates, such as the shear resistance. This paper presents the results of an experimental investigation of the effects of the use of RCA on the shear strength of longitudinally reinforced concrete (RC) beams. Thirteen lightly reinforced 35 MPa concrete beams were tested in a four-point loading test setup at a shear to span ratio of 3. In one series of specimens, the percentages of replacement (*PR*) of NCA with RCA were 0%, 10%, 20%, 35%, 50%, 75% and 100%, and the partial replacement affected all grades of the aggregates equally. It was shown that the use of RCA decreased the shearing strength by 13%–18%. In another series of specimens, the *PR* was 5%, 10%, 16%, 23% and 35% and the replacement affected the smaller grade of coarse aggregates only. The detrimental effects of the use of RCA were alleviated for $PR \leq 15\%$. The experimentally observed shear strengths from this study and from thirty six test data available in the literature were compared with the calculations of the ACI simplified method, the CSA General Method, and the critical shear crack method (CSCT). Based on the experimental results and the comparisons, it was shown that the "square root of the compressive strength of the concrete" term does not adequately account for the detrimental effects that the shearing strength undergoes when RCA are used. It is suggested that a 20% reduction is applied to the shear strength equations of longitudinally reinforced beams when RCA are incorporated in the concrete.

1. Introduction

The manufacture of concrete requires the use of significant amounts of cement and aggregates. The negative environmental impact of the production of these ingredients from non-renewable sources led to a global interest in finding alternative sources.

The use of recycled cementitious materials has increased considerably. Byproduct materials such as fly ash, silica fume and slag are commonly used around the globe as partial replacement of cement. This use has also been standardized e.g. [1].

The use of recycled alternatives to the NCA has also been explored on a wide scale. It can lead to considerable savings in natural resources, landfills and energy [2]. Concrete that is produced using RCA is commonly referred to as recycled aggregate concrete (RAC). Research has shown that RCA generally have inferior qualities relative to NCA. It has also shown that the percentage of replacement of the NCA with RCA [3,4] and the quality and general properties of the RCA have considerable effects on the properties of the RAC [5].

1.1. Shearing strength of longitudinally reinforced beams

The ultimate shearing strength (v_u) of longitudinally reinforced beams depends on numerous factors. The most commonly recognized ones are (1) the properties of the concrete, (2) the structural actions acting along with shear (such as bending moments and axial forces), (3): the amount of longitudinal non-prestressed and prestressed reinforcement, and (4) the size of the member [6,7]. The first factor is typically considered the most influential one.

Most of the desirable characteristics of concrete can be qualitatively related to its compressive strength (f_c). Consequently, quality control and compliance with specifications of concrete are based mainly on testing concrete in compression [8]. Structural and mechanical properties such as the shearing strength, bond strength, modulus of elasticity and modulus of rupture are typically calculated based on the compressive strength e.g. [9–11].

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Notation

a	shear span in beam
a_g	nominal maximum size of coarse aggregate
b	width of beam
d	effective depth of beam
E'_c	modulus of elasticity of concrete, tested at 28-day
f_c	compressive strength of concrete
f_{cu}	cube compressive strength of concrete, tested same day as beam
f_{cy}	cylinder compressive strength of concrete, tested same day as beam
f'_{cu}	cube compressive strength of concrete, tested at 28 days
f'_c	cylinder compressive strength of concrete, tested at 28 days
AMC	adhered mortar content (by weight of total coarse aggregates)
P	total load on beam
PR	percentage of replacement of NCA with RCA
P_u	ultimate load resisted by beam
v_{ACI}	calculated nominal shearing strength of beam (ACI code)
v_{CSA}	calculated nominal shearing strength of beam (CSA code)
v_{CSCT}	calculated nominal shearing strength of beam (CSCT code)
v_u	observed ultimate nominal shearing strength of beam
α	ratio of E'_c to $\sqrt{f'_c}$
α_n	ratio of α of concrete to $\alpha$of NAC concrete
β	ratio of v_u to $\sqrt{f_{cy}}$
β_n	ratio of$\beta$of concrete to β of NAC concrete
Δ_{mid}	measured vertical deflection at midspan
λ_d	reduction factor for lightweight aggregates concrete
λ_R	reduction factor for recycled aggregates concrete
ε_{Lu}	longitudinal strain at midspan at ultimate load
ρ_L	longitudinal reinforcement ratio in beam

The shearing strength (v_u) of concrete has traditionally been related to the square root of the compressive strength ($\sqrt{f_c}$). One of the simplest yet most commonly used equations for the calculation of v_u is of the form:

$$v_u = \text{constant} \sqrt{f_c} \tag{1}$$

In the ACI code [9] for example, the constant is equal to 0.17 when MPa units are used. Research has shown that the term $\sqrt{f_c}$ does not account for the effects of all the concrete-related factors which influence v_u. For example, the use of lightweight aggregates influences v_u more severely than $\sqrt{f_c}$. Design codes e.g. [9–12] introduced an additional factor to the shear equations to accommodate this effect. For example, the ACI and CSA equations for the concrete contribution to the shear resistance include a factor $\lambda_d$which ranges from 0.75 to 1, depending on the composition of the aggregates used.

Furthermore, research has shown that the nominal maximum aggregate size (a_g) affects v_u and $\sqrt{f_c}$ differently. The coarse aggregates contribute to the shear resistance via "aggregate interlock". Larger a_g increases the roughness of the diagonal cracks in normal strength concrete (NSC), and hence increases the interlock [6,7,13]. Current design codes e.g. [10,11] have also introduced the term a_g in the calculation of v_u.

There is relatively limited research on the effects of factors such as aggregate grading on the shearing strength. This may indicate a general belief that their effect is limited, or is adequately accounted for indirectly through their effect on $\sqrt{f_c}$.

1.2. Effect of use of RCA on shear strength

The use of RCA affects the various mechanical properties of concrete (such as compressive and tensile strengths and modulus of elasticity) differently [3,5,14]. It is likely that the concrete resistance mechanisms which are most affected by the use of RCA are those mechanisms which rely more on the strength and the overall properties of the coarse aggregates, such as the shearing strength (v_u).

In NSC, a diagonal shearing crack passes through the cement paste and along the interface between the aggregate and the paste. In HSC, the strength of the cement paste is considerably higher. The shearing crack passes through both the cement paste and the coarse aggregate [15] and hence, the aggregate interlock is reduced. The CSA code [10] accounts for this effect by setting the value of a_g used in the strength equation by reducing it gradually to zero as f'_c goes from 60 MPa to 70 MPa.

The use of RCA influences the shearing strength of concrete. The presence of a cement-aggregate interface within the RCA can reduce the effective size of the aggregate because the shearing crack can pass through this interface both in NSC and HSC. Hence, it is likely that the use of RCA influences v_u more than $\sqrt{f_c}$. Research is needed to gain a better understanding of the relationship between the shear strength of RAC beams and $\sqrt{f_c}$.

There have been numerous investigations of the effects of the use of RCA on the shear strength of longitudinally reinforced shallow beams [4,16–19]. Percentages of replacements ranged from 10% to 100%, but the maximum number of nonzero percentages in an individual study was 3. For PR values from 10% to 30%, the effect of the use of RCA on the normalized shearing strength ($v_u/\sqrt{f_c}$) ranged from negligible [4] to an improvement of 8% [18]. For PR values larger or equal to 50%, the effect ranged from a reduction of 15% [19] to an improvement of 23% [16]. Hence, the use of RCA can influence more than $v_u/\sqrt{f'_c}$.

It is to be noted that the ratio of longitudinal reinforcement ρ_L of the beams in these studies [4,16–19] was relatively very high, ranging from 1.27% to 3%, with an average of 2.4%. High reinforcement ratios limit the opening of the diagonal cracks and influence the strength and overall behavior. Tests on beams with ρ_L within a more practical range of values can provide a more realistic understanding of the relationship between v_u and $\sqrt{f_c}$.

1.3. Variations in shear strength

The above mentioned experimental observations need to be carefully interpreted. The 23% increase in normalized shearing strength is based on the difference between the strength of one NAC beam and one RAC beam with PR = 50%. Variations in shear strength results are not uncommon. Sadati et al. [19] tested twelve beams with variable PR, ρ_L and cementitious binder constituents. Duplicates to the twelve beams were also cast and tested. The variation in normalized shearing strength amongst the duplicate beams ranged from 0.5% to 25% and averaged 7%. Michaud [18] tested triplicate beams for each of the six different concretes she