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Strength of Natural and Recycled Aggregate Concrete under Shear and Compression Based on Pushoff Tests

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Abstract – The fast depletion of the aggregates required for the production of concrete has led to an increase in the interest in alternatives such as aggregates made from recycling waste concrete. Recycled coarse aggregates (RCA) made by crushing waste concrete has been shown to be a viable alternative to natural coarse aggregates (NCA) but with generally inferior properties. The stress transfer mechanisms of recycled aggregates concrete (RAC) which depend considerably on the quality of the aggregates, such as the shear strength are of interest. This paper investigates the strength of plain natural aggregates concrete (NAC) and recycled aggregates concrete under shear and compression. Pushoff type of concrete specimens made using NAC and RAC in mixes of water-to-cement ratios ranging from 0.31 to 0.72 are tested. The results indicate a considerable reduction in both the compressive strength as well as the shear cracking strength. The shear cracking strength is commonly related to the square root of the compressive strength. Such relation captures but slightly underestimates the detrimental effects of the use of RCA on the shear strength.

***Keywords*:** compression, concrete, recycled aggregates, shear, strength

1. Introduction

The demand on concrete and its constituent materials has increased considerably over the past few decades. The increasing demand on the coarse aggregates increased the interest in crushing waste concrete to produce recycled coarse aggregates (RCA) as an alternative to the natural coarse aggregates (NCA). This has the other advantages of reducing the demands on landfills and energy. The recycled aggregates have inferior properties relative to the natural ones, necessitating a thorough knowledge of the structural properties or concrete made using RCA [1, 2].

The inferior strength of the recycled aggregates affects considerably those properties which depend on the aggregate to transfer the stresses, such as shear resistance, which depend on aggregate interlock. The bearing zones in a precast girder and corbels are examples of elements where shear stresses have to be transferred across a plane subjected to compressive stresses. See Fig. 1. Steel bars are designed to transfer a part of or the full shear stresses after cracking. Steel can be proportioned using empirical methods such as those based on the shear-friction model [e.g. 3, 4] or other more rational models [e.g. 5, 6]. To reduce the possibility of a brittle failure, a minimum area of steel reinforcement is required to ensure ample reserve strength after first cracking. Proper proportioning requires an accurate calculation of the shear stress that causes first cracking. The cracking shear strength (v_{cr}) is known to increase in the presence of a compressive stress (σ) and hence the use of cracking strength equations commonly used in codes may lead to unconservative results because these equations are typically lower bound estimates of the cracking strength. An accurate calculation of the cracking strength along shear-transfer planes subjected to compressive stresses can be of interest in the design of structures. The use of RCA can affect the compressive strength (f_{cu}) as well as v_{cr} of concrete and hence its effect on the shear-transfer mechanism is of interest. Typically, v_{cr} is related to the square root of the compressive strength: $\sqrt{f_{cu}}$. It is of interest to investigate if the effect of using RCA on v_{cr} is relatively similar to that on $\sqrt{f_{cu}}$.

Shear-transfer strength is typically studied experimentally by testing pushoff type of specimens under compression. See Fig. 1. This type of test produces combined shear and compressive stresses along the shear-transfer plane of the specimen and hence can represent the state of stresses along the transfer plane of corbels and support zones of precast beams.

This paper uses data produced by the authors [7] on pushoff specimens to develop an equation for the cracking strength of pushoff specimens. It also investigates if the effect of using RCA on v_{cr} is relatively similar to that on $\sqrt{f_{cu}}$.

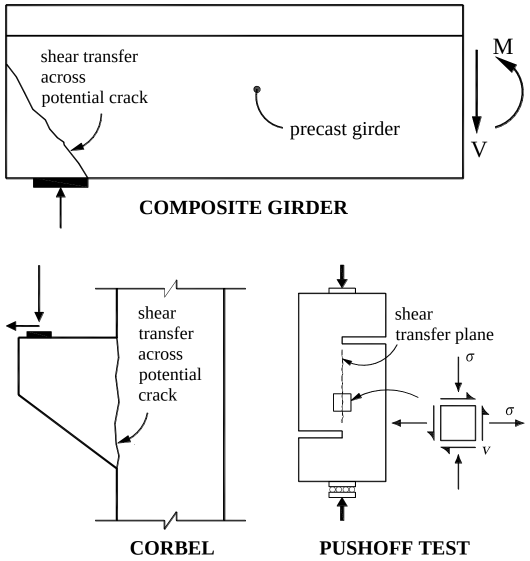

Fig. 1: Example of elements where shear is transferred along a plane, and a typical pushoff test setup.

2. Experimental data

The shear strength based on plain pushoff specimens depend on the compressive strength of the concrete, the type and size of the aggregates, and the size of the specimen. It also depends on and the details of the inner side of the notch where stress concentration is expected. To concentrate on the effect of the type of coarse aggregates and the compressive strength, data used in the analysis is limited to one comprehensive study [rahal and Yahia]. Data is available from other similar tests [e.g. 8, 9] but the specimens were or different sizes and/or subjected to different curing regimes and testing conditions. Fig. 2 show the details of the specimens, which were 150x150x320 mm in dimensions, with a 116x150 mm shear transfer area.

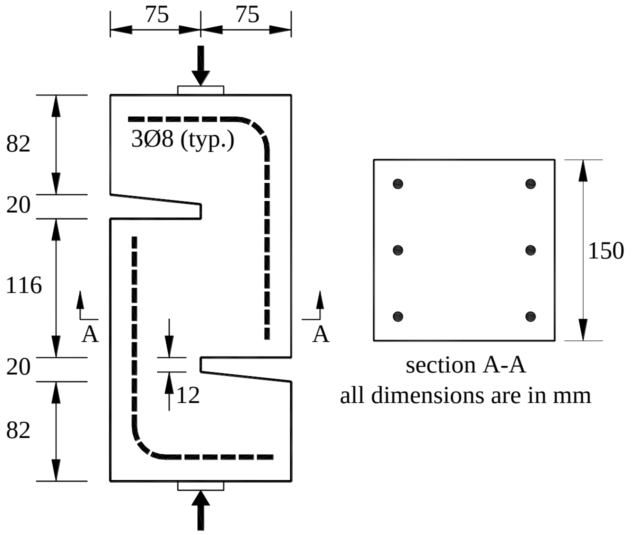

Fig. 2: Details of test specimens

The natural aggregate concrete (NAC) was made with Gabbro or with Limestone crushed rock while the recycled aggregate concrete (RAC) was made with crushed waste old concrete. The waste concrete was the result of demolition of of forty to sixty years old buildings which served under hot environment and made with a relatively high water to cement ratio [7]. The recycled aggregates were free of debris and non-concrete materials. The maximum size of the coarse aggregates aggregates was 12.5 mm, and the water cement ratio ranged from 0.31 to 0.72. The specimens were moist cured for 28 days days and were tested about two hours after removal from the curing.

The shear-transfer plane was not reinforced. However, reinforcement was placed in the two legs of the specimens to avoid premature failure outside the test region.

A total of 45 NAC specimens and 41 RAC specimens were tested. The concentric load was applied at the rate of 5 kN/minute. The shear cracking strength v_{cr} was calculated as the maximum applied load divided by the area of the shear-transfer plane.

Table 1: Properties of test specimens and summary of results.

Group	Aggregates	Cement content (kg/m^3)	C. Agg. content (kg/m^3)	F. Agg. content (kg/m^3)	w/c	f_{cu} (MPa)	$N^{\dagger}$	v_{cr} (MPa)	$\frac{v_{cr}}{f_{cu}}$	$\frac{v_{cr}}{\sqrt{f_{cu}}}$
L72	Limestone	250	1100	825	0.72	24.9	5	3.86	0.115	0.71
L54	Limestone	320	1145	720	0.54	36.3	6	4.43		
L42	Limestone	400	1150	675	0.42	54.8	5	5.11		
L31	Limestone	470*	1150	650	0.31	56.0	5	5.60		
G72	Gabbro	250	1108	825	0.72	22.2	6	3.11		
G54	Gabbro	320	1159	720	0.54	36.6	6	4.23		
G42	Gabbro	400	1159	675	0.42	47.1	6	4.93		
G31	Gabbro	470*	1159	650	0.31	56.7	6	5.07		
R72	Recycled	250	937	825	0.72	19.2	6	2.82	0.121	0.677
R54	Recycled	320	975	720	0.54	30.0	6	3.48		
R42	Recycled	400	979	675	0.42	40.0	6	4.29		
R31	Recycled	470*	979	650	0.31	49.3	6	5.48		
HVR72	Recycled	224	1130	738	0.72	20.4	6	2.73		
HVR42	Recycled	356	1176	601	0.42	32.1	5	4.02		
HVR31	Recycled	417**	1172	577	0.31	41.6	6	4.49		

† N is number of pushoff specimens; * in addition to 20 kg. of Silica fume; * in addition to 18 kg. of Silica fume,

Table 1 provides the basic information about the concrete and summarizes the test results. Multiple similar specimens were cast and tested from the batches to obtain average values of v_{cr}. The three series HVR72, HVR42 and HVR31, significantly higher coarse aggregates content per cubic meter relative to the other ingredients, in order to test maximize the detrimental effects of the use of RCA and hence further test the relation between v_{cr} and f_{cu}.

3. Experimental results

All specimens failed in shear by separation of the two legs of the pushoff specimens along the shear transfer plane. Separation occurred as soon as cracks appeared and hence the specimens did not show any post-cracking strength.

Table 2 reports average cracking strengths and average normalized cracking strengths for the data after lumping all results from the NAC specimens together and all the RAC specimens together. Tables 1 and 2 show that for the same *w/c*, the use of RCA reduced f_{cu} as well as v_{cr}. The reduction in f_{cu} between all the RAC specimens relative to all the NAC specimens ranged from 16% to 29% and averaged 21%. The reduction in v_{cr} ranged from 10% to 32% and averaged 20%.

A larger variation in the numbers is observed in the shear cracking strength, likely due to the cracking due to tension in the principal stress direction. It is also observed that the reduction in the shear cracking strength is lower at higher compressive strengths. Reductions are expected results as the inferior quality of RAC relative to NAC has been well established [e.g. 1, 2, 10].

Table 2: Summary of reduction in strengths.

w/c	Reduction in f_{cu}	Reduction in v_{cr}
0.72	16%	24%
0.54	18%	32%
0.42	29%	16%
0.31	19%	10%
average	21%	20%

Fig. 3 plots v_{cr} versus f_{cu} for the pushoff specimens. Typically, the shear strength is related to the square root of the compressive strength. Based on such relationship, the results suggest that the cracking shear strength for the pushoff specimens ranged from $0.6\sqrt{f_{cu}}$ to $0.8\sqrt{f_{cu}}$, and was on average:

$$v_{cr} = 0.7\sqrt{f_{cu}} \quad (1)$$

This value is considerably higher than that for pure shear, suggested to be close to 0.33 times the square root of the cylinder compressive strength [11]. This is expected since the compressive stresses acting in combination with the shear stresses increase the cracking strength.

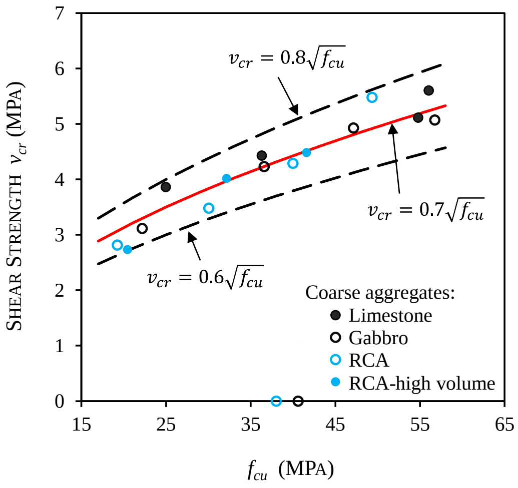

Fig. 3: Cracking strength versus compressive strength

In Table 2, it is shown that the detrimental effects of the use of the RCA on v_{cr} are underestimated if this strength is related to $\sqrt{f_{cu}}$ and is used for NAC and RAC. It is on the other hand overestimated if it is related directly to f_{cu}.

4. Conclusion

Tests conducted on pushoff specimens made using natural aggregates concrete and recycled aggregate concrete with water-to-cement rations ranging from 0.31 to 0.72 were used to study the effect of the use of RCA on the concrete strength in shear and compression. The shear transfer planes of the specimens were subjected predominantly to shear and compression and were unreinforced. The recycled aggregates used in the production of the recycled aggregates concrete were made by crushing waste concrete of relatively low strength.

The results indicate that the use of the recycled aggregates reduced the compressive strength and the shear cracking strength of the specimens. For the wide range of water-to-cement ratios, the reduction was about 20% in each of the two strengths. However, the reduction was less severe on the shear strength for the specimens made using lower water-to-cement cement ratios.

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