Behavior of Shear Friction Push-off Specimens Made Using Normal and Recycled Aggregates

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Abstract

This paper presents the experimental results of a study whose objective was to study the shear-friction behavior of normal-aggregate and recycled-aggregate reinforced concrete. Four specimens were cast and tested in a push-off set up. Two specimens were cast using natural coarse aggregate concrete (NAC) and two were made using recycled coarse aggregate concrete (RAC). The two NAC specimens were similar to the RAC specimens except for the type concrete. The specimens of the same concrete contained two different amounts of clamping reinforcement. The results showed that the general behavior of the RAC specimens was similar to that of the RAC specimens. It was also observed that the ultimate strength was reached soon after the yielding of the clamping reinforcement, and that the specimens resisted significant post-peak reserve strength. In all the cases, the ACI shear-friction model provided conservative estimates of the shear strength.

Key words: Push-off specimens, Reinforced Concrete, Shear-friction, Strength

1. Introduction

The use of recycled aggregate (RA) is considered one of the viable means of producing a more "environmentally friendly" concrete. Using crushed concrete as coarse and fine aggregate reduces the use of natural resources and reduces the use of landfills. Sources of concrete for crushing can be obtained from various sources such as demolished buildings and reject concrete from ready mix plants (Rahal 2007).

Recycled coarse aggregates can be weaker than natural aggregate (NA) (Forster 1986; Tavakoli and Soroushian 1996; Rahal 2007). The suitability of the use of RA as aggregate for structural concrete needs to be justified using research on different aspects of its behavior. This paper concentrates on the shear behavior of RAC.

The shear behavior of concrete depends on numerous factors including a phenomenon referred to as aggregate interlock (Collins and Mitchell, 1991). This paper reports the preliminary results from an experimental program whose objective is to compare the shear behavior of NAC and RAC concrete. A push-off setup is selected because of its simplicity and its ability to represent the behavior of design cases such as the interface between two bodies of concrete which can slide across each others.

2. Experimental Program

Two different mixes were used to cast the NAC and RAC specimens. The mixes were similar except for the type of coarse aggregate used and the amount of water (and consequently the water to cement ratio). In both mixes, the coarse aggregate used in the mix were brought to a saturated surface dry state before batching. The mix proportions were as follows: 410 kg/m^3 of cement, 705 kg/m^3 of sand, 260 kg/m^3 of 19-mm coarse aggregate, 340 kg/m^3 of 13-mm coarse aggregate, and 500 kg/m^3 of 10-mm coarse aggregate. The water to cement ratio was 0.4 in the RAC mix and 0.46 in the NAC mix. The specimens were moist cured for seven days and then they were stored in air till the day of testing, which was 42 days for the NAC and 28 days for the RAC specimens.

Two push-off specimens were cast using RA concrete. The specimens were identical except for the amount of clamping reinforcement. Two specimens identical to the RAC specimens except that they were made using NA. Figure 1 shows the details of the push-off specimens. In addition, standard cylinders and 150 mm cubes were cast from the same concrete, and cured in conditions similar to those of the push-off specimens. A strain gauge was attached to one stirrup in each specimen, at the location of the shear transfer plane.

Samples of the reinforcing steel was tested in accordance of the relevant ASTM standard. The yield stress in the ϕ6 mm and the ϕ8 mm bars used as clamping steel was 258 and 408 MPa, respectively. The yield stress in the ϕ12 mm used as longitudinal reinforcement was 453 MPa.

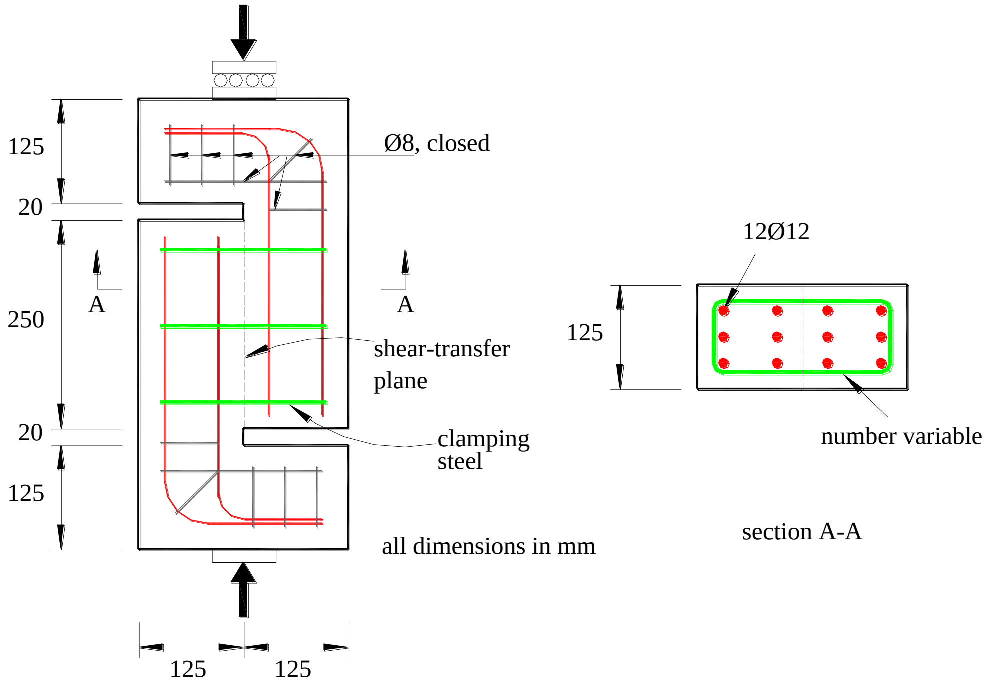

Fig. 1: Details of the shear-critical push-off specimens and concrete strength

specimen	Clamping steel	Coarse Aggregate	Age (days)	f_c'' (MPa)	f_{cu} (MPa)	$\rho_v f_{yv}$ (MPa)
35-2T6-L1-0	2ϕ6	NA	42	41.8	43.4	0.934
35-2T8-L1-0	2ϕ8					2.63
35-2T6-L1-100	2ϕ6	RA	28	44.8	48.7	0.934
35-2T8-L1-100	2ϕ8					2.63

Table 1: Details of the specimens and concrete strength

In Table 1, f_c'' refers to the average strength obtained from the cylinders and f_{cu} is the average strength obtained from the cubes. The terms ρ_v and f_{yv} refer to the ratio and yield strength of the clamping reinforcement, respectively.

The specimens were loaded continuously at a rate of 1 mm/minute. Slip was measured across the shear-transfer plane as shown in Figure 2. The surface of the concrete near the shear transfer plane was closely monitored to check for the first development of cracks.

Fig. 2: Measurement of slip across shear-transfer plane

3. Experimental results

Table 2 summarizes the results of the study and Figs. 3 and 4 show the four specimens after failure was reached and the load released. All stress calculations are nominal values, assuming a uniform distribution across the shear-transfer plane. The following sections described the observed behavior of the specimens.

Clamping 2ϕ6

35-2T6-L1-0

Clamping 2ϕ8

35-2T8-L1-0

Fig. 3: NAC Specimens with after failure and release of load

Clamping 2ϕ6

35-2T6-L1-100

Clamping 2ϕ8

35-2T8-L1-100

Fig. 4: RAC Specimens with after failure and release of load

3.1 Specimen 35-2T6-L1-0

This specimen was cast using NA concrete and was reinforced with 2ϕ6 clamping stirrups. Figure 5 shows the experimentally observed shear stress versus slip across the shear transfer plane. The behavior was relatively linear up until the start of yielding in the clamping steel at about v_y=5.25 MPa. A vertical crack across the shear transfer plane was soon observed at v_{cr}=5.44 MP. Once it first developed, the width of the crack steadily increased.

The maximum stress of 5.55MPa at a slip of 0.145 mm was reached soon after the occurrence of yield and cracking. After that, the stress decreased consistently as shown in Fig. 5, to stabilize near a stress of about v_p=2 MPa. It is to be noted that the specimen sustained considerable deformation, and the loading stopped before the 20 mm gap on either side of the shear transfer plane closed completely. Figure 3 shows the specimen after the loading have been released. Damage was concentrated along the shear friction transfer plane.

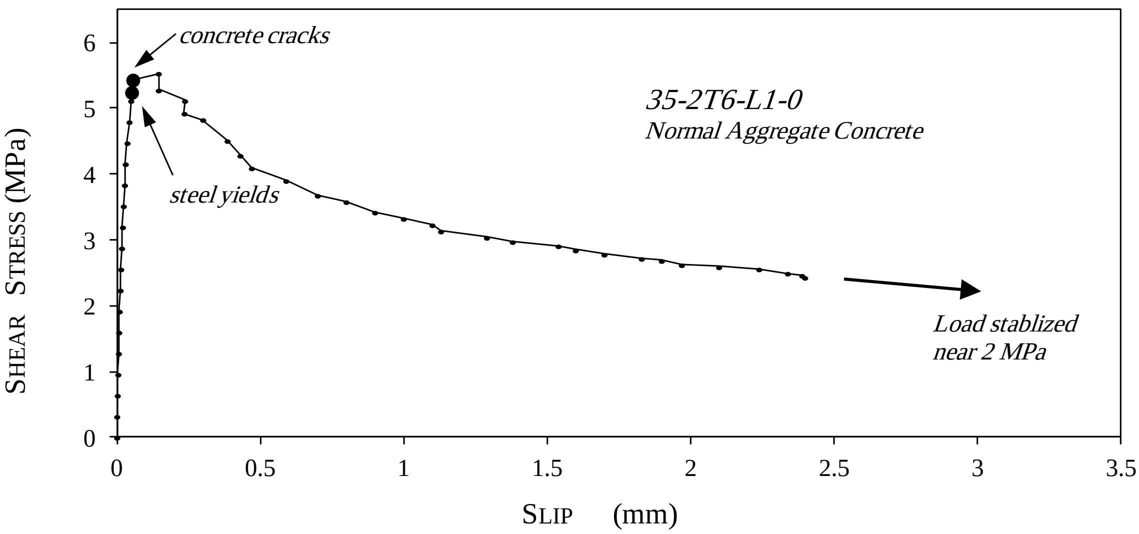

Fig. 5: Shear stress versus slip in NAC Specimen 35-2Y6-L1-0

specimen	Clamping steel	$\rho_v f_{yv}$ (MPa)	v_{cr} (MPa)	v_y (MPa)	v_u (MPa)	S_u (mm)	v_p (MPa)
35-2T6-L1-0	2ϕ6	0.934	5.44	5.25	5.55	0.145	2.0
35-2T8-L1-0	2ϕ8	2.63	7.55	7.55	7.94	0.50	3.9
35-2T6-L1-100	2ϕ6	0.934	5.2	5.4	5.63	---	1.63
35-2T8-L1-100	2ϕ8	2.63	5.0	7.33	7.54	2.0	4.0

Table 2: Summary of Results

3.2 Specimen 35-2T8-L1-0

Specimen 35-2Y8-6Y12-0 was similar to the specimen described in the previous section except that it was reinforced with 2ϕ8 instead 2ϕ6 clamping stirrups. Figure 6 shows the experimentally observed shear stress versus slip across the shear transfer plane. The behavior started relatively linear and softened as it approached the maximum stress. At a shear stress of about v_{cr}= v_y=7.55 MPa and a corresponding slip of 0.30 mm, concrete cracking along the shear plane and yielding in the clamping steel took place nearly simultaneously. The maximum loading capacity was reached at a stress of 7.94 MPa and a slip of 0.50 mm.

Spalling of concrete along the shear transfer plane was observed at *v*=5.31 MPa. A more severe disintegration of the concrete along the shear plane took place at *v*=4.8 MPa and a slip of about 4mm. A considerable post-cracking response was observed. The loading resistance stabilized at a shear stress of about v_p=3.9 MPa. The loading was stopped when the stroke in the machine reached 14 mm. Figure 3 shows the specimen after the loading have been released.

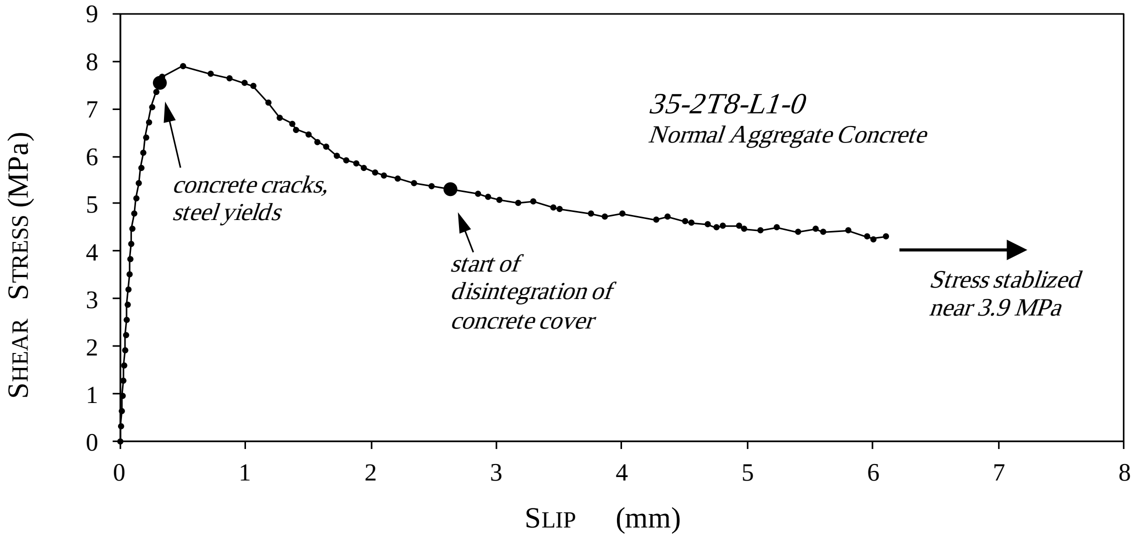

Fig. 6: Shear stress versus slip in NAC Specimen 35-2Y8-L1-0

3.3 Specimen 35-2T6-L1-100

This specimen was cast using 100% RA and was reinforced with 2ϕ6 clamping stirrups.. The first crack developed at a shear stress of v_{cr}=5.2 MPa, which was soon followed by yielding in the clamping steel at v_y=5.4 MPa and then by the ultimate capacity at v_u=5.63 MPa. When the maximum load was reached, the load dropped considerably to less than 1.3 MPa. At this time, the specimen contained only one crack of moderate width.

The load was fully released, and then the reloading started. Considerable amount of deformation was sustained by the specimen. The stress stabilized near a shear stress of 1.63 MPa. This value is taken as the post-ultimate reserve capacity. Figure 4 shows the specimen after the release of the load.

3.4 Specimen 35-2T8-L1-100

This specimen was made of 100% RA coarse aggregate and was reinforced with 2ϕ8 clamping stirrups. The first crack developed near the bottom of the shear transfer plane at v =4.4 MPa. The behavior softened and a diagonal crack developed near mid-height of the shear transfer zone at v_{cr}=5.0 MPa and a corresponding slip = 1.05 mm. The yielding in the clamping steel took place at v_y=7.33 MPa and a slip of 1.96 mm. Soon after yielding, the ultimate capacity was reached at v_u=7.54 MPa and a corresponding slip of 2 mm. When the maximum load was reached, the load dropped considerably. At v=4.2 MPa and a corresponding slip = 7.8 mm, considerable spalling of the concrete was clearly evident.

The stress stabilized near a shear stress of 4 MPa. This value is taken as the post-ultimate reserve capacity. Figure 4 shows the specimen after the release of the load.

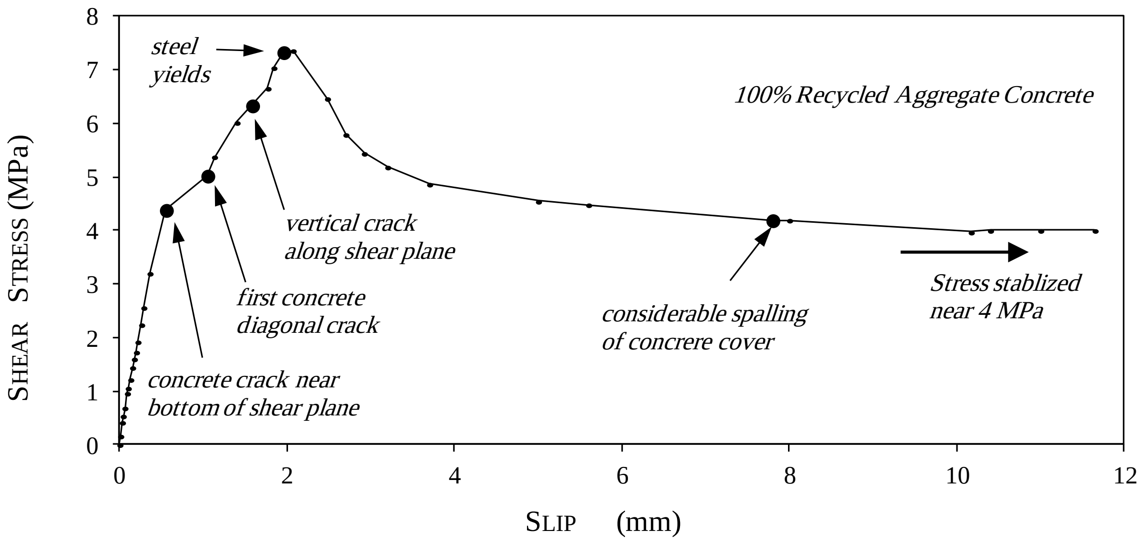

Fig. 7: Shear stress versus slip in NAC Specimen 35-2Y8-L1-100

4. Shear Friction

Figure 8 shows a plot of two of the key values in the shear-friction behavior versus the amount of clamping reinforcement. These are the maximum stress and the reserve post-cracking stress. The figure also shows the results of the shear-friction model as presented in the ACI code (ACI 2008).

It is shown in the figure that the difference in ultimate strength and in reserve strength between RAC and NAC is minimal. Table 2 shows a similar conclusion regarding the shear stresses causing yielding of the clamping reinforcement.

In addition, Figure 8 shows that the ACI code severely under-estimates the ultimate shear-friction strength. However, the calculated shear strength compared very well with the post-capacity reserve strength.

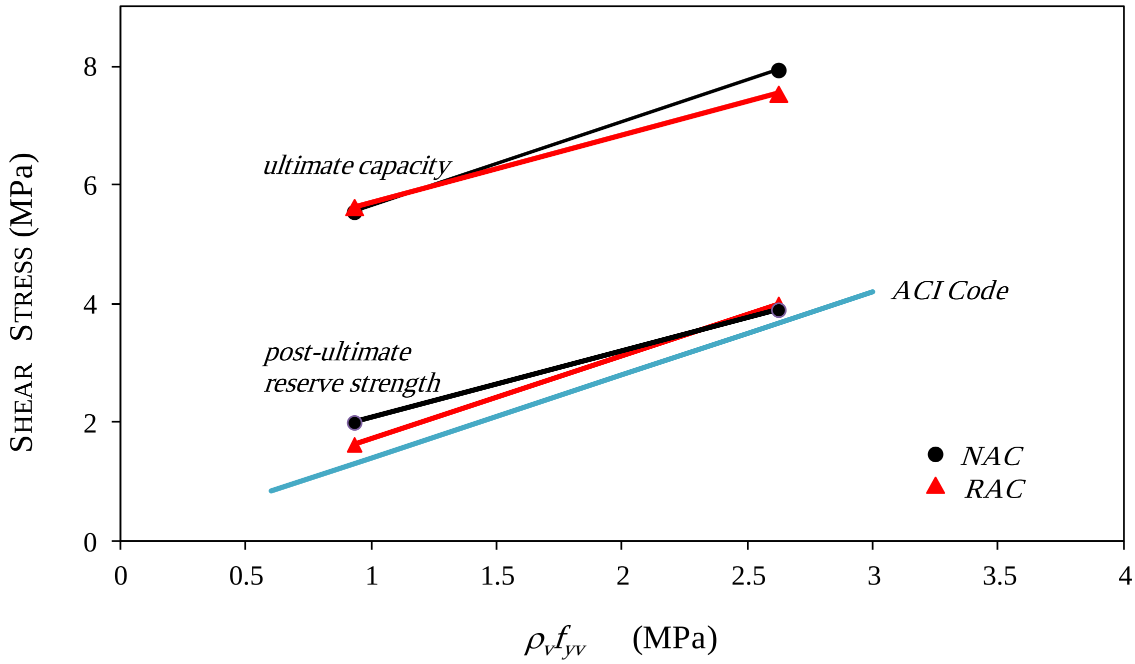

Fig. 8: Ultimate and post-cracking reserve stresses versus amount of transverse reinforcement

5. Conclusions

The results of four tests on NAC and RAC push-off specimens were presented.

It was shown that for both RAC and NAC, the ultimate strength was reached soon after the yielding of the clamping reinforcement. After this ultimate, the resistance was reduced considerably, but the specimens continued to resist a post-cracking shear stress and sustained a considerable amount of deformations.

There was a relatively small difference in strength between the NAC and RAC specimens. This is true for the yielding stress, ultimate stress and the reserve stress.

The results ACI shear-friction model were excessively conservative in comparison with the ultimate strength, but compared well with the post-cracking reserve strength.

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