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Flexural behaviour of recycled reinforced concrete beams strengthened/ repaired with CFRP laminates

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Abstract

This research deals with the flexural performance of reinforced concrete beams which contain Recycled Concrete Aggregates (RCA) and were strengthened by Carbon Fiber Reinforced Polymers (CFRP). For this purpose, seven Reinforced Concrete (RC) beams were manufactured using RCA as a replacement of Normal Coarse aggregates (NCA) with percentages of (0%, 25%, 50%, and 100%). The cross-section of all beams was 150 × 300 mm and 2100 mm overall length and with loaded span of 1800 mm. Firstly four beams (group A) with different RCA ratios were loaded in a four-point loading configuration until failure. Secondly three beams (group B) were loaded to 30% of its ultimate load after that group B beams were strengthened using CFRP laminates on the lower face of the beams to be strengthened to resist flexural stress. Crack pattern, initial cracking load, ultimate load, mid-span deflection, and strain in main reinforcement were monitored. The results show that increasing RCA ratios generally leads to decreasing in the ultimate loads, for RCA ratios of 25%, 50% and 100% the decrease in beams ultimate load was with ratios 4.8%, 25.5% and 26.8%, respectively compared to control beam (0% RCA). The preloaded beams that were repaired with CFRP laminates have higher ultimate loads than beams without CFRP laminates and lower mid span deflection at maximum load (for instance repaired beam with 50% RCA ratio with CFRP laminate has shown higher ultimate load with 56.6% and less deflection with 36.9% compared to its corresponding unstrengthen beam).

Keywords: Recycled aggregates, Repaired, CFRP, Laminates, Beam strengthening, Flexural behaviour, Deflection

Introduction

The recycling process may help for reducing the consumption of natural resources. Recycling concrete has become necessary in Egypt and many countries because of the large demolitions currently taking place due to renovations of facilities and infrastructure. These environmental issues are increasingly getting attention under sustainable development nowadays [1]. It is thought that using recycled coarse aggregate (RCA) made from construction and demolition wastes as a replacement for natural aggregates in the construction industry has positive effect on the environment. Many researchers used RCA in concrete beams to study shear, flexure, and torsion behaviour [2].

The use of carbon fiber-reinforced polymer (CFRP) in civil engineering as construction materials has increased significantly during the past decade. Due to issues with the construction or design, increased load carrying needs, a change in how a building is utilised, damage to structural elements, seismic activity, or compliance with new code standards, using CFRP to strengthen concrete structures became a widely important method [3–5]. Using RCA can lead to accepted quality concrete at low cost. When concrete structures are demolished, the concrete is recycled and used as a primary material for new concrete. The benefits of using recycled coarse aggregate (RCA) are that it is a more attractive solution in the environmental awareness and reduces costs of construction [6].

Sindy et al. [6] studied flexural performance of reinforced concrete beams with RCA, with a rectangular cross section of 30 × 20 cm and length of 360 cm. The beams were made with RCA ratios of 0%, 20%, 50%, and 100. They concluded that the flexure deformations were significantly influenced by the usage of RCA. During the first 200 days, the RC and Normal Concrete Aggregate (NCA) provided the largest deformations. After that, the strain curves tended to stabilize. The behaviour of RCA was significantly influenced by the greater creep coefficients and shrinkage strain of recycled concretes**.** They found that cracking moments decreased with increasing of Recycled Coarse Aggregates ratios. RCA slightly affected the bending moments and deflections. Strain of steel reinforcement and reinforced concrete beams with RCA were higher than these of conventional concrete beams [7]. In flexure behaviour, most authors [6–8] pointed out similar yielding and ultimate behaviour, but some [9] have found little differences in cracking behaviour, in terms of spacing and pattern.

Asad Khan et al. [10] studied the shear behaviour of beams with RCA. It was observed that the initial shear stiffness of concrete specimens made with RCA was less than that of concrete specimens made with Normal Aggregate (NA). Bing Liu et al. [11] studied the shear behaviour of NCA and RCA. They found that compressive strength and shear strength for the RCA was smaller than that of NCA and increasing the ratio of RCA decreases the shear strain. Also, Al Mahmoud et al. [12] found that when a replacement ratio of 30% of RC was utilized, the shear strength of beams decreased by 11% to 19%. Regarding load–deflection response, reinforced concrete beams with RA behaved similarly to NA beams in shear. All specimens broke in the traditional shear failure mode due to a large diagonal shear crack and the local bond failure of the bottom reinforcement near the supports**.** Then Almutairi, et al. [13] concluded that openings in beams with NCA and RCA decrease the shear strength of such beams. Increasing opening height slightly decreases shear strength. Opening position significantly affected the shear strength when approaching the maximum shear zone. Increasing steel reinforcement around the openings improved the shear strength**.**

To improve strength and serviceability, conventional methods of strengthening, like section increase, externally bonded Carbon Fiber-Reinforced Polymers (CFRP) can be used to improve the flexural, shear, and torsional capacity of RC beams. CFRP sheets are highly useful for strengthening beams due to their flexibility, simplicity of use and application, in addition to their stiffness and high weight-to-tensile strength ratio. In 2019, Appu et al. [14] concluded that adding CFRP sheets to corroded RC beams makes it possible to reinforce them while maintaining structural integrity and raising their ultimate strength over the control beam. According to

El Gamal et al. [15], the stiffness of steel yielding and the final capacity both rose as the amount of CFRP increased. Mostafa et al. [16] concluded that the ultimate capacity of repaired RC beams is increased by up to 100% compared to the control beam by increasing the number of plies of FRP sheets/laminates layers. In 2021, Ali et al., [17] observed that in the case of collapsed beam, strengthening enables not only repair but also increases the mechanical strength capacity of the beam by about 11.8%. Gao et al., [18] concluded that RCA with fibers showed lower Deflection and Stirrup Strain than those of recycled aggregate concrete beams without fibers. Ibrahim et al., [19] concluded that the behaviour of the ferrocement beams was highly influenced by the core type and amount of mesh reinforcement. The types of mesh reinforcement used in the study were expanded metal mesh, welded wire mesh, and fibre glass mesh. The study found that ferrocement beams reinforced with fibre glass mesh exhibited higher ultimate loads and ductility index compared to those reinforced with expanded metal or welded wire meshes. The study found that ferrocement beams with polystyrene foam cores exhibited higher first crack loads compared to those with pumice or perlite cores. In terms of ultimate loads, ferrocement beams reinforced with fibre glass mesh exhibited higher ultimate loads compared to those reinforced with expanded metal or welded wire meshes. Then Wael Wael et al., [20] studied the flexural and shear behaviours of Light Weight Concrete (LWC) beams strengthened with Carbon Fibre Reinforced Polymer (CFRP) and Glass Fibre Reinforced Polymer (GFRP) laminates containing polystyrene beads. According to the study, the partial replacement of normal aggregate by polystyrene beads results in LWC with the benefits of maintaining a reasonable strength, reduced overall weight of the LWC test beams by approximately 30% compared to their counterparts of NWC beams, low price, and good insulation of polystyrene. According to this study, reinforcing LWC beams with layers of CFRP and GFRP led to a greater increase in loading capacity and a smaller deflection when compared to the control. The strengthening with CFRP and GFRP reduced crack width and crack propagation, which are particularly significant in LWC beams.

This research uses Recycled Concrete Aggregate (RCA) as an alternative to natural coarse aggregate in concrete. The main objective of the experimental program was to study the flexure behaviour of reinforced beams using recycled aggregates and strengthening beams with bonding CFRP laminates. Seven beams with different ratios of RCA were made, B1-0 & B2-0 with 0% RCA, B1-1 with 25% RCA, B1-2 & B2-1 with 50% RCA and B1-3 and B2-3 with 100% RCA. Three reinforced concrete beams with different RCA ratios (0%,50%, and 100%) were tested to study the behavior of RC beams strengthened using CFRP laminate in the flexure zone. The results of the experimental program include deflection, ultimate load, crack pattern, and strain in longitudinal steel. A comparison of experimental results with beam capacity and calculation using the ECP 203–2020 and ECP 208–2019 codes is made [21, 22].

In addition to the resource management aspect, recycled concrete aggregates absorb a large amount of carbon dioxide from the surrounding environment. The natural process of carbonation occurs in all concrete from the surface inward. In the process of crushing concrete to create recycled concrete aggregates, areas of the concrete that have not carbonated are exposed to atmospheric carbon dioxide [23].

Research objective

The flexure behavior of beams using normal aggregate and recycled concrete aggregates with different ratios of 25%, 50%, and 100%, and the behavior of rectangular reinforced concrete beams repaired by CFRP laminates after preloading subjected to flexure using the experimental program are the main purpose of this research is to study.

In this paper, the structural indicators, namely, first crack load, ultimate load and deflection at ultimate load were recorded. Load–deflection and load tensile strain relations were used in the evaluation of the studied test beams. The specimens used in this research were full scale specimens to understand the actual behaviour of reinforced concrete beams with RCA and the behaviour of repaired reinforced beams with RCA with CFRP. In addition, crack patterns and failure modes of the studied beams were not only observed and recorded but they were also linked and explained by the structural indicators, load-deflections, and load strains relationships. The aim of this research project is to utilize recycled concrete as coarse aggregate with addition of CFRP laminates for production of concrete. It is essential to know whether the replacement of RCA in concrete is acceptable or not.

Methods

The experimental plan included seven beams with different percentages of recycled aggregate (0%, 25%, 50% and 100%) tested under two concentrated vertical loads. In the experiments, the materials used were ordinary Portland cement, natural sand, clean water, recycled coarse aggregates, crushed dolomite aggregate, admixtures, steel reinforcement, and CFRP laminates. The procedures to determine the material properties were as per the guid lines of the Egyptian Standard Specifications (ESS) [24].

Materials

The cement used in this research was CEM I 42.5N. In this mixture, ordinary Portland cement [25, 26] and fine aggregate that is clean and rounded with sizes from 0.15 to 5 mm was used. The fine aggregate's physical properties are shown in Table 1. Natural crushed stone aggregates (dolomite aggregate) consisting of two ranges of size were used in this study. It's becoming more common in the Egyptian market to classify coarse aggregate as size 1 and size 2. Size 1 of crushed stones has a size of less than 13 mm, and size 2 of crushed stones has a size from 13 to 20 mm. Using the recycled coarse aggregate (RCA) was produced by crushing old concrete cubes and cylinders, which are usually provided for testing by previous researchers and construction projects at the Concrete Structure Laboratory of Cairo University. Tables 2 and 3 show physical and mechanical properties of the natural coarse aggregates and recycled coarse aggregates. Cubes and cylinders with compressive strength of 30–35 MPa were selected to be crushed. Potable water was used in the mixture. Deformed high tensile strength bars were used for main

Table 1 The fine aggregate's physical properties

Properties	Results	Specification limits
Specific weight	2.63	2.5–2.75
Clay and fine dust content %	0.85%	Not more than 3%

Table 2 Physical and mechanical properties of the natural coarse aggregates

Properties	Results	Specification Limits %
Specific weight	2.61	2.6:2.7
Bulk Density(t/m^3)	1.65	-
Water absorption%	2.05	Not more than 2.5
Clay and fine dust content%	2.1	Not more than 3
Flakiness Index%	20.8	Not more than 25
Elongation Index %	9.6	Not more than 25
Abrasion Index %	17.8	Not more than 30
Impact Value %	12.6	Not more than 45

Table 3 Physical and mechanical properties of the recycled coarse aggregates

Properties	Results	Specification Limits %
Specific weight	2.25	-
Bulk Density (t/m^3)	1.27	-
Water absorption %	7.35	Not more than 2.5
Clay and fine dust content %	0.53	Not more than 3

Table 4 Mix-design of normal and recycled reinforced concrete (per m^3)

Concrete type	Percentage of RCA (%)	Cement (kg/m^3)	NCA (kg/m^3)		RCA (kg/m^3)	Natural sand (kg/m^3)	Water (kg/m^3)
			Size 1	Size 2			
B1-0 &B2-0	0%	350	630.6	630.6	0	630.6	175
B1-1	25%	350	473	473	315.4	630.6	180
B1-2 & B2-2	50%	350	315.3	315.3	630.6	630.6	185
B1-4 & B2-4	100%	350	0	0	1261.2	630.6	195

steel, with diameter of 12 mm for bottom bars and diameter of 10 mm for top bars. Mild steel bars of diameter 8 mm were used as stirrups. Mix-design of normal and recycled reinforced concrete as shown in Table 4.

The used CFRP laminates were manufactured by BASF Company, which is known as MasterBrace® LAM 100/1.2 CFS. The roll package of laminate had 100 mm width and 1.2 mm thickness. The tensile strength and modulus of elasticity of the laminates are 3000 MPa and 165 GPa, respectively. CFRP laminate's elastic modulus is 165000 MPa with 3000 MPa tensile strength and 1.5% elongation at break. The Master Brace LAM system, used for flexural reinforcement of concrete and other building materials, is based on a ready-to-use carbon fiber laminate that offers high tensile strength and lightweight properties.

The epoxy adhesive is also from BASF's company used as Master Brace ADH 4000 is the adhesive for the Master Brace LAM system. It is available in 6 kg units. To get rid of any existing coatings and other loose material, the surfaces of the elements that need to be strengthened should be ground or treated with abrasive blasting. For about three minutes, mechanically mix components A and B until the mixture is smooth and the substance has no streaks that use for installing CFRP laminate in the beams

Fig. 1 The mixing of component A and B of the adhesive material

Fig. 2 Apply one layer of the epoxy adhesive on the surface of the substrate

as shown in Fig. 1. Apply one layer of MasterBrace ADH 4000 a minimum of 1.5 mm thick onto both the surface of the substrate and MasterBrace LAM as shown in Fig. 2. Immediately install the MasterBrace LAM by hand onto the substrate. Using a roller, exert a constant pressure onto the installed by moving the tool both ways in the direction of the fibres so that the adhesive squeezes out of the sides of the laminate. Remove excess with roller. The adhesive materials used in this experiment. Master Brace ADH 4000 colour is grey with specific gravity 1.75 at 25°C, compressive strength > 80 MPa ASTM C579 [27], flexural strength > 30 MPa ASTM C580 [28], tensile strength > 13 MPa ASTM C307 [29], bond strength > 3 MPa ASTM C579 [27] and pot life 45 min at 40 °C. This's properties of epoxy are given from manufacture.

Concrete tests

For fresh concrete, the slump test was performed to measure the consistency and workability of concrete according to the Egyptian code of practice [25]. For hardened concrete, sixteen standard cubes were taken with dimensions of 150*l50*l50 mm and tested by a 500-ton machine for the four types of mixes used in this experimental program. Compressive strength results at the ages of 7 and 28 days of mixtures with cement content 350 kg/m^3 are shown in Table 5 and Fig. 3.

It can be seen from Fig. 3 that the compressive strength of concrete seems to decrease with the increase of RCA but still it is within the acceptable limits (25- 40) MPa [23, 30].

Table 5 Properties of preliminary concrete mixtures

Group 1 Specimen	Compressive strength 7 days (N/mm^2)	Compressive strength 28 days (N/mm^2)	Slump (mm)
B1-0	26.5	35	90
B1-1	24.2	33.2	100
B1-2	20.5	30	115
B1-4	21.7	29.3	140
B2-0	26.7	35	90
B2-2	20.8	32	110
B2-4	22	30	145

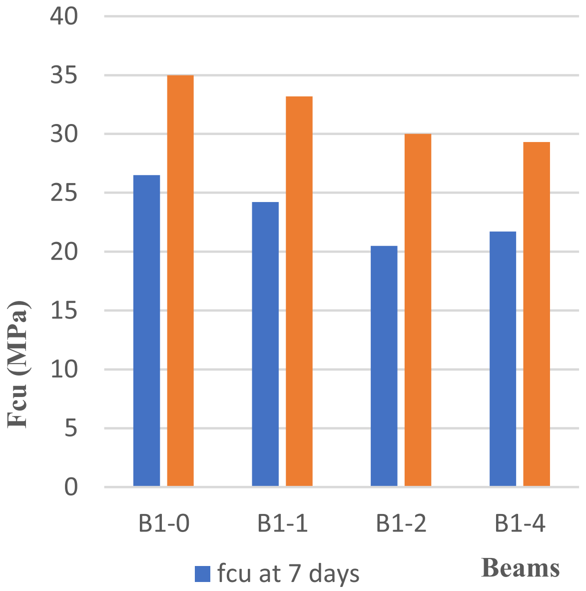


Fig. 3 Compressive strength for mixtures

Specimens preparation

The tests were carried out on seven reinforced concrete beams of 150 × 300 mm and 2100 mm overall length and a loaded span of 1800 mm and used two concentrated loads on the beam. Figure 4 shows the concrete dimensions and reinforcement of all specimens.

Installing carbon fiber laminates

The following steps to strengthen the three beams with carbon fiber reinforced polymer are: firstly, CFRP laminate roll with a width of 0.10 m was cut with the chainsaw to the required length for each specimen of 1.8 m to be installed longitudinally in the bottom of the beams from support to support on the strengthened beams. Must using toner and cotton to make sure to eliminate any carbon dust and any oil or grease out of MasterBrace LAM. Figure 5 shows the procedure of applying CFRP laminates on the strengthened beams.

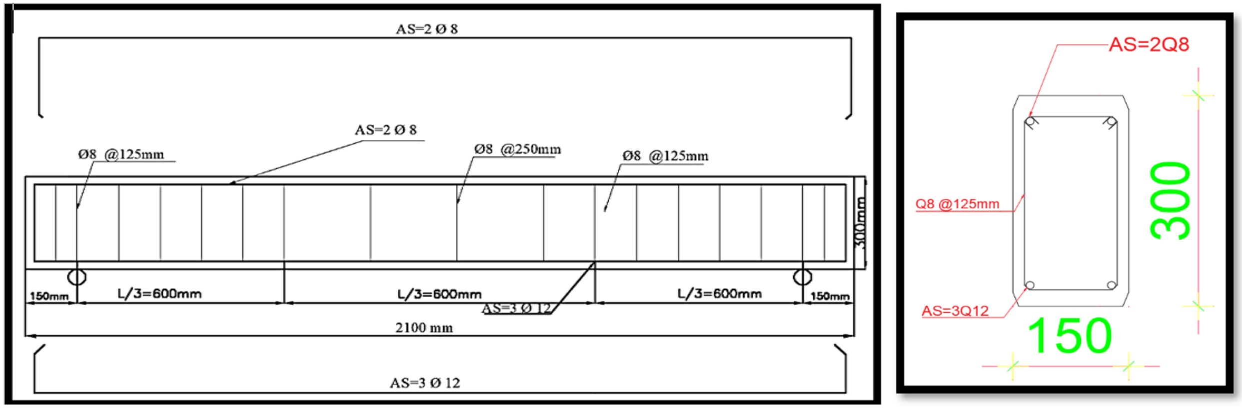


Fig. 4 The concrete dimensions and reinforcement of all specimens

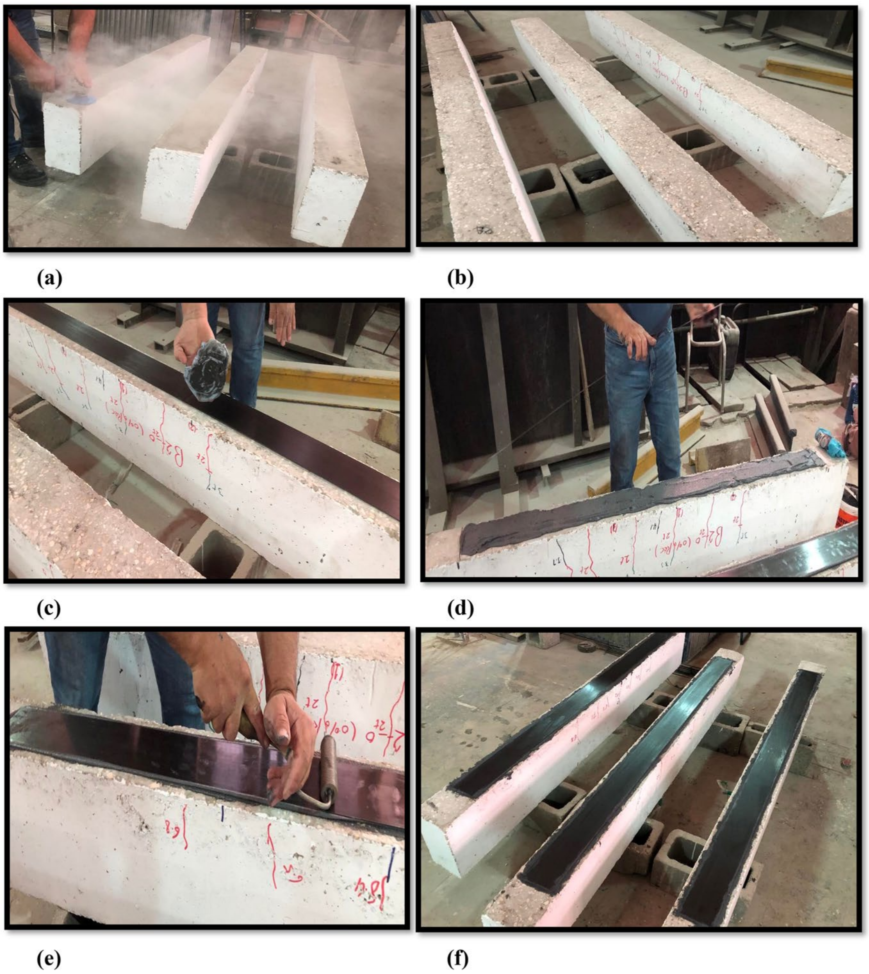


Fig. 5 Steps of applying CFRP laminates on the strengthened beams. **a** Smoothing and cleaning the surface of the concrete beam. **b** Free surface after cleaning. **c** Using toner and cotton to remove any contamination. **d** Putting the epoxy on the surface of the beams before attaching the CFRPP laminate to it. **e** Squeeze out the epoxy under the laminate with a solid roller. **f** The beams were left with the CFRPP laminates that attached for at least 72 h to get full curing

Details of specimens

Seven beams were tested in this experimental program. Beams were classified into two groups. The first group consists of 4 beams without carbon fiber laminates. The second group consists of 3 beams with carbon fiber laminates. Figure 6 shows the details of beams strengthened by the CFRP laminates.

Test setup

The length of each tested beam was 2100 mm. The beams were vertically supported at 1800 mm from center to center as shown in Fig. 7. The specimen is simply supported and subjected to two concentrated static loads. All beams were designed to fail in flexural to achieve the objective of this study. Hydraulic Jack with a capacity of 100 ton was used to apply loading on the tested beams.

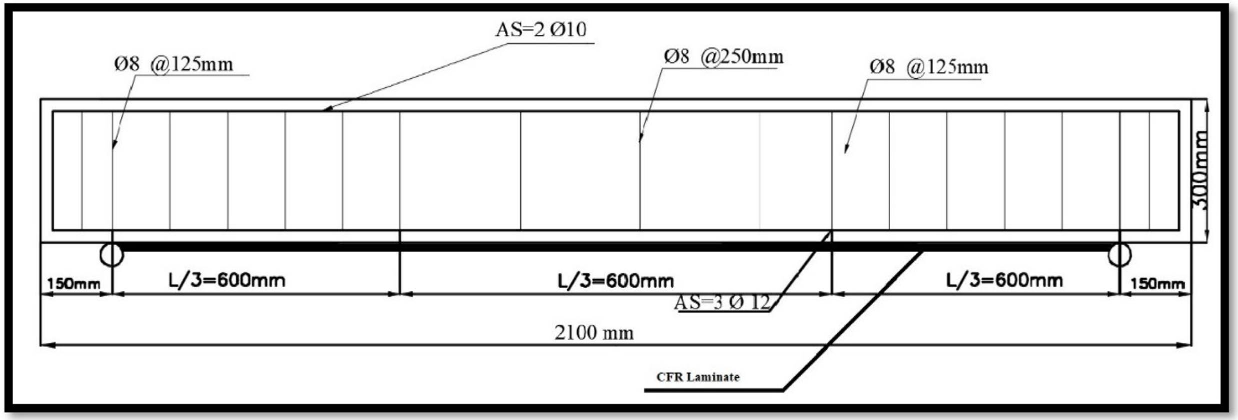


Fig. 6 Detailing of the beams were with the CFRP laminates

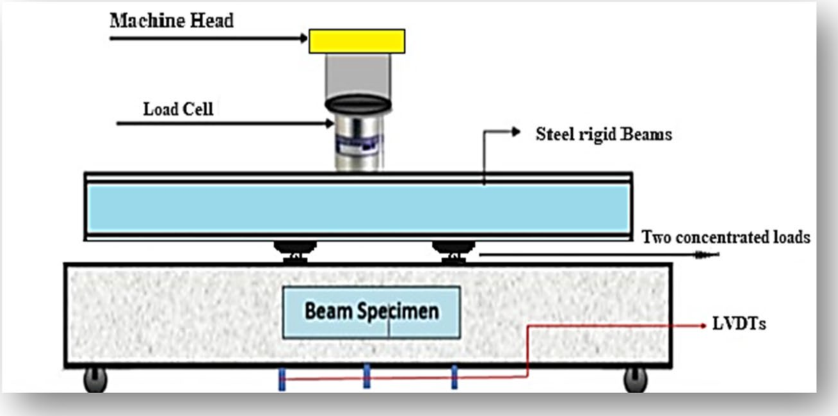


Fig. 7 Schematic of test setup

Table 6 Experimental results

Beam No	Specimen description	Initial Crack Load (kN)	Ultimate Load (kN)	Mid. Span Deflection (mm)	Max. Deflection (mm)	Strain Bot. Reinf. (μm)	Mode of Failure
B1-0	Group (A) Without CFRP	35	167	22.6	29.2	3630	Flexure Failure
B1-1		30	159.3	24	32.1	3189	
B1-2		30	133	24.9	32.9	5060	
B1-4		25	131.7	26.85	34.5	2427	
B2-0	Group (B) With CFRP	35	262.5	14.07	14.07	984	Shear failure
B2-2		30	235	14.25	18.78	984	
B2-4		25	222.5	14.78	19.5	984	

Test procedure

The beam cracks were marked during applying the load. Strain in steel reinforcements, deflection and applied load were recorded. Three linear voltage differential transducers (LVDTs) were used to measure deflection during tests. Strain gauges were used to measure strains of the longitudinal steel reinforcements up to failure.

Results and discussion

The results of experimental tests include, compressive strength, cracking behaviour, mode of failure, relationship between load and deflection, and maximum load. Table 6 summarizes the experimental results including of initial cracking load, ultimate load, mid-span deflection, strain for main reinforcement and strain for concrete for all beams. The deflection at first crack load on the curve is the deflection at the first crack initiation which is the point at which the curve begins to deviate from the initial linear relationship. Ductility index is the ratio of the deflection at ultimate loads to that at the first crack. Higher ductility index value indicates that a beam allows for more warnings before ultimate collapse [19, 31].

Crack pattern

The effect of using RCA on flexural capacity is studied using beams of group (A). This group consisted of four beams (B1-0, B1-1, B1-2, and B1-4) with the same reinforcement and different RCA ratios 0%, 25%, 50% and 100% respectively. The results show that all the beams of group (A) had almost the same cracking pattern. This pattern consisted of a diagonal crack in the middle of the beam span. The failure for all beams was due to flexure. Figure 8 shows the crack pattern for beams of group (A).

For control beam B1-0, limited hair cracks were observed to develop first at the bottom edge of the beam's mid span which agrees with findings of Ibrahim Shaaban et al., [19]. Then, in the other three beams (B1-1, B1-2, and B1-4), the cracks were wider in width and more spaced compared to those of B1-0 beam. Upon increasing the load, the cracks propagated rapidly upwards, and number of cracks increased along the span. The length and width of the cracks increased with increasing the applied load. Spalling of concrete was also observed in the beam [19]. The width of cracks becomes wider when increasing the ratio of RCA and the number of cracks becomes more when increasing the ratio of RCA.

Group (B) is set to study the effect of using RCA with CFRP laminates on flexure. Group (B) consisted of three beams (B2-0, B2-2, and B2-4) with the same reinforcement and different RCA ratios 0%, 50% and 100%, respectively. The crack pattern was similar for these beams. The main cracking pattern consisted of a diagonal crack close to the support of the beam. The failure for all beams in group (B) was shear failure as shown in Fig. 9.

The first crack was a diagonal crack (shear crack) initiated at region of the supports. With the increasing of load, multiple shear (diagonal) cracks parallel to the first diagonal crack were run between the area near the edge of the bearing plate and the junction of the column and face of the corbel; the existing inclined (shear) and vertical cracks

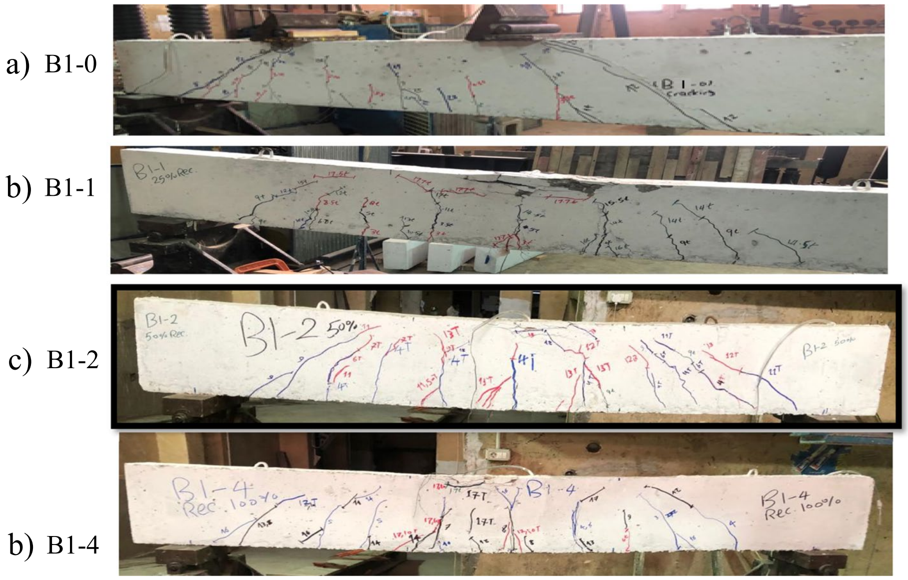


Fig. 8 Crack pattern for beams without CFRP laminates

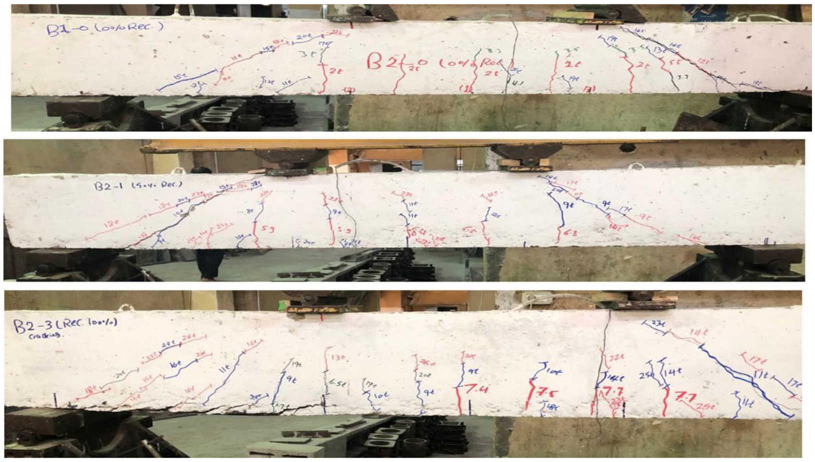

a) B2-0
b) B2-2
c) B2-4

Fig. 9 Cracks pattern for beam 2–0 using CFRP laminate

propagated slowly and were accompanied by formation of new cracks parallel to initial cracks. These cracks grew upward and started be to widen and caused de-bonding of CFRP strips and laminates in specimens externally strengthened CFRP strips and laminates as in [32].

Finally, it can be noticed that the cracks were wider in width and more spaced in the beams without CFRP laminate compared to those of CFRP laminate beams which had numerous finer hair cracks. Using CFRP laminate in the beams lead to reduction of the number of cracks. This supports findings from other researchers who reported that beams with higher number of finer cracks gave higher ductility [20, 24, 31, 33].

Failure mode

The test time after reaching the yield load of the beams was shorter than that of the previous loading stage due to the rapid propagation and widening of cracks and the development of additional cracks. The concrete crushing of all the test beams was observed. Flexural failure was observed for group (A) and shear failure was observed for group (B) strengthened in flexure zone with CFRP laminate.

Deflection

The total applied load was plotted against mid span deflection for all the tested beams as shown in Fig. 10. The load–defection was approximately linear from zero-load to crack initiation in all the beams. The large reduction in stiffness caused by excessive cracking resulted in a relatively large increase in the defection values. Closing to the failure load, the defection continued to increase, even when the applied load was constant as in [20].

The deflections at maximum load for B1-1, B1-2 and B1-4 are 6.2%, 10% and 18.8%, respectively higher than that of the control beam B1-0 without RCA for group (A). On the other hand, in group (B), The mid span deflection at maximum load for B2-0, B2-2 and B2-4 are 37.7%,36.9% and 34.6% respectively lower than that of B1-0 without RCA and without CFRP laminates. Comparing the results of B1-0 and B2-0, it can be seen that applying the CFRP laminates to the beam caused an increase of 57% in the ultimate load. The mid span deflection at maximum load for B2-2 is 42.7% lower than that of B2-0

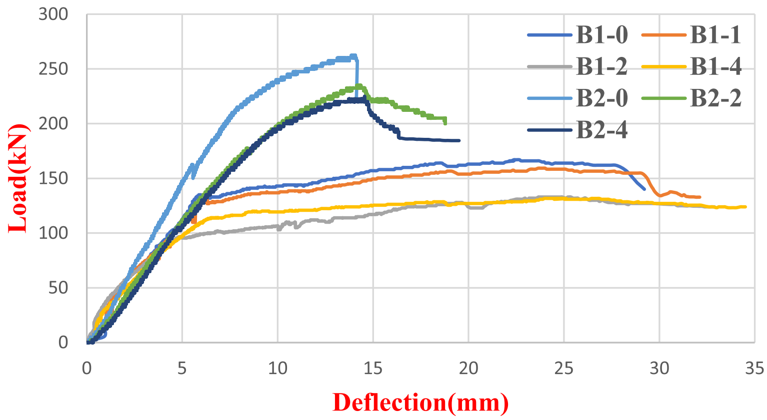


Fig. 10 Deflection of the tested beams

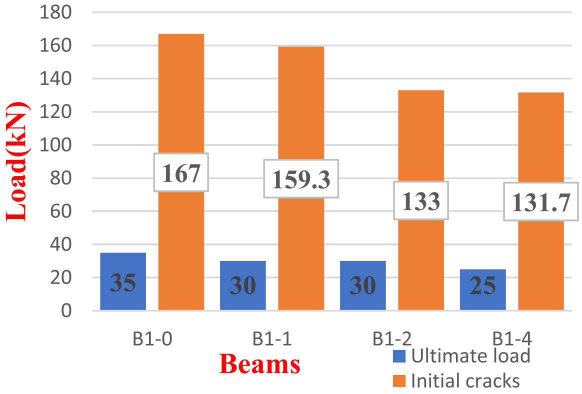


Fig. 11 Initial cracks and ultimate load for group (A)

(without CFRP laminates and with RCA). SO, increasing RCA ratios leads to increasing the mid span deflection at maximum load. And, It can be observed that there is an improvement in stifness as a result of using the CFRP [20 and 24].

Ultimate load

For group (A), the cracking and ultimate loads for beams B1-0, B1-1, B1-2, and B1-4 are compared in Fig. 11. Using recycled concrete aggregates (RCA) with ratio 25%, 50% and 100% decreased the ultimate load with ratios of 14.3%, 14.5% and 28.6%, respectively. On the other hand, in group (B), beams B2-2 and B2-4 strengthened with CFRP laminates had lower ultimate loads than B2-0 which strengthened with CFRP laminate by 10.5% and 15.2%, respectively, as shown in Fig. 12. Comparing the results of beams B2-2 and B 1–0 with and without CFRP laminates, the ultimate load still higher in B2-0 than B1-0 by 57%. So, using CFRP laminates, increase the ultimate loading capacity compared with the reference sample as in [25].

Strain in the main reinforcement

The flexure strain values for main reinforcement for beams, B1-1, B1-2, and B1-4 of group (A) are compared. Using recycled concrete aggregates with ratios of 25%,50%,

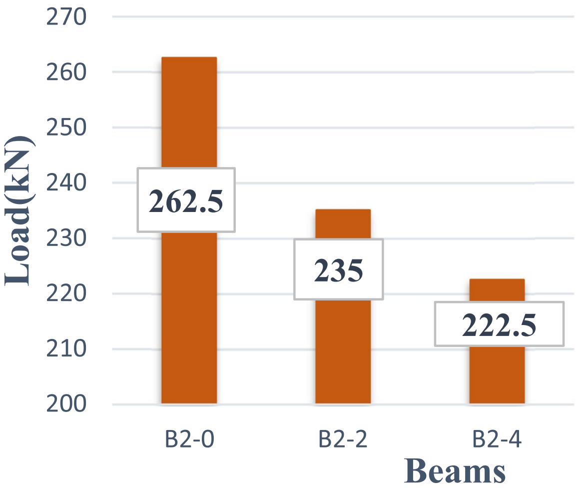


Fig. 12 Ultimate load for group (B)

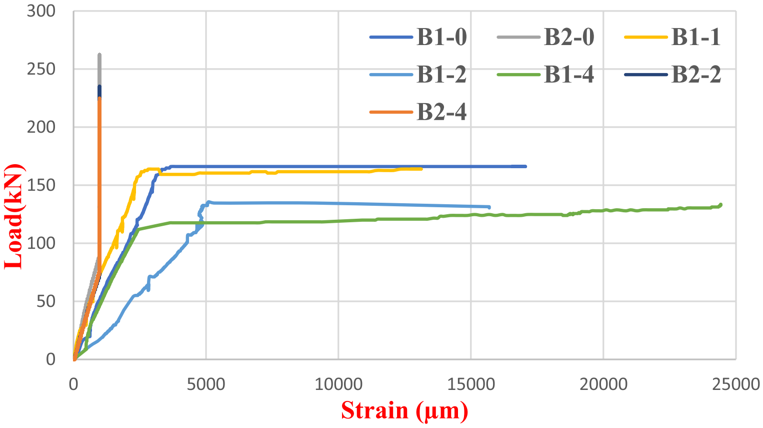


Fig. 13 Strain of main RFT for all samples

and 100% RCA, caused high decrease in the flexure strain for main steel by about 72.9%, 80.5% and 59.4% respectively compared to that of the control beam without RCA. Comparing the results of beams B1-0 and B2-0, using CFRP laminates decreases the flexure strain with ratio 72.8%. Also, comparing the results beam B1-0 with the beams in group (B), it was founded that the strains in these beams are higher than that of beam B1-0. Figure 13 shows the strain results of the tested beams. Increasing RCA ratios caused a decrease in flexure strength. Using CFRP laminates caused high decrease in the strain values in the bottom main steel.

The volumetric strain exhibited a rapid increase in the dilation strain after the peak stress for the unconfined sample, this dilation can be reduced by the CFRP confinement. where a remarkable lateral constrain was provided when the sample was wrapped with CFRP laminate layer similar to [23].

Comparison of experimental results against code provision

All beams were analyzed using ECP 203–2020 [19] and ECP 208–2019 [20] provisions for flexure and shear strength with and without CFRP laminate. To calculate the ultimate load due to shear strength for beams:

$$q_u = Q_u/bd \tag{1}$$

$$q_{u\ max} = 0.70\sqrt{f_{cu}/\gamma_c} \tag{2}$$

Where: q_u is the actual shear stress, Q_u is the shear force at critical section, *b* is the width of the section of beam, *d* is the effective depth, $q_{u\ max}$ is the maximum shear stress, f_{cu} is the compressive strength of concrete and γ_c is 1 as the nominal shear stress is calculated.

To calculate the cracking load for beams:

$$M_{cr} = F_{ctr}.I_g/Y_t \tag{3}$$

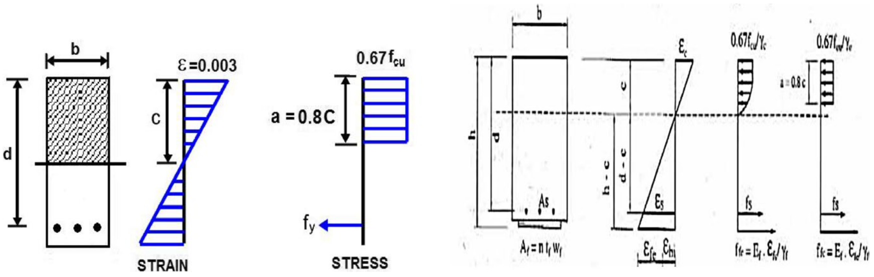
$$F_{ctr} = 0.70\sqrt{f_{cu}} \tag{4}$$

Where: M_{cr} is the cracking moment of the strengthened beams, F_{ctr} is the modulus of rupture of the concrete, I_g is the second moment of inertia of the cross section about neutral axis and Y_t is the distance from the neutral axis to the tension face of the beam. For the strengthened rectangular beams, the theoretical loads were predicted using the rectangular stress block analysis as shown in Fig. 14 (a).

$$M_u = (A_s.f_y/\gamma_s)(d - a/2) > \text{or } M_u \text{ (applied)} \tag{5}$$

$$M_u = (A_s.f_y/\gamma_s)/b(0.67\ f_{cu}/\gamma_c) \tag{6}$$

Where: A_s is the area of longitudinal tensile reinforcement section, f_y is the yield. strength of steel and γ_s is 1 as the nominal moment is calculated. From ECP 208–2019 [20] for sections subjected to flexure strength (with CFRP), the theoretical loads were predicted using the rectangular stress block analysis as shown in Fig. 14 (b).



(a): Analysis of a Rectangular Section

(b): Analysis of a Rectangular Section with CFRP

Fig. 14 Analysis of rectangular section with and without CFRP. **a** Analysis of a Rectangular Section. **b** Analysis of a Rectangular Section with CFRP

$$a = ((A_s.f_s) + (A_f.f_{fe}))/(0.65f_{cu}.b/\gamma_c) \tag{7}$$

$$M_u = A_s.f_s(d - a/2) + A_f.f_{fe}(h - a/2)\Psi \tag{8}$$

Where: A_s is the area of longitudinal tensile reinforcement, f_s is the steel stress, A_f is the area of the CFRP laminate, f_{fe} is the modulus of elasticity of CFRP sheets.

The experimental results for ultimate load for flexure and shear for the tested beams were compared to the analytical results. In Table 7, the results show that for strengthen and unstrengthen beams with CFRP, the predicted ultimate load estimated according to the Egyptian code is less than those recorded in the experimental work for group (A). This means that the code values are more conservative than the test results, and hence, the code provisions can be used safely to estimate the ultimate strength of beams made from RCA the mean value of Pexp/PECP203 ratio were 1.42, 1.36,1.13 and 1.12 respectively. For the beams strengthened with CFRP, the experimental ultimate loads are less than the flexural strength predicted from the code. The mean value of Pexp/PECP203 ratio were 0.82, 0.73 and 0.69 respectively. This is due to the premature shear failure occurred in these beams before reaching the ultimate flexural strength calculated considered the CFRP laminates.

Conclusions

The flexural behaviour of RCA beams is investigated in this research. Seven beams were tested to study the effect of RCA ratio and CFRP laminates on the flexural strength of such beams. Based on the experimental results, the following conclusions can be made:

(1) The compressive strength of concrete seems to decrease with the increase of RCA but still it is within the acceptable limits (25- 40) MPa [23, 22].
(2) The crack pattern is the same for beams with recycled coarse concrete aggregate (RCA) and beams with normal coarse aggregate (NCA) beams.

Table 7 Prediction of ultimate load for beam specimens

Beam No	Specimen description	Cracking Load ECP203-2020 (kN)	Ultimate Load (flexure strength) ECP203-2020 and ECP208-2019 (kN)	Cracking Load (kN)	Ultimate Load (Pexp) (kN)	Ratio Pexp/Pult	Type of failure
B1- 0	Group (A) Without CFRP laminate	27	117	45	167	1.42	Flexure failure
B1- 1				40	159.3	1.36	
B1- 2				30	133	1.13	
B1- 4				25	131.7	1.12	
B2- 0	Group (B) CFRP laminate		321	35	262.5	0.82	Shear failure
B2- 2				30	235	0.73	
B2- 4				25	222.5	0.69	

(3) The cracks appeared earlier in beams with RCA and increased with increasing the ratios of RCA in beams.
(4) Increasing RCA ratios in beams resulted in decreasing the ultimate loads and increasing the mid-span deflection.
(5) Comparing the experimental results with those predicted according to the Egyptian code (ECP 203–2020), the experimental cracking load was higher than the analytical load by 30%.
(6) Beams with RCA ratios of 0%, 50%, and 100% were strengthened with CFRP laminates and had higher ultimate loads by about 57% to 76.7% than that of the control beam without CFRP laminate.
(7) Increasing RCA ratios in the case of using CFRP laminates leads to a slight increase in mid-span deflection at maximum load.
(8) Beams without CFRP failed in flexure, while beams with CFRP failed in shear.
(9) So, CFRP laminates with reinforced RCA beams can be a suitable alternative to the conventional RCA beams for improves their structural indicators such as cracking loads, ultimate loads and ductility. Improvement of these structural indicators may lead to the production of CFRP laminates RCA beams which can compete with conventional reinforced concrete beams in terms of both of cost and sustainability.

Abbreviations

RC	Reinforced concrete
NCA	Normal coarse aggregates
RCA	Recycled coarse aggregates
CFRP	Carbon fiber reinforced polymer
B1-0	Control beam with normal coarse aggregates
B1-1	Beam with recycled coarse concrete aggregates with ratio 25%
B1-2	Beam with recycled coarse concrete aggregates with ratio 50%
B1-4	Beam with recycled coarse concrete aggregates with ratio 100%
B2-0	Preloading beam with recycled coarse concrete aggregates with ratio 0% repaired by CFRP.
B2-2	Preloading beam with recycled coarse concrete aggregates with ratio 50% repaired by CFRP.
B2-4	Preloading beam with recycled coarse concrete aggregates with ratio 100% repaired by CFRP

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Authors' contributions

OA cast the samples, examined and obtained the results from the lab. HA supervised and revised the work and shared in the discussion. HE was a major contributor in writing the manuscript, helped in point selection of study, and supported the experimental lab. All researchers read the manuscript and approved it.

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Availability of data and materials

All materials were available locally in Egypt. All data and materials will be available upon request.

Declarations

Competing interests

The author declares that there's no competing interests.

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