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Shear Behavior of Reinforced Concrete Beams Casted With Recycled Coarse Aggregate

Salah A Aly[1], Mohammed A Ibrahim[2] and Mostafa M Khttab[3]

[1]*Department of Reinforced Concrete Structures,*
Housing and Building National Research Center (HBNRC), Cairo, Egypt
[2] *Department of Reinforced Concrete Structures at Faculty of Engineering, Al-Azhar University, Cairo, Egypt*
[3] *Department of Civil Engineering Department, Faculty of Engineering, Al-Azhar University, Cairo, Egypt*
salahaly62@gmail.com

ABSTRACT

The amount of construction and demolition (C&D) waste has increased considerably over the last few decades. From the viewpoint of environmental preservation and effective utilization of resources, crushing C&D concrete waste to produce coarse aggregate (CA) with different replacement percentage for the production of new concrete is one common means for achieving a more environment-friendly concrete. In the study presented herein, the investigation was conducted in two phases. In the first phase, the selection of the materials was carried out and the physical, mechanical and chemical characteristics of these materials were evaluated. Different concrete mixes were designed. The investigation parameter was Recycled Concrete Aggregate (RCA) ratios. The mechanical properties of all mixes were evaluated based on compressive strength and workability results. Accordingly, two mixes have been chosen to be used in the next phase. In the second phase, the study of the structural behavior of the concrete beams was developed. Sixteen beams were casted to investigate the effect of RCA ratios, the shear span to depth ratios and the effect of different locations and reinforcement of openings on the shear behavior of the tested specimens. All these beams were designed to fail in shear. Test results of the compressive strength of concrete indicated that, replacement of natural aggregate by up to 50% recycled concrete aggregates in mixtures with 350 Kg/m3 cement content led to increase of concrete compressive strength. Moreover, the tensile strength and the modulus of elasticity of the specimens with RCA have very close values to those with natural aggregates. The ultimate shear strength of beams with RCA is very close to those with natural aggregates indicating the possibility of using RCA as partial replacement to produce structural concrete elements. The validity of both the Egyptian Code for the design and implementation of Concrete Structures (ECCS) 203-2007 and American Concrete Institute (ACI) 318-2011Codes for estimating the shear strength of the tested RCA beams was investigated. It was found that the codes procedures gives conservative estimates for shear strength.

Key words: Construction and demolition (C and D) waste, Coarse aggregate (CA), Recycled coarse aggregates (RCA) and Opening

INTRODUCTION

The amount of C&D waste has increased considerably over the last few years. The heaviest materials found in C&D waste are rocks, concrete and ceramic residues. Nowadays, almost all demolished concrete has been mostly dumped to landfills. From the viewpoint of environmental preservation and effective utilization of resources, the interest in using recycled materials derived from C&D waste is growing all over the world. Crushing C&D concrete waste to produce CA with different replacement percentage for the production of new concrete is one common means for achieving a more environment-friendly concrete. This reduces the consumption of the natural resources as well as the consumption of the landfills required for waste concrete. Completed and repeated concrete recycling have recently become important aspects of the construction industry. Since concrete composes only of cementations materials and powders generated during the production of recycled aggregate which can be reprocessed as cement resources, this permits repeated recycling in a fully-closed system. Concrete recycling can be accomplished by reusing concrete products and then processed into secondary raw materials as filling materials, road bases and sub bases, or aggregate for the production of new concrete. The reuse of crushed C&D concrete waste to produce CA for the production of high-grade concrete has up to now been restricted by a lack of standards, experience, and knowledge. It would require extensive and prohibitively expensive screening and testing of the recycled material to produce recycled aggregate that would potentially meet the technical specifications and performance expectations for structural concrete. However, laboratory research and experience at several at recent projects have proven that it is feasible to use recycled concrete as aggregate for new concrete mixtures.

RESEARCH SIGNIFICANCE

The aim of the present study is to:

- Investigating the applicability of using RCA as a partial replacement of CA to produce structural elements.
- Evaluating the effect of RCA ratios, the shear span to depth ratios and openings with different locations and reinforcement on the shear behaviour of the tested specimens.
- Assessment of the adequacy of the Egyptian ECCS 203-2007 and ACI 318-2011 Codes provisions for predicting the shear strength of recycled aggregate concrete beams.

EXPERIMENTAL PROGRAM

The experimental work was developed in two phases. In the first phase, the physical, mechanical and chemical characteristics of the selected materials were carried out and different concrete mixes were designed. According to the mechanical properties (compressive strength and workability) two mixes have been chosen to be used in the next phase. In the second phase, sixteen beams were casted to investigate the effect of RCA ratios, shear span to depth ratios and different locations and reinforcement of openings on the shear behaviour of these specimens.

THE FIRST PHASE

Materials: Tests to determine the properties of the materials used were carried out according to the Egyptian Standard Specifications (ESS) or American Society for Testing and Materials (ASTM) standards.
The Cement: used in this investigation was CEM I 42.5 N. Testing of cement was carried out as the ESS 2421/2005. The used cement complies with the ESS 4756-1/2007.
Water: Clean tap drinking water was used in all mixtures.
Reinforcement Steel: Deformed high grade steel bars of 12 mm diameter were used as longitudinal tension reinforcement. The top reinforcement and the stirrups used were mild steel bars of 8 mm and 6 mm diameter, respectively. The mechanical properties of the steel comply with the ESS 262/2000 as shown in Tables 1, 2 and 3 respectively. [3]

Table - 1 Mechanical Property of 12 mm Steel Bars

Property	Results	Specifications Limits*
Yield stress (N/mm2)	420	Not less than 400
Ultimate stress (N/mm2)	650	Not less than 600
Weight per meter length	0.891	From 0.845 to 0.934
Ultimate stress/ Yield stress	1.55	Not less than 1.05
Elongation %	11.00	Not less than 10

* Limits of ESS 262/2000

Table - 2 Mechanical Properties of 8 mm Steel Bars

Property	Results	Specifications Limits*
Yield stress (N/mm2)	285	Not less than 240
Ultimate stress (N/mm2)	425	Not less than 350
Weight per meter length	0.389	From 0.364 to 0.427
Ultimate stress/ Yield stress	1.49	Not less than 1.1
Elongation %	29	Not less than 20

* Limits of ESS 262/2000

Table - 3 Mechanical Properties of 6 mm Steel Bars

Property	Results	Specifications Limits*
Yield stress (N/mm2)	345	Not less than 240
Ultimate stress (N/mm2)	439	Not less than 350
Weight per meter length	0.22	From 0.205 to 0.240
Ultimate stress/ Yield stress	1.27	Not less than 1.1
Elongation %	27	Not less than 20

* Limits of ESS 262/2000

Table – 4 Physical Properties of FA

Property	Results	Limits*
Specific Weight	2.63	-------
Bulk Density (t/m3)	1.78	-------
Clay and Fine Dust Content (% By Volume)	1.2	Not more than 4

* Limits of ESS 1109/2002

Fine Aggregate (FA): Natural sand composed of siliceous materials was used as FA in this study. Testing of sand was carried out according to the ESS 1109/2002. Table 4 shows the physical properties of the sand. The sand grading is given in Table 5 and Fig. 1.

Table – 5 Grading of FA

Sieve Size (mm)	10	5	2.36	1.18	0.6	0.3	0.15
Passing %	100	97.2	89.5	72.1	38.9	10.3	3.2

Table – 6 Grading of NCA

Sieve Size (mm)	50	37.5	20	14	10	5
Passing %	100	100	100	100	78.3	6.26

Coarse Aggregate: Both natural coarse aggregate (NCA) and RCA were used in this study.

NCA: Natural gravel was used in this study. Testing of NCA was carried out according to the ESS 1109/2002. Mechanical and physical properties of the NCA comply with both ESS 1109/2002 and the ECCS 203-2007. The NCA grading is given in Table 6 and Fig. 2. [1]

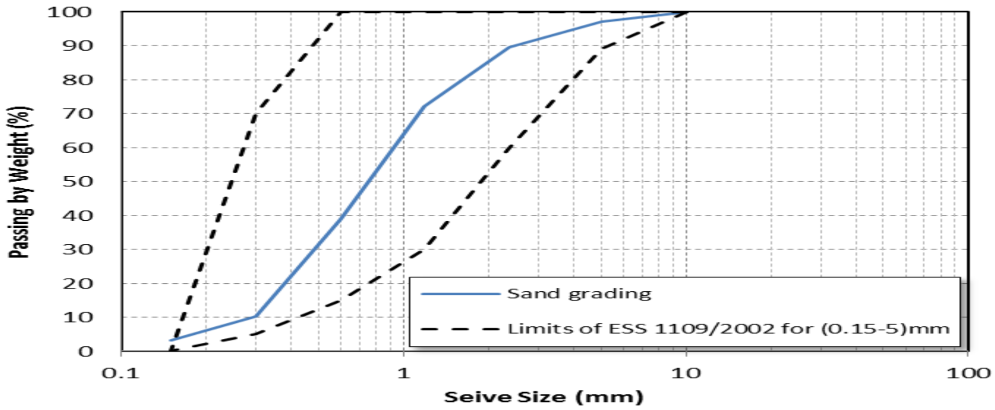


Fig. 1 Grading of Fine Aggregate

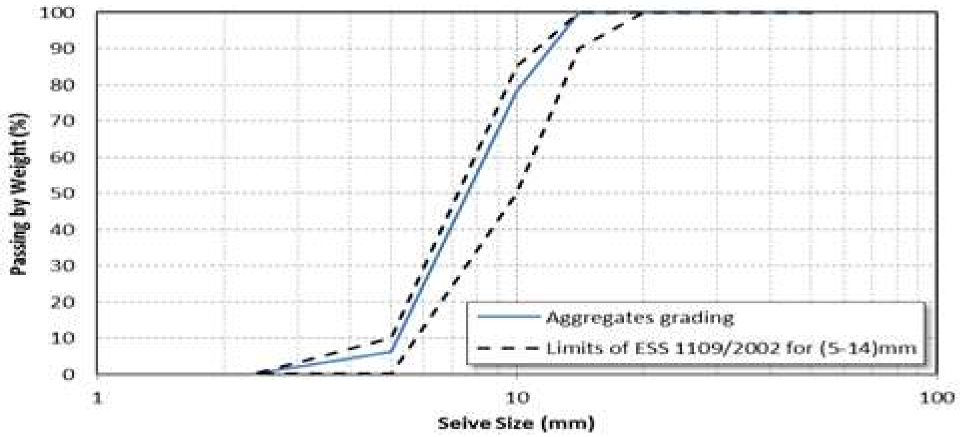


Fig. 2 Grading of NCA

RCA: The recycled coarse aggregates used in this study were produced by crushing the old concrete elements that were used in previous laboratory tests. The crushed concrete has been screened using the sieve analysis method. Testing RCA was carried out according to the ESS 1109/2002. The physical, mechanical and chemical properties of the RCA are shown in Tables 7 and 8. It was observed that the density, water absorption ratio and Los Angeles abrasion were the properties having the highest differences in comparison with natural aggregate. This may be attributed to the adhered mortar as reported by many other researchers. [2]

Table - 7 Physical and Mechanical Properties of RCA

Property	Results	Limits
Specific Weight	2.38	------
Bulk Density (t/m3)	1.4	------
Water Absorption %	5.3	Not more than 2.5**
Clay and Fine Dust Content%	0.33	Not more than 4*
Abrasion Index %	41.93	Not more than 30*
Impact Value %	---	Not more than 45*

* Limits of ESS 1109/2002 ** Limits of ECCS 203/2007

Table -8 Chemical Properties of RCA

Compound	Oxides Contents (%)
Silica Oxide SiO2	65.03
Aluminum Oxide Al2O3	0.87
Ferric Oxide Fe2O3	0.6
Calcium Oxide CaO	12.31
Magnesium Oxide MgO	5.28
Sodium Oxide Na2O	0.09
Potassium Oxide K2O	0.89
Titanium Oxide Ti O2	0.02
Phosphorus Oxide P2O2	0.01
Loss on Ignition (L.O.I)	14.33

Table-9 Mix Design Proportion Ratios

Designation	W/C	C Kg/m^3	W (Kg)	FA (Kg)	CA (Kg)	
					NCA	RCA
M1 (M-0%-350)	0.5	350	175	680	1360	-
M2 (M-25%350)	0.5	350	175	680	1020	340
M3 (M-50%350)	0.5	350	175	680	680	680
M4 (M-75%350)	0.5	350	175	680	340	1020

Concrete Mixes: Four concrete mixes have been designed using the empirical method. All mixes have fine aggregates to coarse aggregates ratio of (0.4:0.8). Water/cement ratio was 0.5 for cement content 350 Kg/m^3. As seen in Table 9 the mixes were designated in the form (M-%RCA-C) where: M, refers to mix. %RCA refers to recycled aggregates replacement percentage of coarse aggregates. C, refers to cement content (Kg/m^3). [4]

Mixing Procedure: Due to high absorption of the RCA, it must be wet before its use in concrete. If the RCA is not humid, it would absorb water from the paste thus losing both its workability in the fresh concrete and also the control of the effective w/c ratio in the paste. In this study, recycled coarse aggregates were wetted the day before they were used and were covered with a plastic sheet in order to maintain their humidity. Mixing was done in a small rotary drum. In the first step of the mixing, the fine and coarse aggregates were dry mixed for 30 seconds. The second step consisted of adding the cement and a further dry mixing of materials for 30 seconds. The third step consisted of adding water to the cement and aggregate mix and mixing for 2 minute before the mixing machine was stopped. Concrete mixes (M1 and M3) were chosen to present concretes with 0%, and 50%RCA ratios. These two mixes were used in casting the reinforced beam specimens. [7]

Tests of Concrete Mixes: Compressive strength and slump tests were conducted for preliminary concrete mixes in order to select three mixes to be used in the reinforced beam specimens taking into consideration compressive strength and economical aspects. In order to evaluate the selected mixes characteristics, both fresh and hardened concrete tests were conducted. Slump test was carried out in the fresh concrete state. Compressive strength test was carried out in the hardened concrete state.

Fresh Concrete Test: Slump test was carried out according to the ESS 1658/2006.

Hardened Concrete Tests: Compressive strength test was carried out according to the ESS 1658/2006. Cubes specimens (150x150x150 mm) were tested to evaluate concrete compressive strength at test ages of 7 and 28 days.

THE SECOND PHASE

The main aim of the this phase is evaluating the effect of different parameters on the structural behaviour of simply supported reinforced concrete beams made from RCA, with different proportions of RCA, in comparison with beams made from NCA.

Test Specimens: The experimental work in this phase consisted of sixteen beams with the same dimensions, longitudinal and transverse reinforcement. All specimens were designed to experience shear mode failure ensuring that the theoretical flexural strength is considerably higher than the expected experimental shear load. The tested specimens have the same concrete mix composition but with different replacement percentage of RCA (0, 25, 50 and 75%). The loading systems were the same in all specimens, but with variable shear span. All specimens had rectangular cross section of 150 mm width and 350 mm thickness, a total length of 2250 mm and were simply supported with a span length of 2000 mm, as shown in Fig. 3. The longitudinal bottom and top reinforcement of all specimens was 3Ø12 and 2Ø8, respectively. All specimens had the same transverse reinforcement of 5Ø6/m.

The tested specimens were divided into four groups (G1 to G4) depending on the studied parameters. The first group was designed to study the effect of different replacement percentage of RCA while the second group was designed to study the effect of shear span. The third and fourth groups were designed to study the effect of location of opening and reinforcement configuration around the opening, respectively. The details of the tested specimens for the fourth groups were illustrated in Table 10 and Fig. 5.

Instrumentation: The specimens were instrumented with a variety of sensors to measure the strains, deflections, the load and stroke of the testing machine. The concrete strain was measured using two horizontal pi-gauges which were attached horizontally to the concrete surface with a gauge length of 200 mm. The pi-gauge was located at the level of tension and compression reinforcement at the mid-span (between the two supports). Five linear variable distance transducers, LVDT's, with stroke 100 mm were attached vertically at equal distance through the interior span (between the two supports) to the bottom surface of the beam to measure and monitor the deflection in the beam. The steel strain was measured using electrical resistance strain gauge which attached to the bottom longitudinal steel bars and stirrups before casting the concrete. At the point of load application, a 1000 kn compression load cell monitored the applied load. A data acquisition system connected to a personal computer recorded all of the instrumentation readings. The formation and propagation of cracks at different locations were also marked and recorded. [9]

Test Setup and Procedure: All beams were tested until failure under monotonic increasing static load using a hydraulic actuator of 1000 kn capacity to measure its maximum load capacity. The beams were positioned under the actuator that was mounted on a steel reaction frame. The hydraulic actuator, load cell and the control vertical LVDT were positioned at the mid-span section. Three different loading types were used according the studied parameters. A very rigid steel beam and neoprene pads were used to distribute the load on the top surface of the beam. The test specimens were simply supported beams with 2000 mm span. The beams were tested with a monotonic increasing load (two point loads) until complete failure took place. The locations of loading points were variable, depending on the shear span of each group. After each load increment, strain readings, deflections and the load were recorded and any visible cracks were marked. The loads were controlled by servo controller and measured with load cell. [15]

Table – 10 Details of the Tested Specimens

Group	Beam	Designation	a (mm)	d (mm)	a/d	Duct opening	
						Along	x (mm)
G1	B1	0% - 1.5	500	340	1.5	-	-
	B2	25% - 1.5	500	340	1.5	-	-
	B3	50% - 1.5	500	340	1.5	-	-
	B4	75% - 1.5	500	340	1.5	-	-
G2	B5	0% - 1	340	340	1	-	-
	B6	50% - 1	340	340	1	-	-
	B7	0% - 2	670	340	2	-	-
	B8	50% - 2	670	340	2	-	-
G3	B9	0% - 2	670	340	2	2Ø12	0
	B10	50% - 2	670	340	2	2Ø12	0
	B11	0% - 2	670	340	2	2Ø12	470
	B12	50% - 2	670	340	2	2Ø12	470
G4	B13	0% - 2	670	340	2	2Ø12	240
	B14	50% - 2	670	340	2	2Ø12	240
	B15	50% - 2	670	340	2	2Ø12	240
	B16	50% - 2	670	340	2	Pl.4mm	240

a = Shear span & d = Beam depth & Aslong = Longitudinal steel &
x = The distance between the external face of rectangular duct opening and right support.

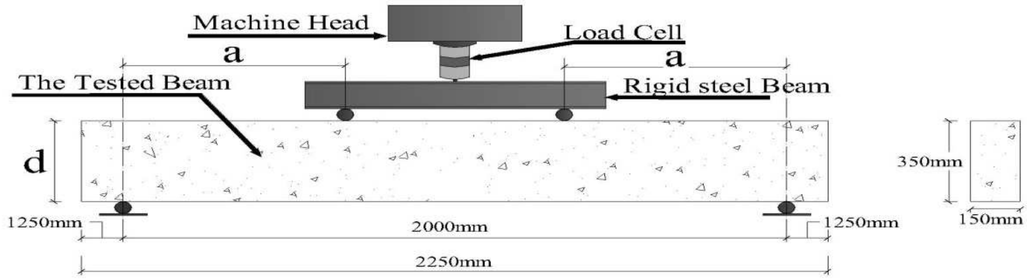


Fig. 3 Test Setup

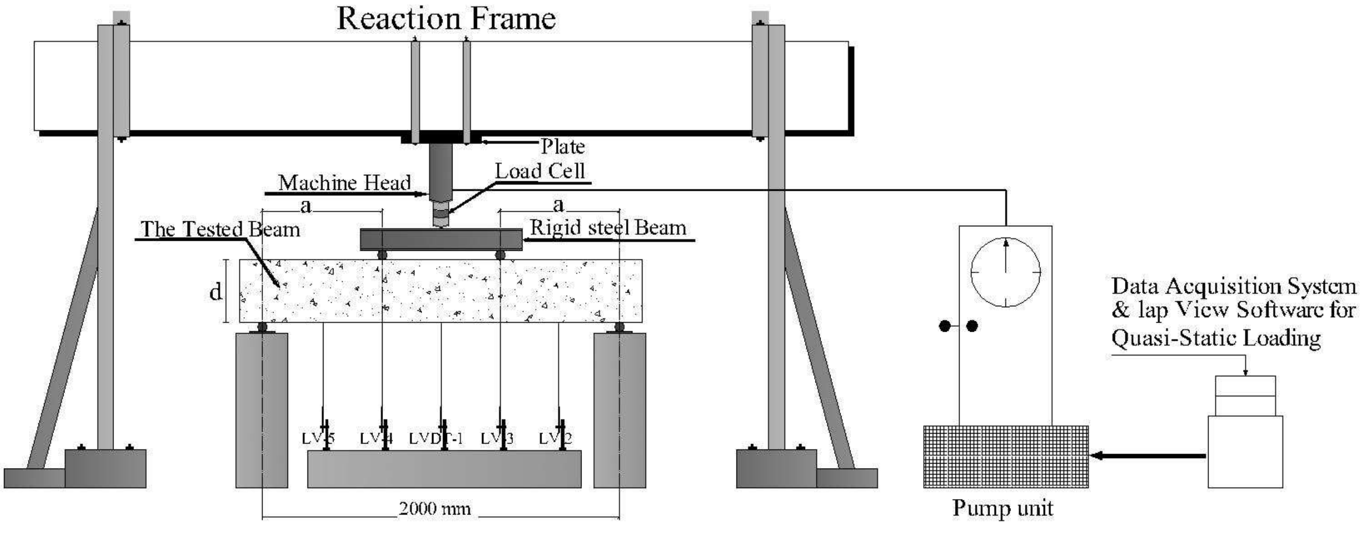
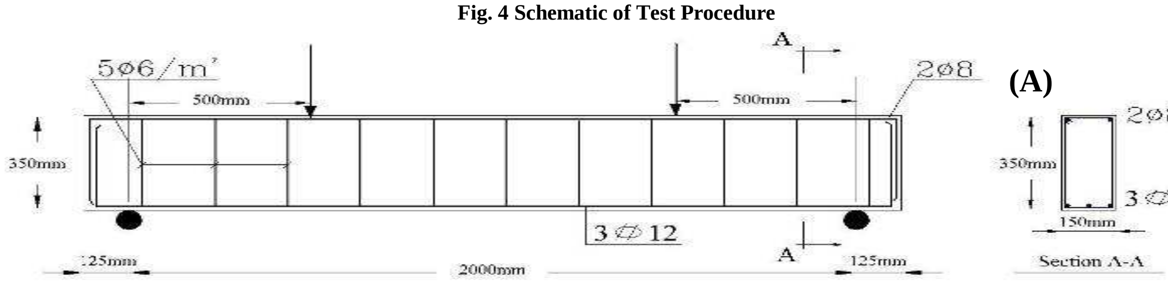


Fig. 4 Schematic of Test Procedure



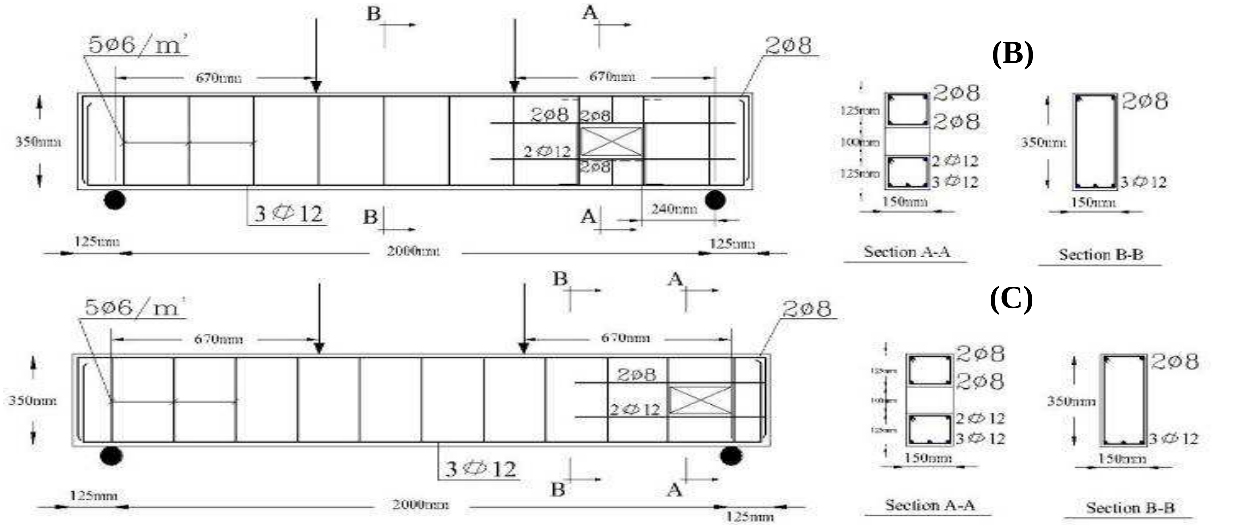


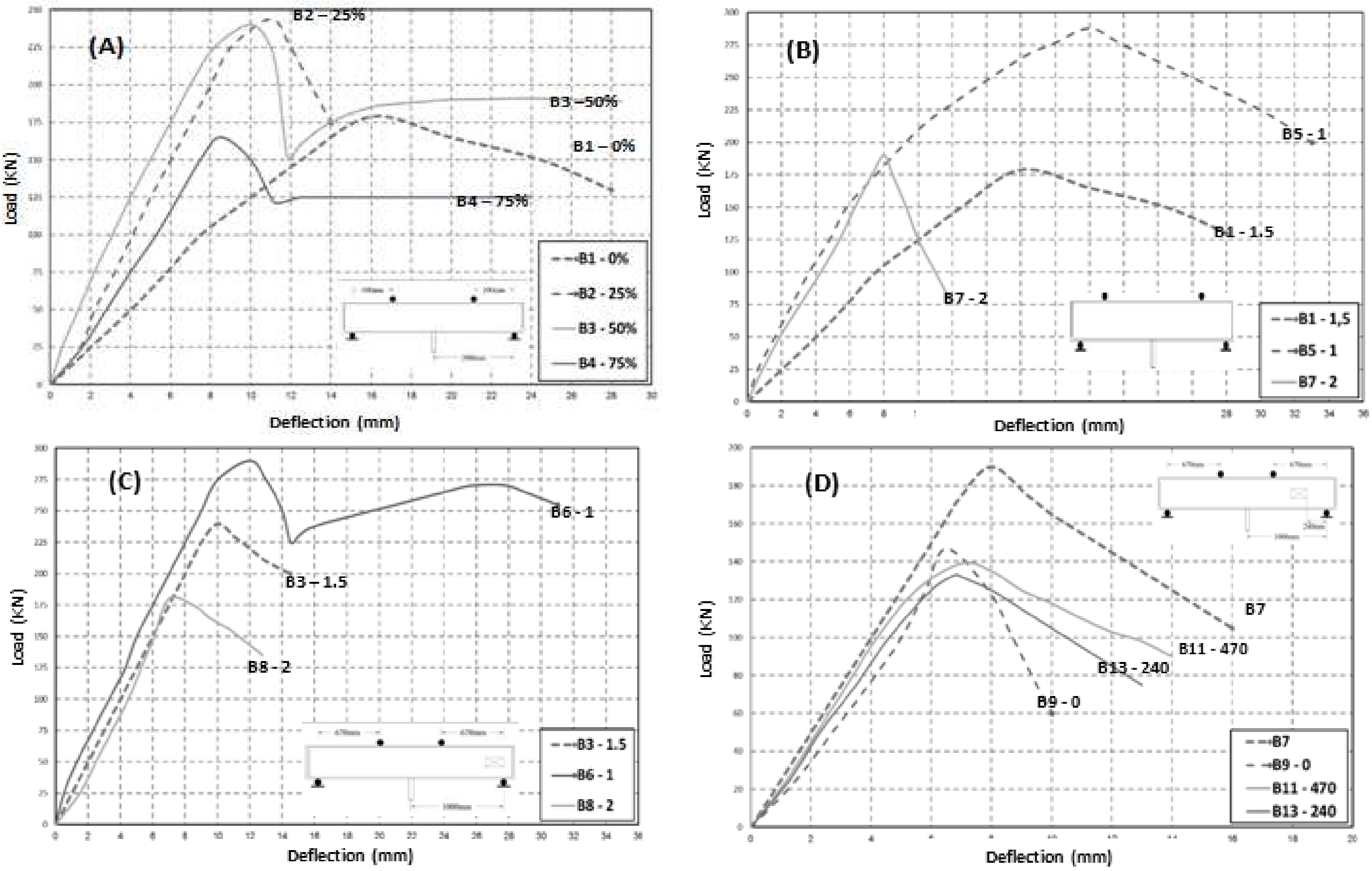
Fig. 5 Details of the Tested Specimens: (A) Beams without Opening, (B) Beams Contained Opening, (C) Beams with Different Reinforcement Details and Opening

EXPERIMENTAL RESULTS

The test results of the specimens are summarized in Table -11, in which the beam characteristics, variable parameters, concrete compressive strength, cracking loads, ultimate loads and corresponding deflections are given for each beam.

Load -Deflection Relationship

Table -11 shows the maximum central deflections of all the test specimens at their failure load. Fig. 6 (A) through (F) shows the load maximum deflection relationships of the test specimens. As shown in Fig. 6, the curves start with steep gradient until the onset of the tensile cracking where the slopes reduce. After this point, the load-deflection relationship is approximately linear till the first yielding of the transverse reinforcement, then the relationship follows a curved path till ultimate load. Beyond the ultimate load, the control specimen (B1 with 0.0% RCA) showed gradual and smooth decrease of the load indicating a semi-ductile behaviour.



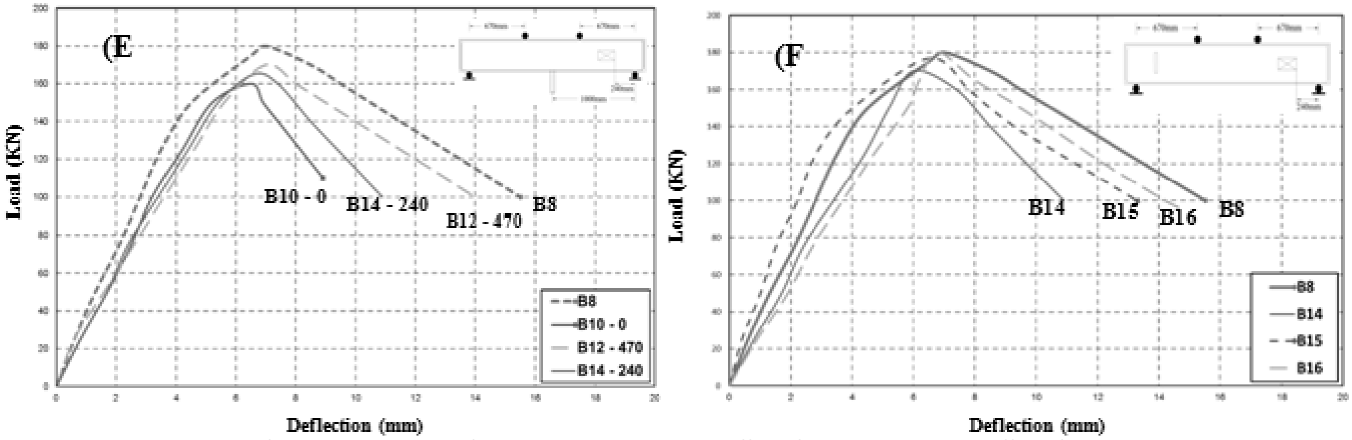


Fig. 6 Load- Mid-Span Deflection Relationship of the Tested Specimens: (A) Effect of the RCA Ratio, (B) Effect of the Shear Span with 0% Replacement of RCA, (C) Effect of the Shear Span with 50% Replacement of RCA, (D) Effect of the Location of Opening with 0% Replacement of RCA, (E) Effect of the Location of Opening with 50% Replacement of RCA, (F) Effect of the Different Reinforcement Details around Openings

Table -11 Summary of Experimental Results

Group	Beam	Designation	fcu (MPa)	pcr (KN)	Pu (KN)	δu (mm)
G1	B1	0% - 1.5	38.5	89	179	16
	B2	25% - 1.5	43.5	110	244	11
	B3	50% - 1.5	48	105	240	10
	B4	75% - 1.5	39.5	95	165	8.5
G2	B5	0% - 1	38	145	288	20
	B6	50% - 1	43.3	166	290	12
	B7	0% - 2	37	80	190	8.0
	B8	50% - 2	39	67	180	7.0
G3	B9	0% - 2	43	68	147	6.5
	B10	50% - 2	45.5	83	160	5.5
	B11	0% - 2	44	67	139	7.0
	B12	50% - 2	46	74	175	6.6
G4	B13	0% - 2	42	70	133	6.8
	B14	50% - 2	45	63	170	6.0
	B15	50% - 2	38.5	79	177	6.5
	B16	50% - 2	39.5	75	180	6.8

On the other hand, most specimens showed rapid and steep decrease of the load indicating a brittle behaviour. Some specimens retained a part of their capacities while sustaining medium to large plastic deformations. This indicates that these specimens had a stable load-deflection response with large area under the curve and can be classified as semi-ductile behaviour specimens. The corresponding deflection profiles at the ultimate failure load of the tested specimens are shown in Fig. 7 (A) through (F).

Strains in Concrete and Steel Reinforcement

In cylinder tests, peak stress was reached at approximately 2800 micro strain. The significance of this strain is that it establishes an estimate of the point at which strain localization should start. It should be noted that the stress-strain curve obtained from a cylinder test does not represent the behaviour of the reinforced concrete in the tested beams. While each cylinder test took about 5 min to complete, each beam test took from 0.75 to 1.2 hr to reach failure. Because of creep, the strain at peak stress in the beam may be significantly larger than the localization strain obtained from cylinder tests. In all cases, the peak stress in the stress-strain curves from the beam tests occurred at a higher strain than in the cylinder test. In most specimens, failure took place without much of a descending branch in the load- deflection curves. The lack of descending branch behaviour in the load-deflection curves implies that these beams may have failed prior to the development of any significant strain localization. Fig. 8 (A) through (F) shows the load-versus-transverse steel strain relationships for the test specimens. The results suggest that the stress in steel stirrups increased until the steel reaches its yield point. Thereafter, a large portion of any extra stress is absorbed by large deformations in the steel, which lowers the increase of concrete compressive strain. Before yield, the strain distribution did not vary significantly throughout the length of the test region. With increasing deformation, the strains started to increase considerably at one section or part of the beam while the strains at other sections either remained constant or increased slightly. The strain distribution became more and more non-uniform as failure was approached. In general, higher compressive strains were measured above the location of cracks.

As can be seen from Fig. 9 (A) through (E), the strain measured on the longitudinal steel bars at the ultimate load was approximately 0.001. This may be attributed that the longitudinal steel bars didn't reach yield strain before crushing of the concrete. At the ultimate load, the strain measured on the transverse steel bars (stirrups) was approximately 0.0025 and the diagonal concrete strain was about 0.003.

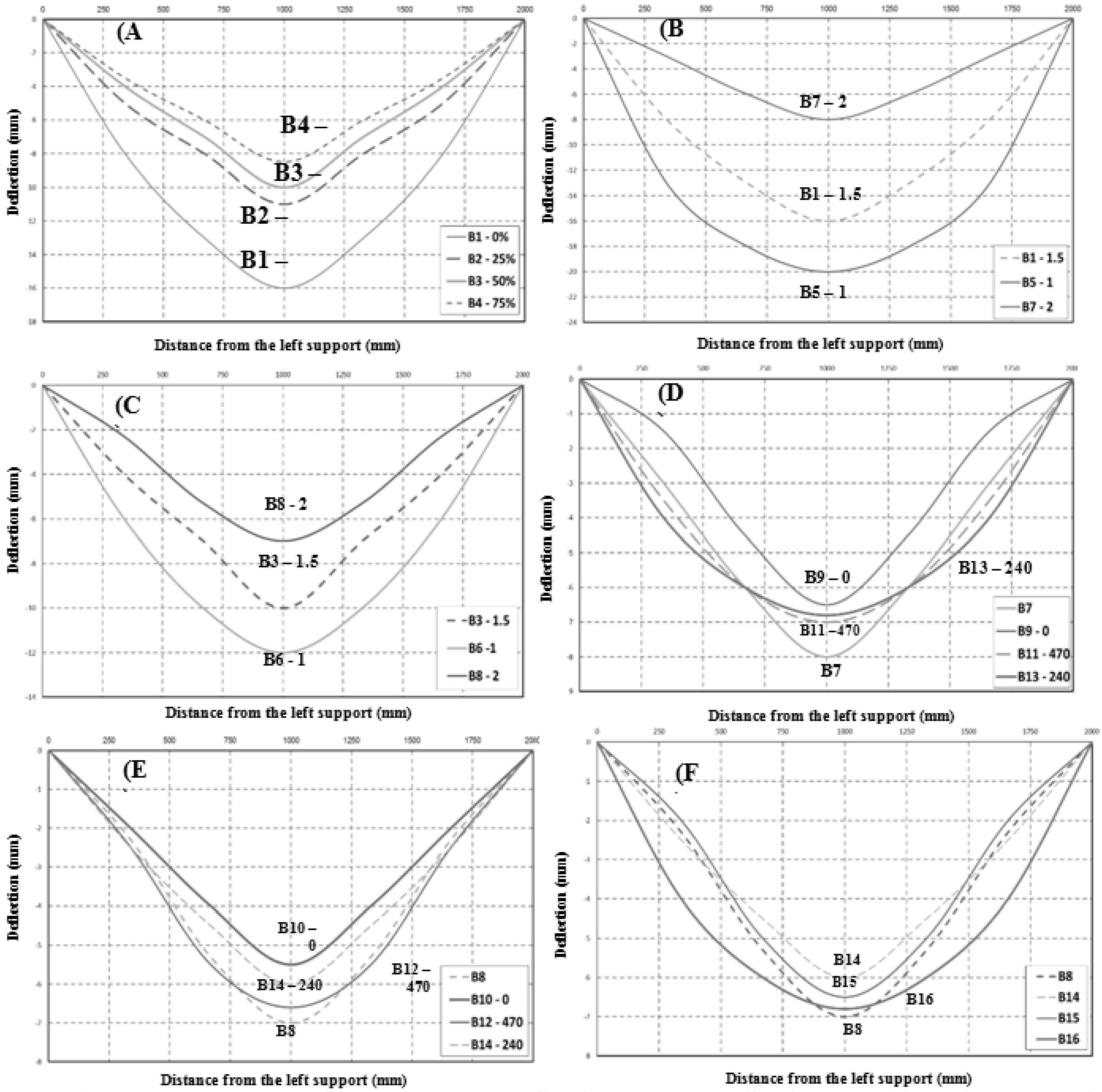
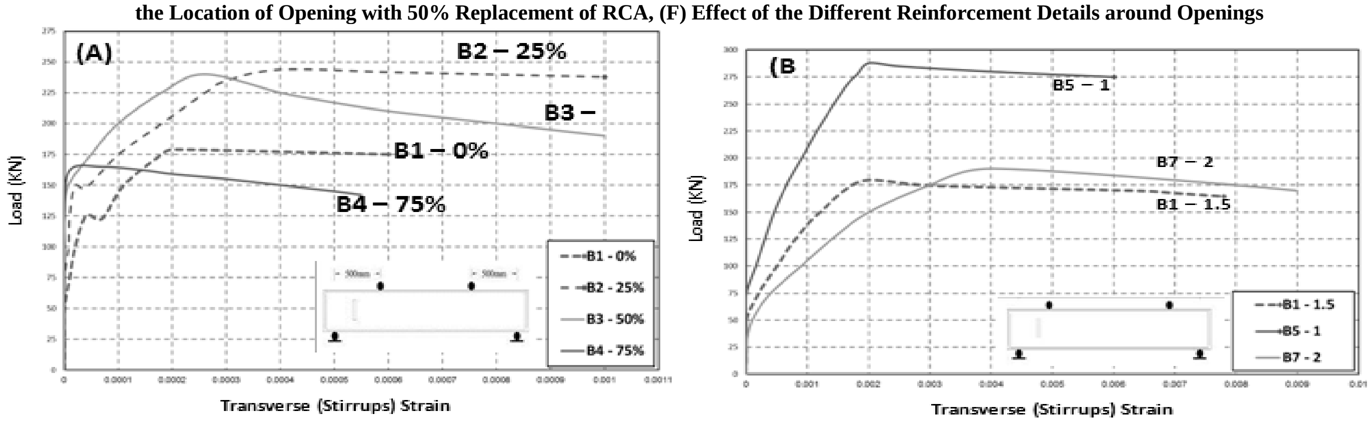


Fig. 7 Deflection Shape at Ultimate Load of the Tested Specimens: (A) Effect of the RCA Ratio, (B) Effect of the Shear Span with 0% Replacement of RCA, (C) Effect of the Shear Span with 50% Replacement of RCA, (D) Effect of the Location of Opening with 0% Replacement of RCA, (E) Effect of the Location of Opening with 50% Replacement of RCA, (F) Effect of the Different Reinforcement Details around Openings



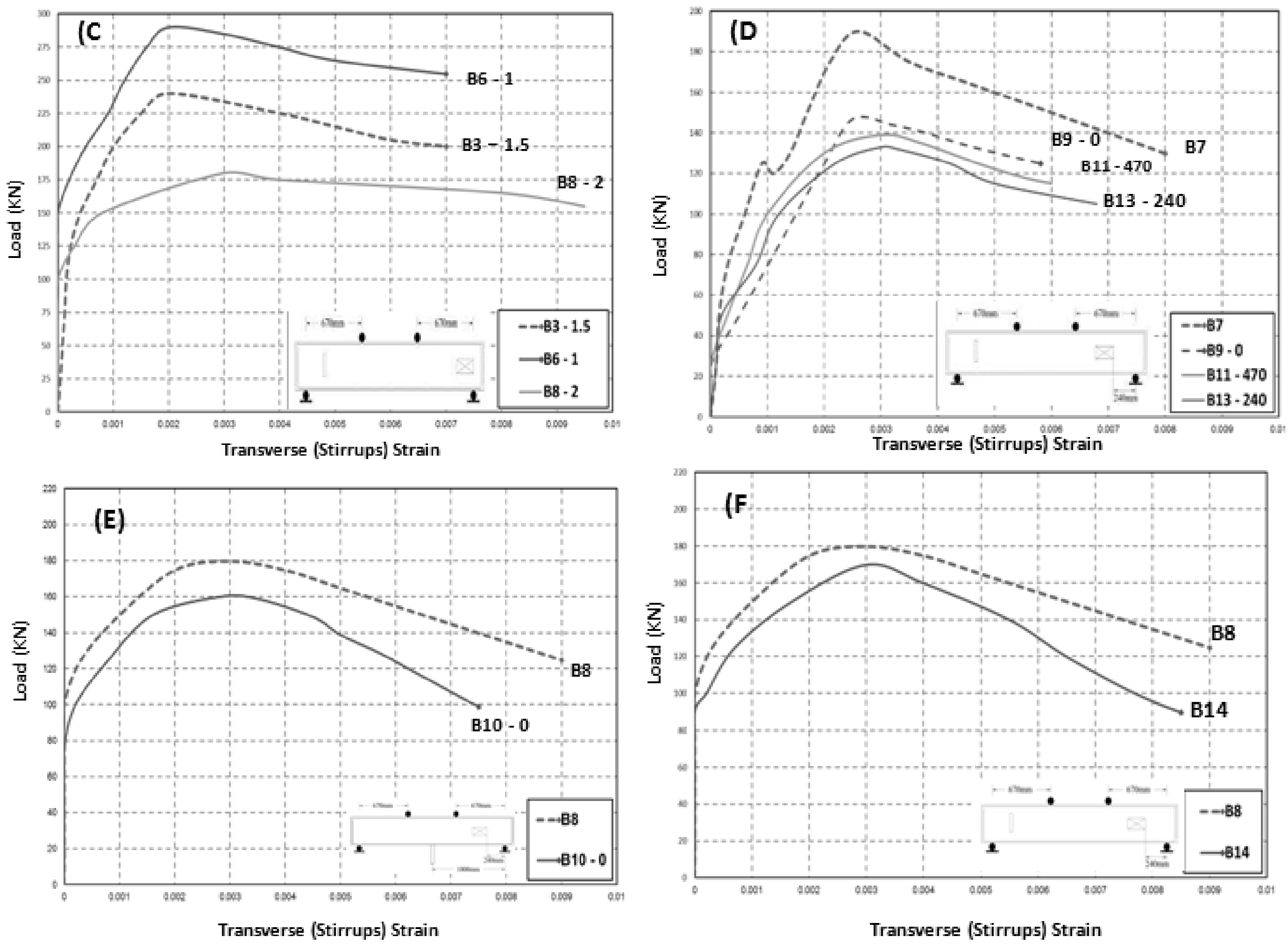
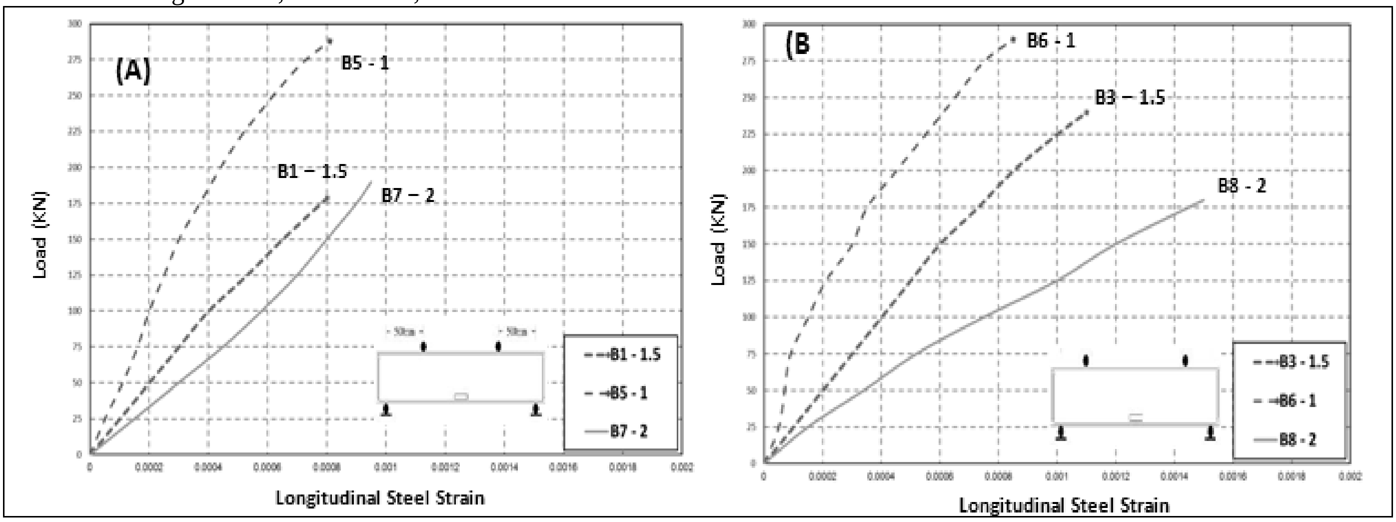


Fig. 8 Load- Transverse Steel Strain Relationship of the Tested Specimens, (A) Effect of the RCA Ratio, (B) Effect of the Shear Span with 0% Replacement of RCA, (C) Effect of the Shear Span with 50% Replacement of RCA, (D) Effect of the Location of Opening with 0% Replacement of RCA, (E) Effect of the Location of Opening with 50% Replacement of RCA, (F) Effect of the Different Reinforcement Details around Openings

Cracking Behaviour and Failure Modes

Fig. 10 (A) through (F) shows the failure modes of all the tested specimens. Similar characteristics were noticed for the cracking patterns of the test specimens. Examination of these figures suggests that all specimens failed in the classical shear failure mode, without any noticeable difference in cracking pattern due to usage of recycled aggregates. At the early stages of loading, specimens exhibited an initial shear crack at the mid height of the tested beam within the shear span. These cracks were first visible at about 40 to 70 present of the ultimate load. Upon increasing the load, the number, width and extensions of the cracks were increased.



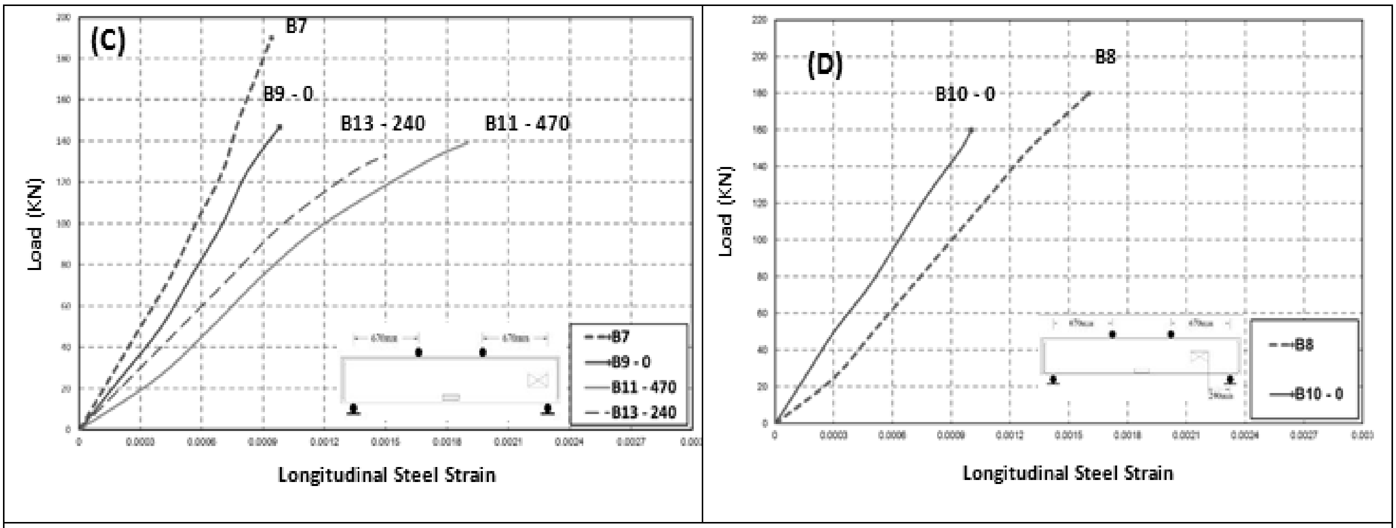
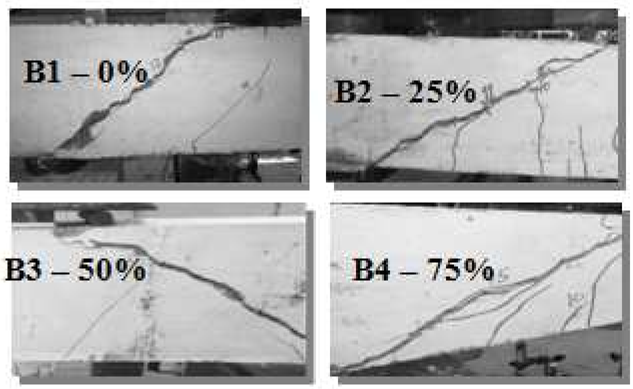


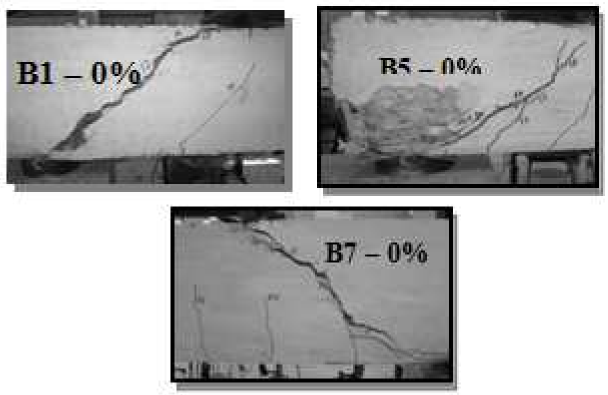
Fig. 9 Load- Longitudinal Steel Strain Relationship of the Tested Specimens: (A) Effect of the Shear Span with 0% Replacement of RCA, (B) Effect of the Shear Span with 50% Replacement of RCA, (C) Effect of the Location of Opening with 0% Replacement of RCA, (D) Effect of the Location of Opening with 50% Replacement of RCA

After the complete formation of the diagonal crack, brittle failure occurred. This may be attributed to the presence of shear reinforcement, which restrict the growth of diagonal cracks and reduces their penetration into the compression zone; and hence increases the part of the shear force resisted by the concrete compression zone.

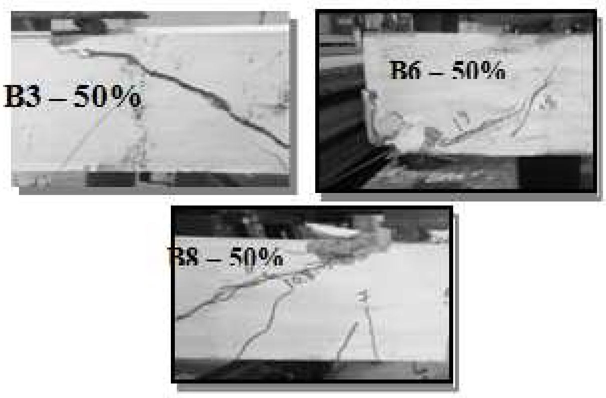
In addition, the presence of stirrups enhanced the dowel action. The diagonal crack width was observed and the maximum load carrying capacity was recorded. For all beams, once the primary diagonal crack extended to the point of load application and to the support or near the support, the beams failed and the shear dominates the failure mode of all beam specimens. The failure was localized at a section where a primary diagonal crack existed. The branches of adjacent primary cracks connected to form a failure plane with crushing at a section.



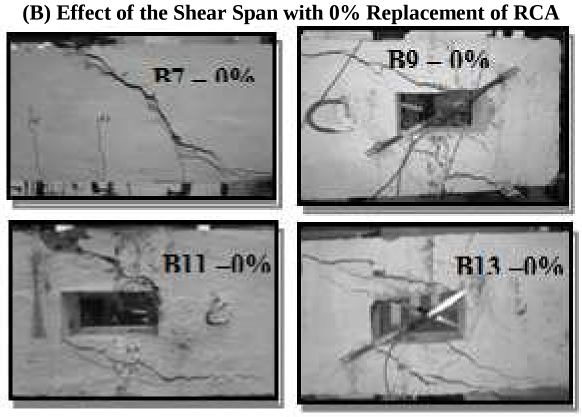
(A) Effect of the RCA Ratio



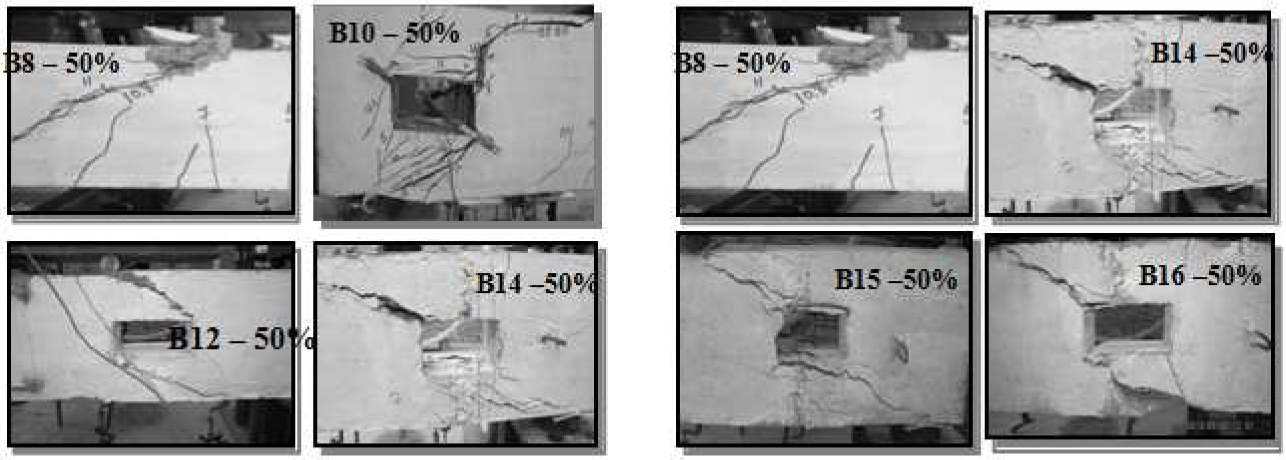
(B) Effect of the Shear Span with 0% Replacement of RCA



(C) Effect of the Shear Span with 50% Replacement of RCA



(D) Effect of the Location of Opening with 0% Replacement of RCA



(E) Effect of the Location of Opening with 50% Replacement of RCA **(F) Effect of the Different Reinforcement Details around Openings**
Fig. 10 Cracking Behaviour and Failure Shape of the Tested Specimens

DISCUSSION OF TEST RESULTS

A. Effect of RCA Ratios

On Deflection: It can be seen from Table -9 and Fig. 6 (A) that the deflection response becomes stiffer as the RCA ratio increases, keeping all the other parameters constant. At the same load level, the deflection of beam with 75 % replacement of RCA (beam B4) is smaller than that of beams with 0.0, 25 and 50 % replacement of RCA (beams B1, B2 and B3), respectively.

On Shear Capacity: It had to be noted that the shear capacity of the tested specimen increases as the RCA ratio increases up to 50%. The ultimate load of specimen B2 (which has 25% replacement of RCA) is greater than that of specimen B1 (which has 0% replacement). On the other hand, specimen B4 (which has 75% replacement of RCA) showed the smallest ultimate load indicating that greater than 50% replacement lead to a reduction on the shear capacity.
On Transverse Steel Strain: It can be seen from Fig. 8 (A) that the RCA ratio has no clear effect on the recorded strain measurements at the early stages of loading. However, beam of higher RCA ratio (B3) recorded higher strain at failure than B1.

B. Effect of Shear Span to Depth Ratio

On Deflection: It can be seen from Fig. 6 (B and C) that the shear span to depth ratio had a minimal effect on the deflection of the tested beams at the early stages of loading. However, beam of lower shear span to depth ratio (B5 and B6) recorded higher inelastic deflections at failure.

On Shear Capacity: As can be seen also from Table XI and Fig. 6 (B and C), the ultimate shear load increases with the decreases of shear span to depth ratio. Beams B5 and B6 with lower shear span to depth ratio recorded higher ultimate load at failure compared with B7 and B8, respectively.

On Transverse and Longitudinal Steel Strain: As can be seen from Fig. 8 (B and C), the test results indicated that beam with higher shear span to depth ratio recorded higher transverse steel strain, beams B7 & B8 compared with beams B5 & B6, respectively. By the same way, Fig. 9 (A and B) showed that beam with higher shear span to depth ratio recorded higher longitudinal steel strain, beams B7 & B8 compared with beams B5 & B6, respectively.

C. Effect of Different Locations of Openings

On Deflection: It can be seen from table 12 and Fig. 6 (D) that the deflection of beams with 0% replacement of RCA increases as the opening becomes far from support, beams B11 and B13 compared with beam B9. By the same way, Fig. 6 (E) for beams with 50% replacement of RCA showed that beam with opening far from support recorded higher deflection, beams B14 & B12 compared with beam B10.

On Shear Capacity: As can be seen from table 12 and Fig. 6 (D), the test results indicated that beam with opening far from the support recorded higher ultimate load, beam B11 and B13 compared with beam B9 (case of 0% replacement of RCA). By the same way, Fig. 6 (E) for beams with 50% replacement of RCA showed that beam with opening far from support recorded higher ultimate load, beams B14 & B12 compared with beam B10.

On Concrete and Longitudinal Steel Strain: Based on the test results shown in Fig. 8 (D) for beams with 0% replacement of RCA, it can be concluded that the strains are higher for beams with nearest opening from the support, B13 and B11 compared with B9. By the same way, Fig. 8 (E) for beams with 50% replacement of RCA showed that beam with opening far from support recorded higher ultimate load, beams B14 & B12 compared with beam B10.

D. Effect of Reinforcement Details around the Opening

On Deflection: It can be seen from table 12 that the deflection increases due to strengthening the opening with steel plate, beam B16 compared with beams B14 and B15.

On Shear Capacity: Referring to table 12, it can be concluded that the ultimate shear capacity increases due to strengthening the opening with steel plate, beam B16 compared with beam B14 and B15. It can be also concluded that strengthening the opening with steel plate can compensate the reduction in the ultimate shear capacity due to the presence of opening, beam B16 compared with beam B8.

On Recorded Strain: The test results showed that the transverse strain for beams with strengthening opening was observed to be slightly greater than that of beams with conventional reinforcement around the opening, B16 compared with B14 as shown in Fig. 8 (F).

CONCLUSIONS

Based on the experimental results of the concrete mixes and the tested specimens, the present study shows that the recycled concrete aggregate (RCA) can be successfully used as a construction material for structural members subjected to different types of shear loading provided that conducting chemical, physical and mechanical tests to ensure its compliance with acceptable criteria because the RCA is non-homogenous material and its properties vary from one batch to another.

Within the scope of the present study and range of investigated parameters, the following conclusions can be drawn:

Conclusions Related to the Concrete Mixes

- Due to the adhered mortar; the variation in density, water absorption ratio and Los Angeles abrasion of the recycled concrete aggregates are much higher than those of natural aggregates. This may cause quality control problems.
- Recycled concrete aggregate should be wetted before using in order to achieve acceptable workability of concrete, i.e. slump value of 10 ± 2 cm.
- Full replacement of natural aggregate by recycled aggregates leads to a decrease in concrete compressive strength and can be considered non-practical.
- For mixes with 350 kg/m3 cement content, compressive strength of mixes with up to 50% recycled aggregate is higher than that of mixes with natural aggregate. Hence, it is more useful to use recycled concrete aggregate in lower strength concrete.

B. Conclusions Related to the Tested Beams

- The shear capacity of the tested specimen increases as the RCA ratio increases up to 50%. On the other hand, specimen B4 (which has 75% replacement of RCA) showed the smallest ultimate load indicating that greater than 50% replacement lead to a reduction on the shear capacity.
- The strain on stirrups increases as the RCA ratio increases.
- The increase of shear span-to-depth ratio led to reduction of shear strength.
- Beam of lower shear span to depth ratio recorded higher inelastic deflections at failure.
- The recycled concrete beams recorded little reduction of the stiffness values compared to natural concrete beams.
- Beam with opening far from support recorded higher ultimate load, beams B14 & B12 compared with beam B10.
- Strengthening the opening with steel plate can compensate the reduction in the ultimate shear capacity due to the presence of opening.
- Both the Egyptian and ACI code provisions were conservative for predicting the ultimate shear strength of both natural and recycled concrete beams.

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