EFFICIENCY FACTORS FOR BOTTLE-SHAPED STRUTS IN DEEP BEAMS MADE OF RECYCLED COARSE AGGREGATE

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Abstract
Based on reanalysis of the shear test results of reinforced concrete beam specimens made of recycled coarse aggregates reported in the literature, this study points out that the strut-and-tie modeling (STM) provisions developed for natural coarse aggregate concrete can be applied to recycled coarse aggregate concrete with no reduction in the efficiency factors of bottle-shaped struts. The experimentally obtained strut efficiency factors in beams made of recycled coarse aggregate concrete were comparable to those in beams made of natural coarse aggregate concrete. The study also highlights lack of conservatism in the STM provisions of current design codes irrespective of the type of coarse aggregates used.

Keywords: *Recycled coarse aggregate; strut-and-tie model; bottle-shaped strut; efficiency factor; shear.*

1. Introduction

The idea of recycling demolished old concrete to manufacture recycled coarse aggregates (RCA) for new structural concrete is driven by an ever increasing global concern for the environment. Amidst controversies over its strength and durability, RCA concrete is gradually receiving due acceptance as an efficient structural material with properties well comparable with conventional natural aggregate concrete. For structural engineers, the foremost concern with RCA concrete is whether the design provisions in the current concrete codes which are developed for natural coarse aggregate concrete can be applied without alteration to RCA concrete. Choi et al. (2010) observed that the direct application of current design methods is acceptable for RCA concrete with RCA replacement ratio of up to 50 % beyond which the shear strength may be reduced by as much as 30 %. On the contrary, Fathifazl et al. (2008 and 2009(2)) have argued that the apparent reduction in the shear strength of reinforced RCA concrete (RRC) beams reported by other researchers are attributable to conventional method of mix proportioning. They have demonstrated that if RCA concrete is proportioned by their equivalent mortar volume (EMV) method (Fathifazl et al. 2009 and 2010), then RCA concrete may even outperform conventional natural coarse aggregate concrete beams in terms of shear strength.

In the present study, the shear strength tests on 12 RRC beams performed and reported by Han et al. (2001) have been reanalyzed using strut-and-tie model to ascertain whether the efficiency factors recommended in the current design codes and the literature can be used for RRC beams.

2. Material and methods

Han et al. (2001) tested 12 reinforced concrete beams using natural, washed recycled and non-washed recycled coarse aggregates. All the beams were of 170 mm width and 300 mm overall depth (effective depth = 270 mm) and were tested under two point symmetrical loading with shear span-to-effective depth (a_v / d) ratios varying from 1.5 to 4.0, **Fig. 1**. The main reinforcement provided in one layer at the beam bottom (1.11 % for specimens at S. Nos. 1 to 6 and 2.21 % for those at S. Nos. 7 to 12) was adequate to ensure that the beams did not fail in flexure. The cover to the tension reinforcement was 30 mm whereby the width of tie was considered to be 60 mm. The specimen details are given **Table 1**, with reference to **Fig. 1**. The two specimens, C-2.0-N and C-2.0-W2, wherein natural coarse aggregates were used served as control specimens. For the two specimens, NR-2.0-N and NR-2.0-W2, recycled coarse aggregate was not washed of the dust etc. For the rest of the specimens, recycled coarse aggregate was washed clean to make them free from surface dirt. The properties of the natural and recycled (washed and non-washed) coarse aggregates and the mixture proportions of different types of concrete used in the specimens can be found in the original paper by Han et al. (2001). The beams were tested under two-point symmetrical loading, interspaced by 540 mm (twice the effective depth), **Fig. 1**.

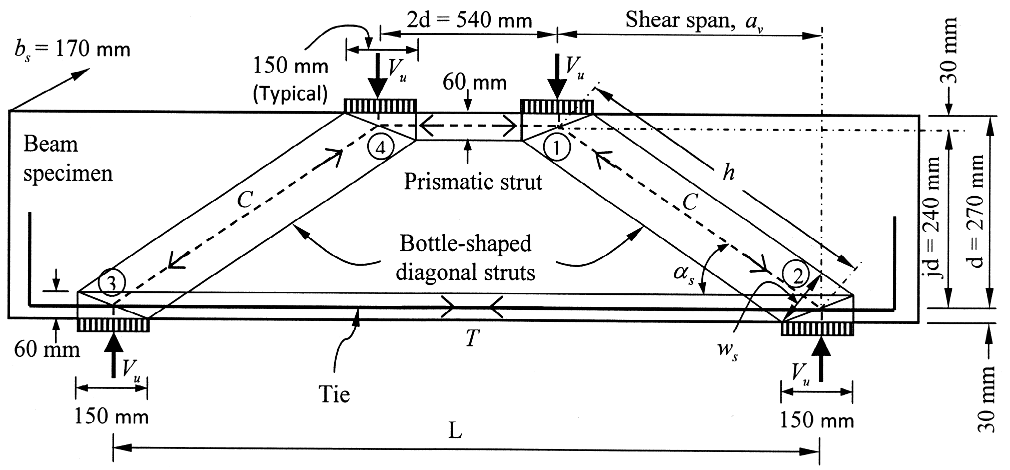

Fig. 1: *Dimensions of a typical beam specimen with strut-and-tie model*

Table 1: *Details of the beam specimens*

S. No.	Beam ID	Coarse aggregate type	f_c' (MPa)	a_v / d	α_s (degrees)	Web steel ratio, ρ_V	ρ_T	h	w_s
I	II	III	IV	V	VI	VII	VIII	IX	X
1	R-1.5-N	Washed Recycled	39.62	1.5	31.0	0	0	466	129
2	R-2.0-N	Washed Recycled	30.57	2.0	24.0	0	0	590	116
3	R-3.0-N	Washed Recycled	31.23	3.0	16.5	0	0	845	100
4	R-4.0-N	Washed Recycled	31.89	4.0	12.5	0	0	1108	91
5	NR-2.0-N	Non-washed Recycled	32.56	2.0	24.0	0	0	590	116
6	C-2.0-N	Natural	37.43	2.0	24.0	0	0	590	116
7	R-2.0-W1	Washed Recycled	41.86	2.0	24.0	0.00089	0.0007	590	116
8	R-2.0-W2	Washed Recycled	41.11	2.0	24.0	0.00244	0.0020	590	116
9	R-2.0-W5	Washed Recycled	31.58	2.0	24.0	0.00507	0.0042	590	116
10	R-2.0-W8	Washed Recycled	41.11	2.0	24.0	0.00823	0.0069	590	116
11	NR-2.0-W2	Non-washed Recycled	37.43	2.0	24.0	0.00244	0.0020	590	116
12	C-2.0-W2	Natural	49.83	2.0	24.0	0.00244	0.0020	590	116

Note: Nomenclature: Coarse aggregate type–a_v / d – web reinforcement detailing. R: washed recycled coarse aggregats. NR: non-washed recycled coarse aggregate. C: natural coarse aggregate. N: No web reinforcement. W1 through W5: ρ_V varies from 0.00089 to 0.00823 as shown in Col. (VI).

3. Theory/calculation

The beams were analyzed by strut-and-tie models, **Fig. 1.** The transfer of loads to the adjacent supports was assumed to take place through arch (direct strut) action as six of the twelve beams at S. Nos. 1 through 6, had no shear reinforcement. For ease of comparison, the same type of load transfer mechanism was assumed for the rest of the beams which had varying amounts of shear reinforcements in the form of vertical stirrups. Since the length of the load and support bearing plates were not reported by Han et al. (2001), the same was scaled from their figures and assumed to be 150 mm, **Fig. 1**. For simplicity, the depth of the top nodes was assumed to be 60 mm and hence, the width of the prismatic strut 1-4 was taken as 60 mm. Accordingly, the lever arm, jd, was calculated as 240 mm, **Fig. 1**. From the given a_v / d ratios, a_v values were calculated knowing d = 270 mm. The angle of inclination of the diagonal struts, 1-2 or 4-3, was computed using the relationship $\cot \alpha_s = a_v / jd$. The length of the strut was calculated as $h = 240/\sin \alpha_s$ and the width of the strut, w_s, was calculated as $w_s = 150 \sin \alpha_s + 60 \cos \alpha_s$. The effective transverse reinforcement ratio, ρ_T, was calculated using the corrected transformation suggested by Sahoo et al. (2009) given below and presented in **Table 1**.

$$\rho_T = \sum \frac{A_{si}}{b_s s_i} \sin^2 \alpha_i \tag{1}$$

where A_{si} is the area of web reinforcement in each layer in the i^{th} orientation crossing the strut, b_s is the thickness of the strut (170 mm), s_i is the spacing of the web reinforcement in the i^{th} orientation, and α_i is the angle between the axis of the strut and the bars in the i^{th} orientation. In the present beams, since the web reinforcement consists of only vertical stirrups, $A_{si} / b_s s_i = \rho_V$ and $\alpha_i = \alpha_s$. Therefore, ρ_T can be expressed as $\rho_V \sin^2 \alpha_s$, **Table 1**.

4. Results

The efficiency factor suggested by these authors (Sahoo 2009, Sahoo et al. 2010) for natural coarse aggregate concrete is given below.

$$\beta_s = \left(0.6 + \frac{0.05}{r_c} + 55\rho_T \right) \frac{\alpha_s}{90} \tag{2}$$

The load concentration ratio (ratio of the load bearing length at the node-strut interface and the width of the imaginary rectangle enclosing the bottle-shaped strut), r_c, was taken as $r_c = w_s /(h/2) = 2w_s / h$, **Table 2**.

The ultimate shear force, V_u, resisted by the beams, **Table 2**, was obtained from the v_u values reported by Han et al. (2001).

$$V_u = v_u b_s d = v_u (170 \times 270)/1000 \text{ kN} = 45.9 v_u \text{ (kN)} \tag{3}$$

The beams were reanalyzed using strut-and-tie models and the compression resisted by the diagonal struts 1-2 or 4-3 was calculated from statics as $C = V_u / \sin \alpha_s$ and the tension resisted by the tie 2-3 was calculated as $T = V_u \cot \alpha_s$. From statics, the compressive force resisted by the prismatic strut 1-4 will be equal in magnitude to T. The axial forces in the struts and the ties have been compiled in **Table 2**. From the C values, the experimental strut efficiency factor, β_{se}, in the ACI 318-08 format, was calculated as below.

$$\beta_{se} = \frac{C \times 10^3}{0.85 w_s b_s f_c'} \tag{4}$$

Table 2: *Test results*

S. No.	Beam ID	$f_c^{'}$ (MPa)	α_s (deg.)	r_c	ρ_T	V_u (kN)	C (kN)	T (kN)	β_{se}	β_s (ACI)	β_s (EC2)	β_s (AASHTO)	β_s [Eq.(2)]
I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV
1	R-1.5-N	39.62	31.0	0.55	0	144	280	240	0.38	0.60	0.51	0.39	0.24
2	R-2.0-N	30.57	24.0	0.39	0	118	290	265	0.57	0.60	0.53	0.26	0.19
3	R-3.0-N	31.23	16.5	0.24	0	55	194	186	0.43	0.60	0.53	0.13	0.15
4	R-4.0-N	31.89	12.5	0.16	0	51	236	230	0.56	0.60	0.52	0.08	0.13
5	NR-2.0-N	32.56	24.0	0.39	0	113	278	254	0.51	0.60	0.52	0.26	0.19
6	C-2.0-N	37.43	24.0	0.39	0	118	290	265	0.46	0.60	0.51	0.26	0.19
7	R-2.0-W1	41.86	24.0	0.39	0.0007	150	369	337	0.53	0.60	0.50	0.26	0.20
8	R-2.0-W2	41.11	24.0	0.39	0.0020	153	376	344	0.55	0.60	0.50	0.26	0.22
9	R-2.0-W5	31.58	24.0	0.39	0.0042	174	428	391	0.81	0.75	0.52	0.26	0.26
10	R-2.0-W8	41.11	24.0	0.39	0.0069	174	428	391	0.61	0.75	0.50	0.26	0.30
11	NR-2.0-W2	37.43	24.0	0.39	0.0020	142	349	319	0.56	0.60	0.51	0.26	0.22
12	C-2.0-W2	49.83	24.0	0.39	0.0020	154	379	346	0.45	0.60	0.48	0.26	0.22

The predicted efficiency factors for the beam specimens have been calculated from the authors' model, **Eq. (2)**, and presented in **Table 2**. The EC2 efficiency factors in the ACI format have been calculated from the expression $\beta_s = 0.6(1 - f_{ck}/250)$ wherein the characteristic strength of concrete, f_{ck}, is taken as the specified cylinder compressive strength, $f_c^{'}$. The AASHTO efficiency factors in the ACI format have been obtained from the expression $\beta_s = 1/0.85(0.8 + 170\varepsilon_1)$ where the principal tensile strain in concrete in the bottle-shaped strut, ε_1, is obtained from $\varepsilon_1 = \varepsilon_s + (\varepsilon_s + 0.002)\cot^2 \alpha_s$ assuming conservatively the strain in the tie reinforcement, ε_s, to be the yield strain of steel used in the tie (0.002).

5. Discussion

The experimentally obtained values of efficiency factor of the diagonal bottle-shaped struts in the 12 beams have been compared in four different groups.

Comparison of β_{se} of bottle-shaped struts in the three beams made of washed recycled, non-washed recycled and natural coarse aggregates at S. Nos. 2, 5 and 6 respectively, with identical sizes, shear span-to-effective depth ratios and having no web reinforcement, clearly shows that the use of recycled aggregate has resulted in no reduction in the strength of the diagonal struts. The experimental efficiency factors of the bottle-shaped diagonal struts in these beams are 0.57, 0.51 and 0.46 respectively, which indicate that recycled (washed/non-washed) coarse aggregate concrete can even outperform the natural coarse aggregate concrete in shear strength expressed in terms of strut efficiency, **Fig. 2**.

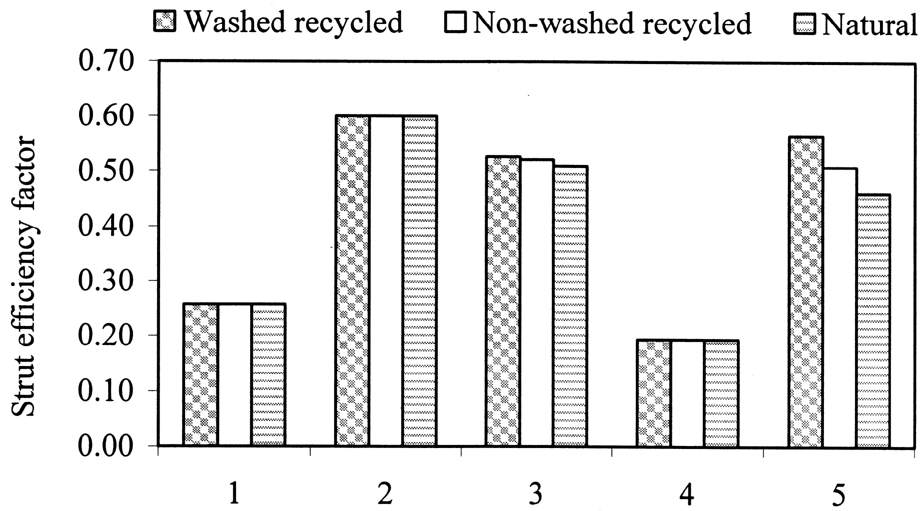

Fig. 2 *Influence of type of aggregates on the efficiency factor of bottle-shaped struts without transverse reinforcement*
[1. AASHTO, 2. ACI, 3. EC2, 4. Authors, 5. Experimental]

The β_{se} values of the three web-reinforced beams made of washed recycled, non-washed recycled and natural coarse aggregate, at S. Nos. 8, 11 and 12 respectively, with identical sizes, identical a_v / d ratios and having identical effective transverse reinforcement, ρ_T , of 0.002, are 0.55, 0.56 and 0.45 in that order. Thus, for RRC beams with web reinforcement also, efficiency factors of bottle-shaped struts are higher than that of natural aggregate concrete beam, **Fig. 3**. Washing of recycled aggregates does not seem to have any significant effect on the strength of the bottle-shaped struts, **Figs. 2 and 3**.

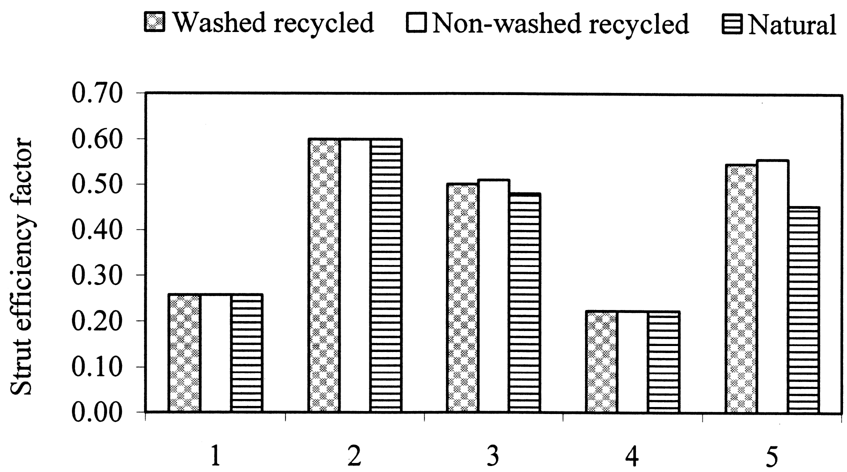

Fig. 3 *Influence of type of aggregates on the efficiency factor of bottle-shaped struts with 0.2% transverse reinforcement*
[1. AASHTO, 2. ACI, 3. EC2, 4. Authors, 5. Experimental]

The β_{se} values of the five specimens at S. Nos. 2 and 7 through 10, made of washed recycled coarse aggregates, are plotted against the effective transverse reinforcement ratio, ρ_T , in **Fig. 4**. The linear trend line (broken line) of experimentally obtained efficiency factor values shows the dependence of β_{se} on ρ_T although the correlation between the experimental values and their linear trend line is weak. The trend of β_s obtained from the authors' model (Sahoo 2009, Sahoo et al. 2010), **Eq. (2)**, is similar to the linear trend in the experimental values. The authors' model is most conservative of all and is in close agreement with the predictions of the AASHTO (2005) model.

Although the EC2 (British Standards Institution, 2004) predictions are close to the experimental values, the margin of conservatism is low. The ACI recommended β_s values of 0.60 (for ρ_T < 0.003) and 0.75 (for $\rho_T \geq$ 0.003) are found to be unconservative in all cases except R-2.0-W5. It may be noted that the low experimental efficiency factor values for bottle-shaped struts compared to the ACI recommended values are not attributable to the use of recycled aggregates, rather the ACI efficiency factor values are unconservative irrespective of the types of aggregate primarily because the ACI efficiency factors do not account for the inclination of bottle-shaped struts with adjoining tie(s) which has a strong influence on the strength of bottle-shaped diagonal struts in beams (Sahoo 2009, Sahoo et al. 2010).

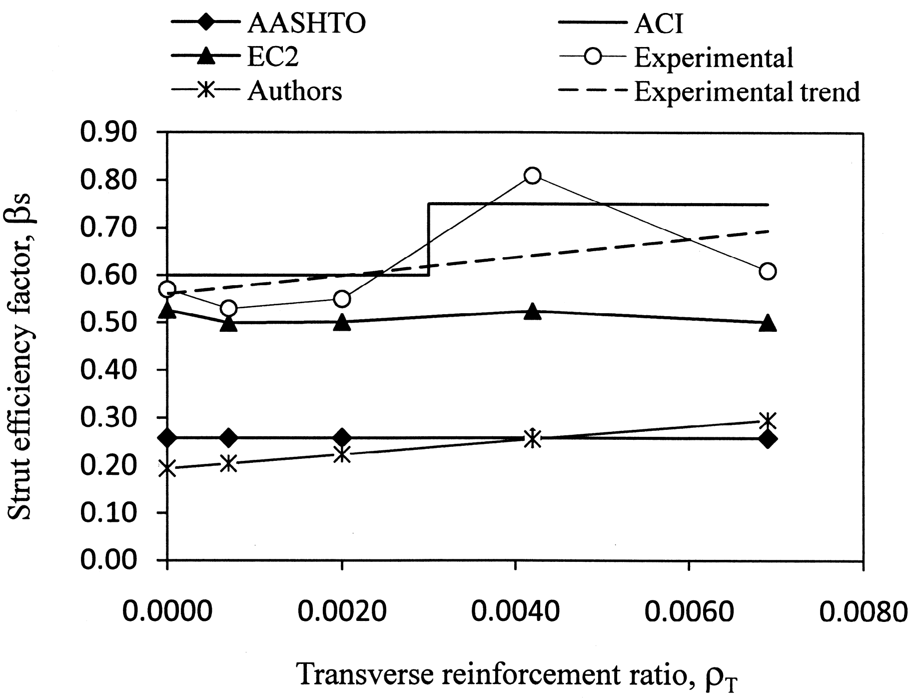

Fig. 4 *Trend in experimental and predicted strut efficiency factors with varying transverse reinforcement ratio (washed recycled aggregate concrete)*

The four beams at S. Nos. 1 through 4 with no web reinforcement for the diagonal bottle-shaped struts had a_v / d ratios of 1.5, 2, 3 and 4 respectively. In the absence of vertical shear reinforcement, it is rational to assume that the load transfer from the loading points to the adjacent supports will take place through direct strut mechanism between the loads and adjacent supports. In **Fig. 5** the experimentally obtained efficiency factors for the diagonal bottle-shaped struts have been plotted against the corresponding strut angles, α_s. The number of data points being few and the strut angles being mostly less than 25°, the experimental efficiency factors show large scatter and no clear trend is discernible. However, the experimentally observed efficiency factor values for all the four beams made of recycled aggregates when compared with those predicted by the AASHTO and the authors' models for natural coarse aggregate concrete indicate that RCA concrete can be treated at par with natural aggregate concrete in terms of strut efficiency factors. However, the experimental values are less than the ACI recommended values in all four specimens and less than the EC2 recommendations in two of the four specimens. However, as mentioned earlier, the apparent low experimental results vis-à-vis the ACI or the EC2 recommended efficiency factors do not indicate inferior strength of RCA concrete; rather it is indicative of the inherent lack of conservatism in the ACI and the EC2 efficiency factor models which do not account for the inclination of struts with adjoining tie(s).

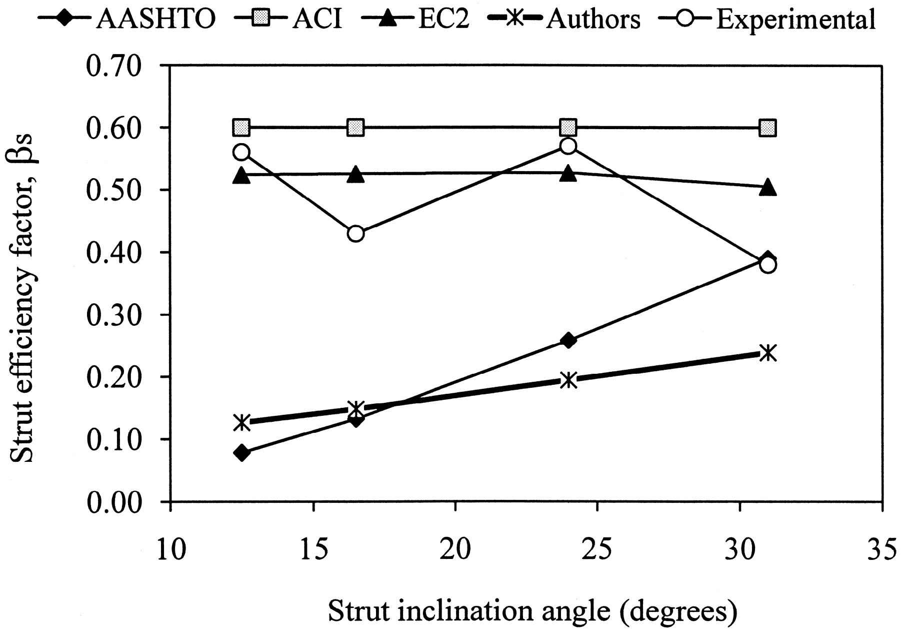

Fig. 5 *Trends in experimental and predicted strut efficiency factors with varying strut inclination (washed recycled aggregate concrete)*

What is notable from the above discussions is that the experimentally observed efficiency factors of bottle-shaped struts in the recycled coarse aggregate concrete beams and the trends in the efficiency factor values with varying transverse reinforcement contents and strut inclinations do not suggest any loss of strut efficiency attributable to the substitution of natural aggregate in concrete with recycled coarse aggregate. Therefore, the use of recycled coarse aggregate in concrete *per se* does not call for any reduction in the values of strut efficiency factors prescribed for conventional natural coarse aggregate concrete.

6. Conclusions

On the basis of strut-and-tie modeling, the results of beam tests reported in the literature were reanalyzed to arrive at the following conclusions.

a) Shear strengths of reinforced concrete beams in terms of strut efficiency factors were found to be no inferior when recycled concrete coarse aggregate is used. The experimentally observed efficiency factors of bottle-shaped struts in the recycled coarse aggregate concrete beams and the trends in the efficiency factor values with varying transverse reinforcement contents and strut inclinations do not suggest any loss of strut efficiency attributable to the substitution of natural coarse aggregate in concrete with recycled coarse aggregate. Therefore, the use of recycled coarse aggregate in concrete *per se* does not call for any reduction in the values of strut efficiency factors prescribed for conventional natural coarse aggregate concrete.
b) The efficiency factors of bottle-shaped struts predicted by the authors' efficiency factor model (2009) were most conservative yet close to the AASHTO recommended values. The Eurocode 2 predicted efficiency factors were most accurate for the test specimens but the extent of conservatism was marginal. The ACI recommended strut efficiency factors were found to be unconservative when compared with the observed values.
c) Washing of recycled aggregates does not seem to have any significant effect on the strength of bottle-shaped struts. Therefore, coarse recycled concrete aggregate can be straightaway used for making fresh concrete without washing.

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