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Shear strength of reinforced recycled concrete beams without stirrups

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Fathifazl *et al.* (2009b) have presented an interesting study on sustainable concrete made with recycled concrete aggregates. The equivalent mortar volume (EMV) method of mix proportioning (Fathifazl *et al.*, 2009a) adopted by the authors ensures that the aggregate content in recycled concrete aggregate (RCA) concrete is not reduced as compared with conventional natural aggregate concrete. However, in RCA concrete, the total mortar volume consists of fresh mortar and residual mortar, the latter fraction being basically inactive mortar sticking on the surface of the virgin aggregates (Figure 15). The presence of inactive residual mortar will create additional interfaces with the fresh mortar, which may weaken the concrete. This raises the question as to whether the strength of RCA concrete – having a combination of residual and fresh mortar – is comparable to conventional natural aggregate concrete that contains an equivalent amount of fully fresh mortar. A more recent study by Choi *et al.* (2010), in which the mix was not proportioned as per the EMV method, indicated that the shear strength of RCA concrete beams was consistently less than that of beams made with conventional natural aggregate concrete, with this reduction being more pronounced at lower shear span-to-effective depth (a/d) ratios. In the light of these findings, the authors may like to reconcile the finding that,

Figure 15. Structure of RCA concrete matrix

in certain cases, their RCA concrete beams outperformed conventional concrete beams.

Using strut-and-tie modelling, the discussers re-analysed the experimental results of 16 of the 20 beams tested by the authors (Figure 16) in order to examine whether the efficiency factors of conventional natural aggregate concrete struts can also be used for RCA concrete (Sahoo *et al.*, 2010). Since experimental peak loads were not reported by the authors, they were scaled from Figure 5 of the original paper. Certain

Figure 16. Typical geometry, loading and strut-and-tie model of the test beams (not to scale) (Sahoo et al., 2010)

other details such as the location of the centroid of the longitudinal tension reinforcement near the beam soffit and the sizes of the bearing plates at the load points and the supports, which are critical inputs for the appraisal, had to be reasonably assumed. The plan dimensions of all bearing plates covering the full thickness (200 mm) of the beams were taken as 200×100 mm. Furthermore, in the absence of exact overall depths of the beams in the first series (Table 4), they were uniformly taken to be 350 mm; the width of the tie A–D, w_{AD} (Figure 16) was calculated for the beams of the first series accordingly. The results of this analysis are summarised in Table 5.

Knowing from statics the axial compressive force resisted by the struts in the truss model of Figure 16, the experimental efficiency factors (β_{se}) of the diagonal bottle-shaped struts A–B or C–D were calculated using Equation 1 and then compared with the predictions of Sahoo's (2009) model (Equation 2) for conventional natural aggregate concrete.

$$\beta_{se, AB} = \frac{F_{AB}}{0.85 f'_c (b \cdot w_{AB})} \quad (1)$$

$$\beta_{s, AB} = \left(0.60 + \frac{0.05}{r_c} + 55 \rho_T \right) \frac{\alpha_s}{90} \quad (2)$$

where F_{AB} is the axial compressive force resisted by

the strut A–B, f'_c is the cylinder compressive strength of concrete on the date of testing of the corresponding beam specimen, b is the beam thickness (200 mm), w_{AB} is the width of the strut A–B, r_c is the load concentration ratio (the ratio of the least strut width and the length of the strut, w_{AB}/l_{AB}), ρ_T is the effective transverse reinforcement ratio ($= 0$ as there is no web reinforcement) and α_s is the least angle of inclination of the strut with the adjoining tie(s) in degrees.

A comparison of the efficiency factors of the inclined bottle-shaped struts in the RCA concrete beams EM-2.7N and EM-M and the nominally identical beams CL-2.7N and CL-M made of conventional natural aggregate concrete shows that the former had higher efficiency factors (Figure 17). A comparison of the strut efficiency factors in the last two columns of Table 5 shows that the experimentally obtained strut efficiency factors (β_{se} , Equation 1) of the RCA concrete struts are consistently higher than the predicted efficiency factors (β_s , Equation 1) for struts made of conventional natural aggregate concrete. In conclusion, a re-analysis of the authors' experimental results indicates that structural concrete made of RCA if proportioned using the EMV method can be conservatively designed using the strut-and-tie method with the same efficiency factors as applicable for conventional natural aggregate concrete.

Table 5. Analysis of the test results (Sahoo *et al.*, 2010)

No. *	Beam ID	f'_c	$P = V_{\max}$: kN	$F_{AB} = P/\sin \alpha_s$: kN	Length of strut AB: mm	w_{AB} : mm	r_c	jd : mm	Shear span, a : mm	α_s : deg	$\beta_{sc,AB}$	$\beta_{s,AB}$
1	EV-1.5N	43.5	195	401	515	136	0.26	250	450	29.1	0.40	0.26
2	EV-2N	43.5	175	456	650	131	0.20	250	600	22.6	0.47	0.21
3	EV-4N	43.5	106	502	1228	109	0.09	260	1200	12.2	0.62	0.16
4	EM-1.5N	36.9	185	381	515	136	0.26	250	450	29.1	0.45	0.26
5	EM-2N	36.9	170	443	650	131	0.20	250	600	22.6	0.54	0.21
6	EM-2.7N	36.9	103	325	844	109	0.13	268	800	18.5	0.47	0.20
7	CL-2.7N	38.0	93	293	844	109	0.13	268	800	18.5	0.41	0.20
8	EM-4N	36.9	83	393	1228	109	0.09	260	1200	12.2	0.57	0.16
9	EV-L	43.5	126	466	561	121	0.22	152	540	15.7	0.52	0.14
10	EV-H	43.5	112	390	1086	161	0.15	312	1040	16.7	0.33	0.17
11	EV-HH	43.5	120	406	1361	171	0.13	402	1300	17.2	0.32	0.19
12	EM-L	36.9	90	333	561	121	0.22	152	540	15.7	0.44	0.14
13	EM-M	36.9	101	348	836	155	0.19	243	800	16.9	0.36	0.16
14	CL-M	38.3	92	317	836	155	0.19	243	800	16.9	0.31	0.16
15	EM-H	36.9	97	338	1086	161	0.15	312	1040	16.7	0.33	0.17
16	EM-HH	36.9	103	348	1361	171	0.13	402	1300	17.2	0.32	0.19

* Series I beams (for a/d ratio effect) are Nos 1–8; series II beams (for size effect) are Nos 9–16; overall depth for Series I beams assumed to be 350 mm. ($V_{\max}$ is the maximum shear force resisted by a beam specimen.)

Figure 17. Comparison of efficiency factors of bottle-shaped struts in the beams cast from recycled coarse aggregate concrete and natural coarse aggregate concrete

Authors' reply

The authors thank the discussers for their interest in this work, and are pleased that they have demonstrated the applicability of the strut-and-tie model to the shear design of RCA concrete beams proportioned by the EMV method. This affirms one of the main conclusions of our study, which stated that structural members made of RCA concrete proportioned by the EMV method can be designed for shear using existing shear design methods for conventional concrete.

In response to the discussers' statement regarding the presence of additional interfaces with the fresh mortar that may weaken the concrete, we wish to state that

although the differences between the strength and density of the residual mortar and the fresh mortar may have some effect on the overall properties of RCA concrete, this effect is relatively small (Fathifazl *et al.*, 2009a). Based on our study, unlike some other mechanical and physical properties of RCA concrete, its compressive strength is primarily a function of the relative strength of its components rather than its total mortar volume. The shape and surface roughness of the natural coarse aggregate in the RCA is another factor that affects the strength of RCA concrete. For example, all other factors being the same, concrete made with coarse RCA containing crushed stone would have higher strength than similar concrete made with virgin river gravel because the interface between the RCA particles and the fresh mortar would be stronger than that between the river gravel and the mortar. The opposite may happen if the virgin aggregate was crushed stone.

As for the statement regarding 'inactive residual mortar', the authors believe that, due to the presence of some unhydrated cement particles in residual mortar, the term 'inactive' might not be an apt description of this mortar because the unhydrated cement particles on the surface of the RCA may hydrate and form a strong bond with the fresh mortar. This interface may be stronger than that between the fresh mortar and the virgin aggregate. On the other hand, the interfacial strength of the residual mortar and the natural aggregate in RCA particles will depend on the quality and strength of the concrete from which the RCA originated. Clearly, if the original concrete was high quality, its aggregate–mortar interfacial strength is expected to be strong.

Finally, regarding the finding of a recent study by Choi *et al.* (2010) about the lower shear strength of

RCA concrete beams proportioned by conventional mix proportioning methods, this finding is in agreement with the results of previous studies (Etxeberria *et al.*, 2007; Han *et al.*, 2001; Maruyama *et al.*, 2004). In our opinion, the main reason for the reported lower strengths is the application of conventional mix proportioning methods to RCA. The conventional method results in lower coarse aggregate content in the RCA concrete and therefore fewer coarse aggregate particles are expected to cross the cracked shear plane, which would potentially reduce crack roughness and weaken the aggregate interlock mechanism of shear resistance (Fathifazl *et al.*, 2009b).

References

- Choi HB, Yi CK, Cho HH and Kang KI (2010) Experimental study on the shear strength of recycled aggregate concrete beams. *Magazine of Concrete Research* **62**(2): 103–114.
- Etxeberria M, Mari AR and Vázquez E (2007) Recycled aggregate concrete as structural material. *Materials and Structures* **40**(5): 529–541.
- Fathifazl G, Abbas A, Razaqpur AG, *et al.* (2009a) New mix design method for recycled aggregate concrete. *ASCE Materials Journal* **21**(10): 601–611.
- Fathifazl G, Razaqpur AG, Isgor OB, *et al.* (2009b) Shear strength of steel reinforced recycled concrete beams without stirrups. *Magazine of Concrete Research* **61**(7): 477–490.
- Han BC, Yun HD and Chung SY (2001) Shear capacity of reinforced concrete beams made with recycled-aggregate. *ACI Special Publications* **200**: 503–516.
- Maruyama I, Sogo M, Sogabe T, Sato R and Kawai K (2004) Shear behaviour of reinforced recycled concrete beams. *Proceedings of Conference on the Use of Recycled Materials in Building and Structures, Barcelona*, pp. 610–618.
- Sahoo DK (2009) *An Investigation of the Strength of Bottle-shaped Struts*. PhD thesis, Indian Institute of Technology Roorkee, Roorkee.
- Sahoo DK, Singh B and Bhargava P (2010) Strut efficiency factors for structural concrete made from coarse recycled concrete aggregates. *Journal of Structural Engineering, Special Issue on Sustainable Built Environment* **37**(1): 49–54.