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Experimental Study on Shear Behaviour of High Strength Reinforced Recycled Concrete Beam

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ABSTRACT

Recently, there has been great interest on the applicability of Recycled Concrete Aggregate (RCA) as a new ecological construction material that can be sustainable in a gradually expanding construction industry. This paper reports the structural performance particularly on shear behaviour of high strength reinforced recycled concrete beams. Compressive cube strength of the tested beams ranged from 65-74 MPa at the age of 28-days. The experimental program compared conventional concrete mix with concrete mix having substitution of 25% recycled concrete aggregates of grade 25-30 MPa. In this study, three 150 mm x 200 mm x 1200 mm simply supported rectangular concrete beams in each mix were tested under a four-point bending static load with various shear span to effective depth ratios (*a/d* = 1.0, 1.5, 2.0). Subsequently, the shear behavior of the beams was investigated through studies of load-deflection responses, effect of *a/d* ratios and crack patterns. The test results reported that the substitution of 25% recycled concrete coarse aggregates barely affects the shear capacity of the high strength reinforced concrete beams with *a/d* of 1.5 onwards. Finally, experimental results were compared using existing design codes by ACI 318, Eurocode-2 and AS3600 which lie on the safe side

Keywords: Recycled concrete aggregate, high strength concrete, recycled beam, shear, shear span

INTRODUCTION

As a result of enormous increase in demolitions of concrete building, great amount of concrete waste has been generated. The Central and Southern regions of Malaysia only, have deposited the construction and demolition (C&D) debris that comprises 28.34% of the total waste (Mohd Nasir *et al.*, 1998). As far as environmental concern, potential uses of Recycled Concrete Aggregate (RCA) in new concreting works are constantly investigated by researchers since few decades ago. While utilization of recycling concrete could solve the growing waste disposal and conserve the

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precious limited natural sources of aggregates, it also appeared as an economical solution as the prices for natural aggregate have significantly grew in the latest decade (Ajdukiewicz & Kliszczewicz, 2007). Undoubtedly, some significant breakthroughs of RCA as replacement of natural aggregate in concrete had been successfully established by researchers in the recent past, it can be seen in the overwhelming literatures that available nowadays.

Various efforts have been put into the investigation on the mechanical properties, strength, failure mechanism and durability characteristics of the optimum concrete mix with RCA (Brito & Alves, 2010; Fonseca *et al*., 2011; Li, 2008; Rahal, 2007; Chakradhara *et al*., 2011; Xiao *et al*., 2005). The statement of Recycled Aggregate Concrete (RAC) possessed lightly lower strength than the conventional concrete was reported in (Casuccio *et al*., 2008). On the other hand, Rao concluded that the concrete with 25% RCA is able to maintain its strength under low velocity impact load (Chakradhara *et al.*, 2011). In addition, the RAC with water cement ratio (*w/c*) of 0.55 demonstrated comparable compressive strength as the conventional concrete however showed no significant increase in strength with *w/c* below 0.40 (Rasheeduzzafar & Khan, 1984). Overall, these researchers pointed out that utilization of RCA in concrete is technically possible.

Comparatively, reports on structural behavior especially in shear capacity of the reinforced recycled concrete beams made by RCA are scarce. Researchers from the past have summarized that the shear performance of reinforced recycled concrete beams are little affected, as good as or even superior to the conventional beams made with natural aggregates (Fathifazl *et al*., 2010; Fathifazl *et al.*, 2011; González-Fonteboa & Martínez-Abella, 2007; González-Fonteboa *et al*., 2009). Some results indicated that the shear strength diminishes as the substitution of less than 30% RCA in the concrete (Etxeberria *et al*., 2007; Choi *et al*., 2010).

Research on mechanical properties of high strength RAC has been carried out (Ajdukiewicz & Kliszczewicz, 2002), nonetheless the structural performance in shear of high strength reinforced recycled concrete beams need to be exposed and therefore are presented herein. Six (6) full-scale reinforced concrete beams produced by concrete mix with natural coarse aggregates and substitution of 25% coarse RCA are studied. Through the results, the authors hope to enhance the understanding on the shear behavior of high strength reinforced recycled beams as well as to reveal that the prediction of existing codes on the shear capacity of high strength reinforced recycled beams can be applied without any modifications.

METHODOLOGY

The experimental program comprised two series of specimens with a total number of six (6) high strength reinforced concrete beams. Specimens in series 'CB' were cast with conventional concrete mix whereas series 'RB' was produced by concrete mix with 25% coarse RCA. The coarse RCA was obtained solely from laboratory concrete cube wastes with reliable compressive strengths of approximately 25-30 MPa. The concrete cubes with age less than one year, protected against weather and aggressive conditions were crushed by jaw crusher and sieved to a maximum size 20 mm in accordance to British Standard, BS812-103: 1985 (British Standard, 1985) . The crushed recycled concrete coarse aggregates were angular and fractured in nature. The specific gravity, Los Angeles abrasion and absorption (24 hours) values of recycled concrete coarse aggregates were tested in accordance with BS812-2: 1995 (British Standard, 1995) and presented in Table 1.

TABLE 1
Physical Properties for Recycled Coarse Aggregate

Aggregate	Bulk specific gravity (SSD)	Apparent specific gravity	Los Angeles abrasion (%)	Absorption
RCA	2.46	2.55	35	2.45

Both concrete mixes consisted of Ordinary Portland Cement (OPC), uncrushed river sand, and either crushed natural or recycled coarse aggregates adopted optimum mix proportion of 1:1.1:2.1 and *w/c* of 0.41. Table 2 summarizes the concrete mix proportion produced. The established concrete mixes were aimed at producing concrete workability with slump of 10-30 mm and targeted compressive strength greater than 50 MPa at 28 days age. The concrete produced was very stiff and demonstrated a 20 mm slump for recycled concrete compared to a 25 mm slump for conventional concrete. The concrete compressive cube strength ranged from 65-74 MPa was measured from three (3) concrete cubes at 28 days lifetime with 100 mm standard mould size for each mix according to the British Standard, BS1881-116:1983 (British Standard, 1983).

TABLE 2
Mix Proportion

Mix Matrix (kg/m^3)	OPC	Sand	Natural Coarse Aggregate	Coarse RCA	Water
CB	570	630	1200	-	235
RB	570	630	900	300	235

In both series, three (3) reinforced concrete beam specimens were designed to a size of 150 x 200 x 1200 mm based on the British Standard, BS 8110-1: 1997 (British Standard, 1997). The specimens were fabricated with two (2) 10 mm diameter high yield deformed longitudinal reinforcement bars with characteristic strength of 460 N/mm^2 in both the compression and tension zone. 6 mm diameter mild steel bars with characteristic strength of 250 N/mm^2 spaced at 200 mm centre to centre were used as shear links. The concrete cover was 30 mm.

Each of the simply supported specimens in both series were loaded to fail under a four-point bending static load test with different shear spans (*a*), namely 160 mm, 240 mm and 320 mm arriving at a shear span to effective depth ratio (*a/d*) of 1.0, 1.5 and 2.0 respectively. The details of the specimens are shown in Table 3 while the experimental set-up is illustrated in Fig.1. A load beam acted as a medium to transfer a load source into two static point loads to the beam specimens through steel rods. An external linear variable differential transducer (LVDT) was placed at the middle of the beam soffit to measure its central deflection. The deformation of the compression reinforcement was measured by electrical resistance strain gauges. All the data were automatically recorded by built-in data acquisition.

TABLE 3
Specimens Details

Specimen notation	CB1.0	RB1.0	CB1.5	RB1.5	CB2.0	RB2.0
Shear span, a (mm)	160	160	240	240	320	320
Shear span to effective depth ratio, a/d	1.0	1.0	1.5	1.5	2.0	2.0
Compressive cube strength, (N/mm^2)	73.25	64.77	73.25	64.77	73.25	64.77

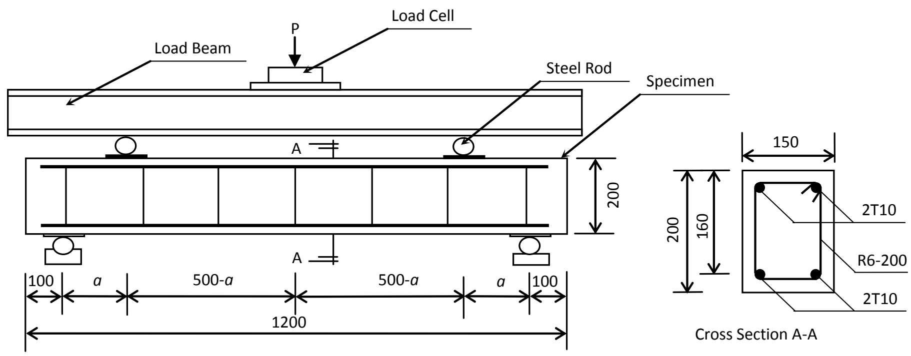

Fig.1: Beam specimen details (Units: mm)

RESULTS AND DISCUSSION

The effectiveness in shear of high strength recycled reinforced concrete beam specimens are examined here. The discussion will be on based the load-deflection response, effect of *a/d* ratio and crack patterns of the recycled specimens compared to conventional specimens. Eventually, the shear capacity of the specimens will be compared with the predicted shear capacity by existing codes, such as ACI 318, Eurocode-2 and AS3600 (ACI Committee, 2005; Eurocode, 1992; Australia Standard, 2009).

Load Deflection Response

Table 4 shows the mid-span deflection at first crack (δ_c) and ultimate failure (δ_u), shear force at the first crack (V_c) and ultimate failure (V_u). The comparison is explained in terms of maximum mid-span deflection and ultimate shear force of the recycled specimen compared to the conventional specimen for each *a/d* ratio, which is denoted as deflection ratio (DR) and ultimate shear ratio (VR) respectively. It also shows the ductility (δ_u/δ_c) and reserve strength (V_u/V_c) of the specimens. The results reveal that the recycled specimens perform well in deflection control and have slightly better shear capacity compared to conventional specimens at *a/d* ratios 1.5 onwards and are stable at approximately 0.61 (DR) and 1.01 (VR). On the contrary, their performance in deflection control and shear capacity show a significant drop at *a/d* ratio 1.0. It is noted that the ductility and reserve strength of the recycled specimen are generally lesser than the conventional specimen at *a/d* ratio 1.5 onwards with a corresponding difference of 35.51% and 44.89% respectively. Nevertheless, the recycled specimens present positive ductility and reserve strength at *a/d* ratio 1.0.

TABLE 4
Summary of Test Results

Specimens Notation	δ_c (mm)	δ_u (mm)	V_c (kN)	V_u (kN)	DR	VR	δ_u/δ_c	V_u/V_c	Mode of failure
CB1.0	0.76	9.84	32.41	113.66	1	1	12.95	3.51	Shear
RB1.0	0.71	13.93	26.27	99.46	1.42	0.88	19.62	3.79	Shear
CB1.5	1.1	25.05	23.11	63.51	1	1	22.77	2.75	Flexural-Shear
RB1.5	0.6	15.48	21.26	64.41	0.62	1.01	25.80	3.03	Flexural-Shear
CB2.0	1.1	23.07	18.51	44.24	1	1	20.97	2.39	Flexural-Shear
RB2.0	0.86	13.82	19.15	45.03	0.60	1.02	16.07	2.35	Flexural-Shear

Fig.2 records the load-deflection curves. Generally, the slopes in the elastic region are identical and close to each other for all the specimens and have subsequently undergone the plastic region before failure. Under the same concrete mix, the decrease in *a/d* ratio has led to a steeper slope. The phenomenon can be explained as the specimens become stiffer to sustain the greater load and are enhanced in deflection control when the load is closer to the support. Furthermore, the curve for the recycled specimens climbs closely to the curve for the conventional specimens with slightly better performance in load carrying capacity except for specimens in *a/d* ratio 1.0. CB1.5 and CB2.0 reach shear force 35.04 kN and 25.08 kN at reinforcement yield and RB1.5 and RB2.0 are 11.74% and 15.67% better off. However, RB1.0 only reaches approximately 62% shear force at reinforcement yield (84.09 kN) of the CB1.0. Meanwhile, the mid-span deflection of the specimens are discussed and compared at the yield load. The recycled specimens demonstrate a reduction in deflection at 7.18%, 27.05% and 32.34% for *a/d* ratios 2.0, 1.5 and 1.0 respectively compared to the conventional specimens. In other words, the recycled specimens show significant improvement in deflection as *a/d* ratios decrease.

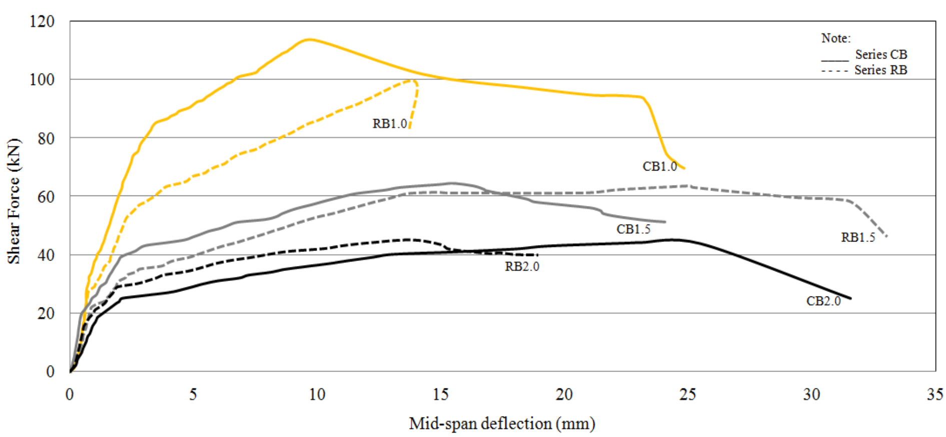

Fig.2: Load deflection curves

Effect of a/d

Fig.3 shows the ultimate shear force and mid-span deflection for different *a/d* ratios. It can be observed that the ultimate shear force decline substantially and then steadily as the *a/d* ratio increases. The ultimate shear force of the conventional specimen outweighs the recycled specimen in lower *a/d* ratio however, is overtaken by the recycled specimen in minimal gap after *a/d* ratio 1.5. With regards to the maximum mid-span deflection, the conventional specimen exhibit considerable growth in lower *a/d* ratio and falls gradually after *a/d* ratio 1.5. Whereas, the recycled specimens show maximum mid-span deflection stabilizing at approximately 14 mm for the entire *a/d* ratio. It is essential to point out that the linear variation in Fig.3 is insufficient to represent the actual variation due to limited data in the experiment.

Crack Patterns

Fig.4 demonstrated the crack patterns for all the beam specimens. In specimen CB1.0, first shear crack occurred at the left support followed by flexural crack at the bottom mid span of the specimen. With increment of applied loads, the shear crack elongated diagonally within the shear span while a series of minor flexural cracks distributed evenly along the tension zone and propagated vertically towards the compression zone of the specimen.

The specimen failed abruptly with a diagonal shear crack splitting the concrete at angle approximately 51^{o}. RB1.0 exhibited similar crack formation as CB1.0 but failed in crush at the left hand side load under shear and compression stress.

On the contrary, specimens CB1.5 and RB1.5 presented their first flexural cracks at the mid span and subsequent minor flexural cracks developed towards the supports. As the applied loads increased, shear cracks formed diagonally within the shear span and sudden crush happened at the middle top of the specimens. Specimens CB2.0 and RB2.0 demonstrated the same crack patterns but nevertheless showed lower load-carrying capacity. Basically, recycled concrete specimens demonstrate smaller crack widths and larger gaps in flexural cracks, otherwise show similar mode of failure compared to the conventional specimens in the same *a/d* ratio.

Two general modes of failure, mainly shear and flexural-shear that were observed in the experiment are shown in Table 4. Both recycled and conventional specimens fail in similar mode under the same *a/d ratio.*

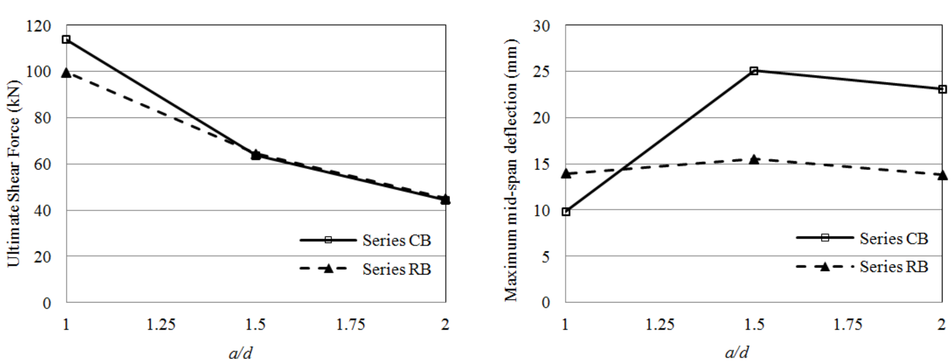

Fig.3: Ultimate shear force and mid-span deflection for different *a/d*

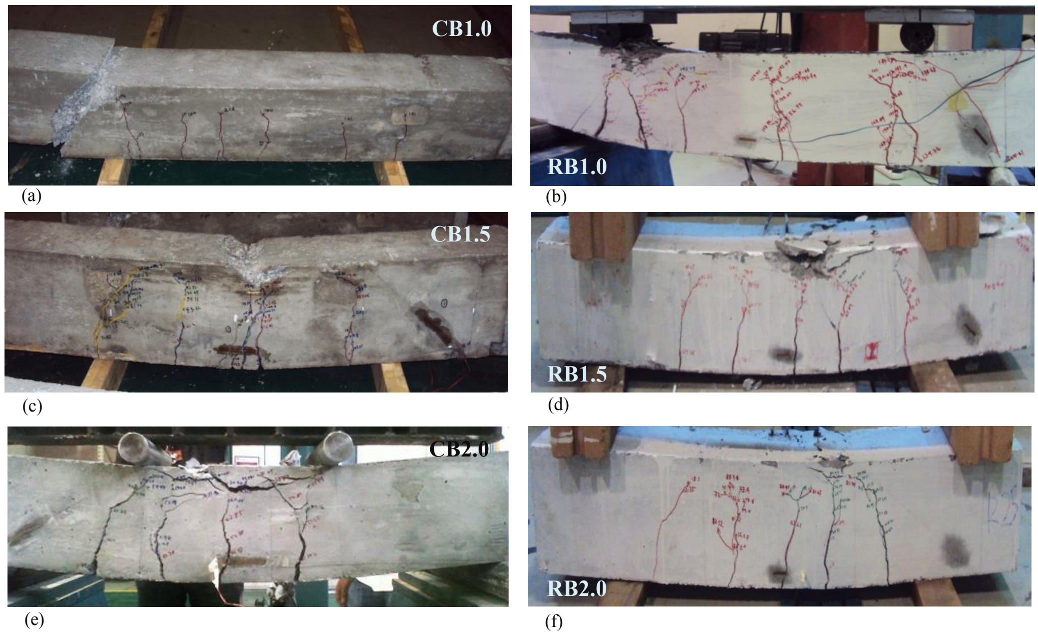

Fig.4: Crack patterns of beam specimens

Experimental and predictions of the concrete shear capacity (kN)

Table 5 shows the recommended expressions for determining shear capacity of beams in existing codes while Table 6 summarizes the comparison between the experimental shear and predicted shear by existing codes. Regardless the different procedures in each existing codes, the code Eurocode-2 gives the most conservative prediction on the shear capacity of the beams followed by the code AS3600 and thereafter ACI 318. It can be observed that ACI 318 and AS3600 predict well for both recycled and conventional specimens in *a/d* ratio 2.0 yet still remain conservative with ratios less than 1.7. Nonetheless, all the predictions in the existing codes show a divergence of up to 5.78 from the experimental shear as the *a/d* ratio decreases.

TABLE 5
Recommended Expressions for Determining Shear Capacity of Beams in Existing Codes

Code	Recommended expression	
ACI-318	Clause 11.3	$V_c = \frac{\sqrt{f_c'}}{6} b_w d$
Eurocode-2	Clause 6.2.2	$V_c = \left[\frac{0.18}{\gamma_c} k\left(100\rho_s f_c\right)^{\frac{1}{3}}\right] b_w d \geq \left(0.035 k^{\frac{3}{2}}\sqrt{f_c'}\right) b_w d$ $f_c' \leq 100\text{MPa}\ k = 1 + \sqrt{\frac{200}{d}} \leq 2.0, \rho_s = \frac{A_s}{b_w d} \leq 0.02$
AS3600	Clause 8.2.7.1	$V_c = \beta_1 \beta_2 \beta_3 b_w d_o \left[\frac{A_{st} f_c}{b_w d}\right]^{\frac{1}{3}}$ $\beta_1 = 1.1\left(1.6 - \frac{d_o}{1000}\right) \geq 1.1;\ \beta_2 = \beta_3 = 1$

TABLE 6
Comparison between Experimental Shear and Predicted Shear by Existing Codes (kN)

Specimens Notation	Experimental Shear	ACI 318	Eurocode-2	AS3600
CB1.0	113.66	31.24 (3.64)	19.68 (5.78)	27.99 (4.06)
RB1.0	99.46	29.39 (3.38)	18.90 (5.26)	26.87 (3.70)
CB1.5	63.51	31.24 (2.03)	19.68 (3.23)	27.99 (2.27)
RB1.5	64.41	29.39 (2.19)	18.90 (3.41)	26.87 (2.40)
CB2.0	44.24	31.24 (1.42)	19.68 (2.25)	27.99 (1.58)
RB2.0	45.03	29.39 (1.53)	18.90 (2.38)	26.87 (1.68)

CONCLUSIONS

The paper presents the results of an investigation on the shear capacity of high strength reinforced concrete beam specimens with 25% recycled concrete coarse aggregates. Based on the experimental results, the following conclusions are drawn:

1. Concrete mix with utilization of 25% 25-30 MPa non-aggressive exposure coarse RCA achieved comparable compressive strength as the conventional concrete mix. Both were mixed with optimum proportion of 1:1.1:2.1 and *w/c* 0.41 yielded high strength concrete grade ranging at 65-74 MPa.
2. Recycled specimens demonstrated lower shear capacity in *a/d ratio* 1.0 otherwise performed quite similarly as the conventional specimens as the *a/d* ratio increased. Nonetheless, the recycled specimens presented good ductility and reserve strength at *a/d* ratio 1.0.
3. Although maximum mid-span deflection reached a peak at *a/d* ratio 1.5 for both recycled and conventional specimens, conventional specimens showed an upward trend as *a/d* ratio increased whereas all the recycled specimens stabilized at approximately 14 mm.
4. Both recycled and conventional specimens failed in shear in *a/d* 1.0 and flexural shear in *a/d* ratio 1.5 and 2.0. Smaller crack width and larger spacing in the flexural cracks were discovered in recycled concrete specimens.
5. Existing codes ACI 318, Eurocode-2 and AS3600 can be used in shear design for the recycled specimens with 25% coarse RCA, however the shear capacity for both conventional and recycled specimens is conservatively predicted especially when *a/d* ratio increases.

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