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Performance of deep beams made by moderate strength concrete with recycled concrete aggregate

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ملخص البحث

يهدف البحث لأستنباط من النتائج المعمليه تصرف الكمرات الخرسانيه العميقه المستخدم في خلطتها الخرسانيه الركام المعاد تدويره من الخرسانه سواء كان ركام كبير أو ركام صغير. تم أختبار عدد ستة كمرات عميقه بأبعاد 20سم عرض و70سم عمق و80 سم طول خالص ذات مقاومة خرسانيه 40 نيوتن/مم2.تحت حمل مركز في منتصف الكمره. الكمره الأولي تم أستخدام ركام طبيعي فقط فيها, تم أستبدال نسبه من الوزن للركام الكبير الطبيعي بالركام الكبير المعاد تدويره من الخرسانه 20,30,40% في الكمرات الثلاث التاليه و تم أستبدال نسبه من الوزن للركام الصغير الطبيعي بركام الصغير المعاد تدويره من الخرسانه 20,30% في الكمراتين الأخيرتين. تم دراسه تأثر من ناحية الحمل والأنحناء ,عمق الشروخ و الممطوليه في القص.ولقد وجد أن المقاومة القصوي للخرسانة تقل بأستخدام الركام الصغير المعاد تدويره ويكون الأنهيار حاد, بينما استخدام الركام الكبير المعاد تدويره تسبب في زيادة المقاومه القصوي للقص وكان الأنهيار مصطحب بممطوليه تم مقارنة النتائج مع الكود الأمريكي وأظهرت النتائج توافق كبير مع ال ACI 318-14, ACI 318-19 .

ABSTRACT

This paper is aimed to investigate experimental results on the shear behaviour of reinforced concrete (RC) deep beams without and with coarse or fine recycled concrete aggregates (RCA). Six large scale deep beams made of 40 MPa. concrete were tested the first one was a control beam with only natural aggregates , three beams with replaced percentage of coarse aggregates by coarse recycled concrete aggregates(RCA) with percentages (20,30,40%), and two with replaced percentage (20,30%) of fine aggregates by fine (RCA). The beams had depth 700 mm, clear span 800mm, and width 200 mm were tested to understand the effect of recycled concrete aggregates on the behaviour of deep beams including load-deflection curves, crack width, and shear ductility had been investigated. The beams tested under three-point loading failed in shear and failure modes were influenced by the beam type and amount of recycled concrete aggregates. The shear strength was found to decrease with using fine recycle concrete aggregates exhibited brittle failure, which was attributed to decrease of compressive strength. Using coarse concrete recycle aggregates in beams turned brittle failure in to ductile and increase shear strength of beams. The widths of shear crackes increase at failure with using coarse recycle concrete aggregates. With increased percentage of coarse concrete recycle aggregates is offered to sustain greater crack widths. Shear ductility (= capability of withstanding severe cracking and deformation) decreases in deep beams with fine recycle concrete aggregates and increases in deep beams with coarse recycle concrete aggregate. Significant reserve strength beyond diagonal cracking was observed in deep beams. The results were compared with ACI 318-99, and STM method in ACI 318-14 and ACI 318-19 as shows very good agreement.

Keywords: Deep Beam; reinforced concrete; Recycled Concrete Aggregate; Shear ductility; Shear strength.

INTRODUCTION

Construction and Demolition waste constitutes a major portion of total solid waste production in the world, and most of it is used in landfills. Research by concrete engineers has clearly suggested the possibility of appropriately treating and reusing such waste as aggregate in new concrete. Recycling is the act of processing the used material for use in creating new product.

Deep beams are classified as nonflexural members, in which plane sections do not remain plane in bending. Therefore, the principles of stress analysis developed for slender beams are neither applicable nor adequate to determine the strength of deep beams. An important characteristic of deep beams is their high shear strength. The greater shear strength of deep beams is due to internal arch action, which transfers the load directly to a support through concrete struts. The reinforcement acts as a tie and, hence RC beams are analogous to steel trusses. Deep beams are also classified as disturbed regions, which are characterized by nonlinear strain distribution. Elastic solutions of deep beams provide good description of their behaviour before cracking. However, after cracking major redistribution of strains and stresses takes place and the beam strength must be predicted by nonlinear analysis. For a simple deep beam with concentrated load on top, the top load and bottom reactions create large compressive stresses at a right angle to beam axis. These stresses interact with shear stresses to form complicated stress field in the web. Because of short horizontal distance between top and bottom load points i.e. small a/d ratios, the effect of such stresses result in arch action unique in deep beams. Because of these complexities, study of deep beams has become a special interest. Over the years various models have been proposed by many researchers and extensive test campaigns have been carried out.

LITERATURE REVIEW

Ajdukiewicz and Kliszczewicz [5] studied the structural behavior of beams and columns made with different ratio of coarse and fine recycled concrete aggregate as a replacement .They conclude that load-bearing capacity of beams made with (RCA) was smaller in average of 3.5% in case of flexural failure, they also find that (RCA) beams showed greater deformation at mid span (a bout 18%) as compared with beams made with

natural concrete . Zsutty [6] classified beams failing in shear into major categories :

1-Slender beams ($a/d > 2.5$) for which the shear strength

(Vu) is given by : $V u = 2.17(f'c \rho d/a)^{1/3}$

2-Short beams ($a/d < 2.5$) with the direct loading conditions. The shear strength is given by: $V u = 5.43(f'c \rho d/a)^{1/3} (d/a)^{4/3}$

.

The study on deep beams has been an interesting topic by varying the parameters. However, some studies have been reported on the investigations on the behaviour of deep beams in shear recently. As for the definition of deep beams, ACI 318 defines deep beams as those loaded on one face and supported on other face and the shear span-to- depth ratio is less than or equal to two. Due to their geometric proportions deep beams fail in shear. A disturbance in internal stresses is caused by shear action with compression in one direction and tension in the perpendicular direction. This leads to an abrupt shear failure of beam as the beam depth increases .Yang and Chung[4]. The

development of crack pattern is much faster than small size deep beams and then leading to sudden failure. Bakir and Boduroglu,
[3].Several modifications have been incorporated in the shear design of deep beams in the codes of practice. ACI 318-14[2]. and Commentary (ACI 318R-14) consider the contribution of concrete, percentage longitudinal and transverse reinforcement, shear span-to-depth ratio for estimating the shear strength of deep beams. Failure in deep beams is generally due to crushing of concrete in either reduced region of compression zone at the tip of inclined cracks or by fracture of concrete along the crack. In deep beams with shear span-to-depth ratio 2.5, there seems to be some reserve strength in the post-cracking region, resulting in relatively less brittle in nature, Khaldoun [7]. Therefore, to estimate the reserve strength and ductility of deep beams in shear, the influence of various parameters need to be investigated. Raghu et al. [8] conducted a comprehensive experimental and technical investigation to assess the concrete component of shear resistance in beams made of high strength concrete(HSC). The experimental program consists of testing of 24 beams, with and without shear reinforcement, to determine the contribution of concrete to shear strength. The data from the experimental observations and literature were compared with shear provisions in codes of practice. When extrapolated the current provisions for shear resistance of HSC, the safety margins for structural designs are reduced. Angelakos et al[9] reported on tests of 21 large RC beams in shear. It has been revealed that concrete strength is the most important parameter influencing shear stress at failure and the longitudinal reinforcement has only negligible effect. The shear stress at failure decreases substantially as member size increases and as the longitudinal reinforcement ratio decreases. Yang et al. [4] tested twenty one beam specimens to investigate the shear characteristics with various variables such as concrete strength, shear span-to-depth ratio, and beam depth. It has been found that decrease in shear span- to-depth ratio and increase in beam depth at a shear span-to-depth ratio resulting in more brittle failure with wide diagonal cracks and high energy release rate related to size effect. Also, HSC deep beams exhibited more remarkable size effects with brittle behaviour.

RESEARCH SIGNIFICANCE

Objective of the work described in this paper is to investigate the structural behavior of concrete made with recycled concrete aggregate (RCA) as a partial replacement of coarse or fine aggregate in moderate strength concrete deep beam.
The behaviour of RC deep beams is governed mainly by shear strength. The shear strength of deep beams seems to be significantly greater than that of the slender beams due to redistribution of internal stresses. Several parameters affect the strength of RC beams in shear, which include shear span-to-depth ratio, concrete strength, anchorage of reinforcement into the supports, size effect, amount and arrangement of tensile and web-reinforcement. The design codes are developed from experimental test results using low strength concrete and on RC beams. Thus, it is necessary to investigate the shear behavior of deep beams with moderate strength concrete and studying the effect of using moderate concrete with fine or coarse recycled concrete aggregate (RCA) on deep beam behavior.

EXPERIMENTAL PROGRAM

Materials

Concrete used for this program was designed to achieve compressive strength of 40MPa. for the control beam. Mix of the concrete used for achieving the required strength was using high strength Portland cement. Table 1 shows the constituent materials used for the concrete without and with recycled aggregates. The water cement ratio used was 0.4. Along with each set of RC deep beams, six companion plain concrete cubes of size 150x150x150mm were cast and tested to find the characteristic compressive strength of concrete. The coarse aggregate was 20mm maximum size aggregate Sand was naturally obtained. Coarse and fine recycled aggregates were prepared at the laboratory from previously reinforced concrete tested specimens The recycled concrete aggregates were incorporated in concrete as replacement by weight of natural aggregate, according to their size (that is, keeping the grading distribution constant in all mixtures). A total of six concrete mixtures were prepared. The recycled concrete beads sizes are shown in Figure 1. and Figure 2. Finally, the water-cement ratio (w/c) was kept constant in all mixtures as shown in Table 1...Potable water was used for mixing of concrete and curing purpose. Thesteel reinforcement consists of high strength deformed bars (diameter 16 mm) for longitudinal flexural reinforcement and longitudinal shear reinforcement (diameter12 mm) in all the beams 450MPa. The strength of stirrups (bars diameter 8 mm) was of 240MPa.

Table 1. Mix Design Proportion.

Material	Control Mix	Recycled Concrete Aggregate (RCA)Replacement Weight %				
		Coarse Recycled Concrete Aggregate			Fine Recycled Concrete Aggregate	
		20%	30%	40%	20%	30%
Cement (kg\m 3)	350	350	350	350	350	350
Natural Coarse Aggregate (kg\m 3)	1080	864	756	648	1080	1080
Natural Fine Aggregate (kg\m 3)	740	740	740	740	592	518
Coarse Concrete Recycled Aggregate (kg\m 3)	0	216	324	432	0	0
Fine Concrete Recycled Aggregate (kg\m 3)	0	0	0	0	148	222
Water (Liter/m3)	175	175	175	175	175	175

Fig. 1 Coarse Concrete Recycled Aggregates Sample

Fig. 2 Fine Concrete Recycled Aggregates Sample

Description of Beam specimens

There are six beams the control beam CB made only from natural aggregates. The beams with coarse recycled concrete aggregate replacement in percentages 20, 30, and

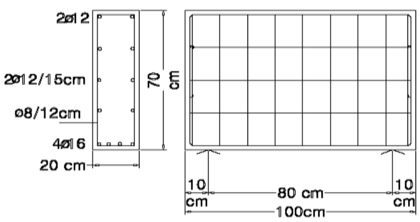
40% are nominated as CRCA20, CRCA30 and CRCA40 respectively. The beams with fine recycled concrete aggregates in percentages 20 and 30% replacement are nominated as FRCA20 and FRCA30. Classification of beam specimens is shown in Table 2. Details of specimens with reinforcement are represented in Figure 3.

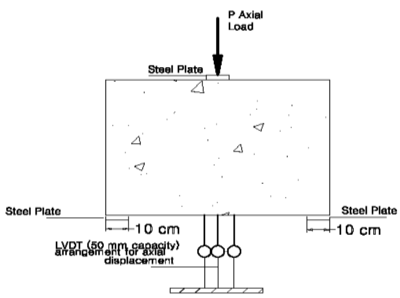
Table 2: Classification of Beam Specimens

Beam ID	Coarse Recycled Concrete Aggregates Replaced %	Fine Recycled Concrete Aggregates Replaced %
CB	0	0
CRCA20	20	0
CRCA30	30	0
CRCA40	40	0
FRCA20	0	20
FRCA30	0	30

Experimental setup and testing of beams

Six simply supported RC deep beams were tested up to failure under three-point loading. Each beam was loaded with a central concentrated load and supported on two simply supported ends. Ends of all beams were extended by 100 mm from the line of action of support reaction. Bearing plates of dimensions 100x200x20 mm were provided at the supports and below the point loading. All the beams were tested using 5000kN capacity compression testing machine. Three LVDTs was attached at the mid span to measure the deflection of beams under the point loading. At each displacement increment, the load applied on the beam, mid span deflection, maximum crack width in concrete was measured. Figure4 shows beam setup.





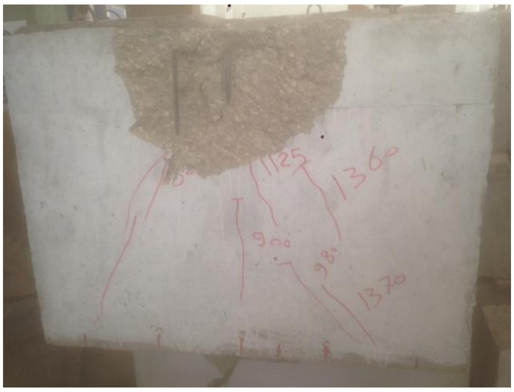
DISCUSSION OF RESULTS

Modes of Failure

All the beams tested under three-point loading failed in two modes of failure. Shear compression mode of failure, after the appearance of the inclined crack, the concrete portion in the top load point experience high compression and it then finally fails. This mode of failure is equally a brittle mode of failure as in beams CB, CRCA20,FRCA20, FRCA30. The second mode of failure appear is the diagonal-splitting failure, characterized as shear failure, is brittle, A critical diagonal crack joining the loading point at the top and support point at bottom is developed as in , CRCA30, and , CRCA40.

In all the beams, cracks started as flexural cracks, but no cracks were observed up to 60% of the ultimate load. In the range of load between 40-70% of the ultimate load a major diagonal tension crack formed at the middle of shear span. With further increase in the applied load, new inclined cracks appeared within the shear span, their orientation being the same as that of the previously- formed major inclined cracks. Eventually, beam failure occurred due to crushing of concrete in either reduced region of compression zone at the tip of inclined crack or by the fracture of the concrete along the inclined crack. In all the beam failures, the inclined cracking pattern reveals a tied-arch action, with tension reinforcement acting as a tie rod and portion of beam between the inclined cracks as struts. The deterioration of concrete and cracking were symmetric just before failure.. As the percentage of coarse recycle concrete aggregate increase, the failure mode changes from Shear compression mode type to diagonal-splitting failure and the inclination of the diagonal crack was steeper. At failure only a major crack was widened. Typical crack pattern and modes of failure are shown in Figure 5.

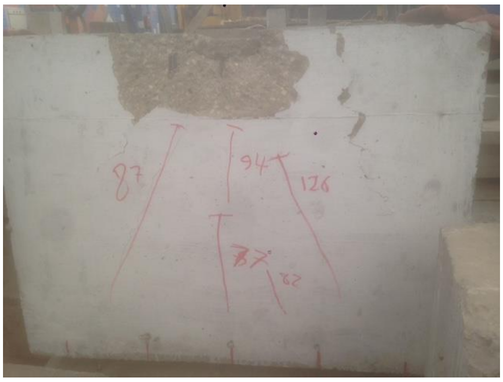
Control Beam

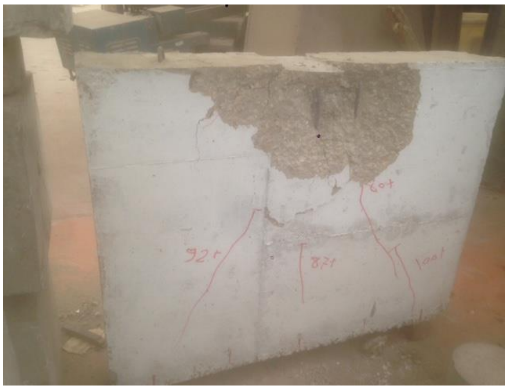


CRCA20 Beam

CRCA30 Beam

CRCA40 Beam





FRCA20 Beam **FRCA30 Beam**

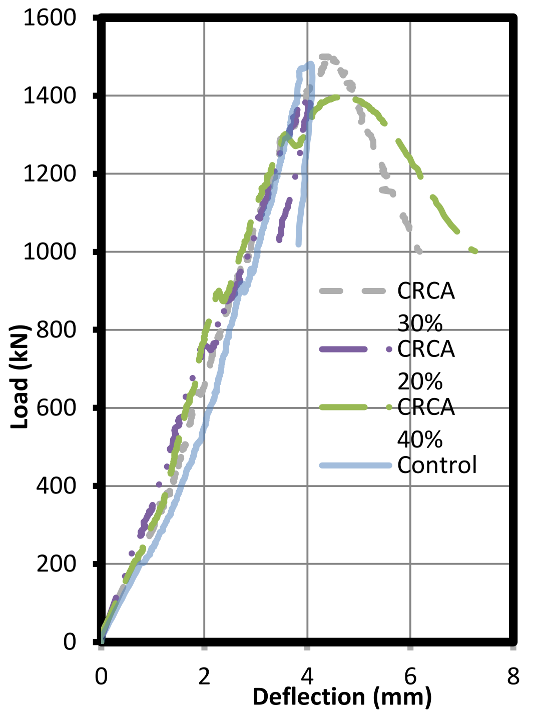
Fig. 5. Failure Mode and Crack Pattern o Beams

Load-Deflection Curves and Ultimate Strength

Figure 6a shows the load–deflection curves of beams control beam and beams with coarse recycled concrete aggregates. It has been observed that beams with coarse recycled concrete aggregates have higher or close value of deflection and shear strength at ultimate load to control beam, and their failure is relatively ductile than that of control beam. The shear strength increase in beam CRCA30 by negligible amount 1% and reduced by 3% for CRCA20 and CRCA40of control beam. From figure 6b it is clear that the failure of beams with fine recycled concrete aggregate seems to be indicating brittle failure and shows smaller deflection and shear strength Than control beam that attribute to decreasing in compressive strength in concrete with fine recycled concrete aggregates. The decrease in strength was 7% and 8% for FRCA30 and FRCA20 respectively.

Shear ductility

Though deep-beam failure is considered brittle in design provisions, under certain circumstances deep beams exhibit a reasonable ductility. To understand ductility of beams failing in shear, shear ductility is defined as the ratio of Ac/Au, where Au is the area under the load deflection curve up to ultimate load and Ac is the area under the load deflection curve for a beam up to its complete collapse. With certain limitations shear ductility can measure the ductility of RC beams failing in shear. It has been observed that shear ductility increases with increases contribution of coarse recycled concrete aggregates percentage in concrete mix. However, it has been observed that contribution of fine recycled concrete aggregates in beams exhibited pure brittle failure.



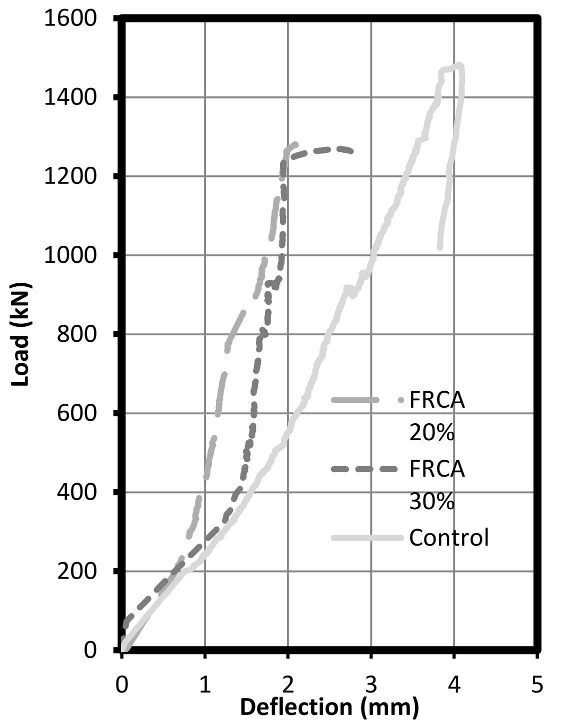


Fig.6a Load-Mid-Span Deflection for Control Beam and Beams at different percentage of Coarse Recycle Concrete Aggregate Replaced

Fig.6b Load-Mid-Span Deflection for Control Beam and Beams at different percentage of Fine Recycle Concrete Aggregate Replaced

Comparison of Experimental Results with code provisions

The ratio of experimental shear strength and those evaluated using ACI 318-99, Vu/VACI and Vu/STM are compared in all tested beams . It has been noticed that the shear strength provisions are more conservative for deep beams according ACI 318-99 than those of STM for ACI 318-14 and changes in ACI 318-19 [6].

EVALUATION ON CODE DESIGN FORMULAS FOR SHEAR

ACI 318-99 Section 11.8

In ACI 318-99 Code, the sectional shear strength of deep flexural member is calculated by combining the contributions of both concrete and distributed shear reinforcements. Ultimate shear strength by concrete and reinforcement are shown in from Eq. (1) to Eq. (3). The concrete contribution can be counted by Eq. (1) or Eq. (2).

$V\,c = 2\sqrt{fc'}b_w\,d$ (psi, in.) (Eq. 11-28) (1)

$V\,c = (3.5 - 2.5\frac{Mu}{Vud})(1.9\sqrt{fc'} + 2500\rho_w\frac{Vud}{Mu})b_w d \le 6\sqrt{fc'}\,b_w\,d$ (psi, in.) (Eq. 11-29) (2)

where *3.5-2.59*$(\frac{Mu}{Vud})$ is to be kept less than or equal to 2.5; and fc' = specified compressive strength of concrete; b_w = web width; *As*= area of nonprestressed tension reinforcement; *d* =distance from extreme compression fiber to centroid of longitudinal tension reinforcement; *Vu*=factored shear force at critical section; ρ_w = ratio of tension reinforcement; L_n = clear span; *a* = shear span; *Mu* = factored moment occurring simultaneously with *Vu* at the critical section.

The use of shear reinforcement is required whenever the factored shear force at the critical section
exceeds the shear strength by concrete. The contribution from the shear reinforcement is computed with Eq. (3).

$$V_s = [\frac{Av}{s}[\frac{1+\frac{Ln}{d}}{12}] + \frac{Avh}{s}[\frac{11-\frac{Ln}{d}}{12}]] f_y d \quad \text{(psi, in.) (Eq. 11-30) (3)}$$

where *Av* = area of shear reinforcement perpendicular to flexural tension reinforcement within a distance *s*; *Avh* = area of shear reinforcement parallel to flexural tension reinforcement within a distance *s2*.
The ACI 318-99 Code defines an upper limit for the shear strength of deep flexural members as shown in
Eq. (4).

$$V_n = \begin{cases} 8\sqrt{fc'}\, b_w d & \text{for } \frac{Ln}{d}<2 \\ 2/3\,[(10+\frac{Ln}{d}]\,\sqrt{fc'}\, b_w d & \text{for } 2 \le \frac{Ln}{d} \le 5 \end{cases} \quad \text{(Eq. 11-27) (4)}$$

In ACI 318-14 state that ultimate shear strength for Deep beam dimension be

$$V_u = \phi\, 10\, \sqrt{fc'}\, b_w d \quad (9.9.2.1) \quad (5)$$

ACI 318-14 Building Code Chapter 23 and Changes to the Concrete Design Standard ACI 318-19

ACI 318-14 code provides new approaches to the shear design of deep beam. In the Strut-and-Tie Model (STM) approach. STM consist of the struts, ties and nodal zones. The permitted stress of all struts, ties and nodal zones shall not exceed the limited value. The effective compressive strength of the concrete in strut and at face of nodal zone shall be taken as Eq. (5) and Eq. (6).

Strut : $f_{ce} = 0.85\, \beta\, s\, f_c'$ (psi) (Eq.(23.4.3)) (6)

Nodal zone : $f_{ce} = 0.85\, \beta\, n\, f_c'$ (psi) (Eq.(23.9.2)) (7)

where the value β *s* and β *n* range 0.4-1.0 and 0.6-1.0, respectively.
In case that concrete compressive strength is less than 6000 psi. crossing the strut, or required steel in same direction

$\Sigma\, Asi\, /\, bs\, si\ \sin\alpha i \geq 0.003$ (Eq.(23.5.3)) (8)

where A*si* is the total area of distributed reinforcement spacing S*i* in the *i*th direction of reinforcement crossing a strut at an angle α*i* to the axis of a strut, and b_s is the width of the strut.
Strength of strut

a) Strut without longitudinal reinforcement

$F_{ns} = f_{ce} A_{CS}$ (23.3.1a) (9)

b) Strut with Longitudinal reinforcement

$F_{ns} = f_{ce} A_{CS} + A_s' f_s'$ (23.4.1b) (10)

Where F_{ns} shall be evaluated at each end of the strut and taken as the lesser value, A_{CS} is the cross-sectional area at the end of the strut under consideration, A_s' is the area of compression reinforcement along the length of the strur; and $f_{s'}$ is the stress in the compression reinforcement at the nominal axial strength of the strut. It shall be permitted to take $f_{s'}$ equal to $f_{y'}$ for grade 40 or 60 reinforcement.

Comparison of test results with design formulas

A comparison between the measured and calculated shear strength for the tested specimens was carried out. The codes considered for the comparison are the ACI 318-99, and the STM of ACI 318-14 and changes in ACI 318-19, The material safety factors for concrete and steel reinforcement have been set to unity for comparison purpose. Table 3 shows the comparison. The shear design procedures of the ACI 318-99 underestimated the shear strength of deep beam. While the STM of the ACI 318-14 and ACI 318-19 gives good results This means that STM is recommended as a most desirable method because it has lowest standard deviation although its predicted shear strength is relatively higher than that of ACI 318-99.

Table 3 Summary of Experimental and predictions for ultimate shear strength of deep beams

Specimen	Comressive Strength f_{cu} (kN)	Cracking Load V_{cr} (kN)	Ultimate Load V_{ULT} (kN)	V_{ACI} (kN)	V_{STM} (kN)	V_{ACI}/ V_{ULT}	V_{STM}/ V_{ULT}
CB	40	850	1482	970	1422	0.65	0.96
CRCA20	40	900	1394	970	1422	0.7	1.02
CRCA 30	42	920	1499	983	1453	0.66	0.97
CRCA 40	40	890	1398	970	1422	0.69	1.02
FRCA 20	31	770	1281	933	1287	0.73	1
FRCA 30	29	800	1271	923	1256	0.73	0.99

CONCLUSIONS

1. The modes of failure in reinforced concrete deep beam are influenced by the type of aggregates used in concrete mix. However, using either natural aggregated or fine recycled concrete aggregates the failure seems to be due to shear-compression failure.

But using coarse concrete aggregates leads to diagonal-splitting failure

2. As the amount of coarse partially recycled concrete aggregate increase the shear ductility of beam increases, the crack width also increases.
3. It is not recommended to use fine recycled concrete aggregates as it reduces the compressive stress of concrete and consequently the shear strength of the deep beam with brittle failure. The decrease in strength was 7% and 8% for FRCA30 and FRCA20 respectively.
4. It is highly recommended to use coarse recycled concrete aggregate as it didn’t Influence the compressive stress of concrete and the shear strength of the deep beam, but Leading to ductile behavior.
5. ACI 318-99 shear strength provisions on deep beams are conservative, While the STM of the ACI 318-14 and ACI 318-19 provisions are appropriate for deep-beam design. As it gives good results This means that STM is recommended as a most desirable method because it has lowest standard deviation although its predicted shear strength is relatively high.

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