Flexural and Shear Behavior of Rubberized High Strength Reinforced Concrete Beams Strengthened with CFRP

Ahmed S. Eisa, Ahmed Gab Allah, Ragab Shaker Mahmoud
Department of Structural Engineering, Faculty of Engineering, Zagazig University, Zagazig, Egypt
Email:ahmedeisa@zu.edu.eg, eng_ahmedgaballah2010@yahoo.com, Ragabshaker@yahoo.com

Ahmed Ibrahim
Department of Civil and Environmental Engineering, University of Idaho, Moscow, ID, 83843, USA
Email:aibrahim@uidaho.edu

***Abstract*—This study presents an experimental investigation of the flexural and shear behavior of strengthened high strength concrete (HSC) beams made with rubberized concrete. CFRP has been used in strengthening of all beams in shear and bending. The concrete mixtures have included a 15% of sand replaced with crumbed rubber with a size of 2 mm. Ten (10) simple span concrete beams have been prepared and tested to promote both flexure and shear failures. The tested beams were divided into two groups, where each group was divided into five beams. The first group was tested to fail in flexure and the second group in shear. Beams with crumbed rubber showed very good flexural and shear strength and all the strengthening techniques used were very effective in both flexure and shear. It was found that the most effective flexural and shear failure loads were increased by 51% and 64%, respectively. Overall, the results showed the feasibility of using rubberized beams in structural applications.**

***Index Terms*—crumb rubber, compressive strength, strengthening, flexural Strength, CFRP, ductility**

I. Introduction

In the last 40 years, the compressive strength of cast-in-place concrete has been quite doubled, from 35 to 85 MPa. Strengths as high as 140 MPa are often achieved within the laboratory and on rare occasions in the field. Ultra-high strength concrete has been accomplished using reactive powder concrete with no coarse aggregates included. These advances have been made possible by two major developments: the introduction of high range water-reducing admixtures (HRWRA) and the utilization of nano-silica fume. Chemical admixtures allow the generation of workable concrete with very low water-to-cement ratios, and silica fume could produce cement paste with very low porosity.

Nowadays, high strength concrete (HSC) is being used more and more frequently which offers smaller sections and thus result in more useable floor space compared to normal strength concrete (NSC). In addition, HSC has been used in joints between precast columns and beams for full development strength and for improving durability and service life. In addition, early strength development of HSC could accelerate construction schedules significantly. For example, a 105 MPa of HSC could gain a one-day compressive strength of 35 MPa compared to NSC which gains it in a month. Also, HSC exhibits excellent workability and ability to self-desiccate, thus reducing or eliminating moisture problems.

Various research have investigated the replacement of fine and coarse aggregates by crumb rubber to produce rubberized concrete. Neil et al. [1], investigated the strength characteristics of rubberized concrete and examined the relationship between the size, percentage, and shape of rubber aggregate size and the strength measured. Rubberized concrete was found to possess acceptable workability, and a smaller unit weight compared to plain concrete. Overall, rubberized concrete showed greater ductility than normal concrete specimens. Toutanji et al. [2], investigated the effect of the replacement of mineral coarse aggregates by shredded rubber tire chips. All specimens were moist cured for 28 days at a temperature of 29 “C (850 F) and at a relative humidity in excess of 95%. A total of 50 cylindrical specimens were made (25 for compression and 25 for flexure). The study concluded that the failure of specimens containing rubber tire chips exhibited a ductile mode of failure compared to the control specimens. The incorporation of these rubber tire chips in concrete exhibited a reduction in compressive and flexural strengths. the reduction in compressive strength was approximately twice the reduction of the flexural strength. Similar conclusions were obtained by Zheng et al. [3], Raghvan et al. [4], and Khatib et al. [5].

The rehabilitation of infrastructures is not new, and various projects have been carried out around the world over the past two decades. Historically, steel has been the ordinary material used to strengthen concrete bridges and buildings. Bonded steel plates or stirrups have been applied externally to successfully repair concrete girders

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that are deficient in bending or in shear [6-8]. However, using steel as a strengthening element adds additional dead weight to the structure and normally requires corrosion protection. Among different types of fiber reinforced polymer (FRP) materials, carbon fiber reinforced polymers (CFRP) appears to be the most applicable in the field, regarding strength, stiffness, durability and fatigue characteristics. CFRP materials are also known to perform better at elevated temperatures [9], possess better damping characteristics and they have robust resistance to chemical corrosion compared to other FRPs.

Experimental investigation on the behavior of rubberized reinforced concrete beams has been performed by various researchers. Amer et al. [7] , investigated the effect of replacing 50% of sand by textured rubber (Crumb Rubber) that reduced 10% from specimen's weight, then using the CFRP to strengthen the flexural efficiency of beams. Five specimens with 200 x 300 x 2000 mm dimensions were investigated. Three various methods of CFRP installation have been investigated; area exposed to flatten, the second in both regions of tension and compression and the last one covered all faces by CFRP. Laboratory results showed that the weight of beams decreased by 9% and increased the ductility by 74%, in addition to crack width reduction by 9%. Strengthening beams by CFRP strips have increased the average yield and ultimate loads by 40% and 35%, respectively and by covering all beam sides, the improvements were 60% and 63%. Overall, using crumb rubber has decreased the deflection by 27% on average [8-9].

Eldin et al. [10], have reported the compressive strength results of rubberized concrete. Results of various studies indicate that the size, proportions and surface texture of rubber particles significantly affect compressive strength of rubberized concrete mixtures. Concrete mixtures with tire chips and crumb rubber aggregates exhibit lower compressive and splitting tensile strengths compared to NSC. A significant reduction of approximately 85% and 50% in compressive and splitting tensile strengths, respectively was reported when coarse aggregate was fully replaced by coarse crumb rubber chips, Eldin et al. [10]. However, a reduction of 65% in compressive strength and up to 50% in splitting tensile strength was observed when fine aggregate was fully replaced by fine crumb rubber, Eldin et al. [10]. Regardless of the strength reduction, each of those mixtures demonstrated a ductile failure and had the ability to absorb large amount of energy under compressive and tensile loads. Imam et al. [11], reported the results of strengthening reinforced concrete beams by CFRP. Sixteen reinforced concrete beams (120 x 200 x 2300 mm) were tested. The beams had been divided into four groups; each group contained four beams. Two groups were strengthened against flexural failure, while other groups were strengthened against shear failure. The variables included, longitudinal reinforced ratio, shear span-to-depth ratio (a/d), strengthening ratio and strengthening type. Laboratory results confirmed that the cracking load of the control beam for the flexural group was 30 kN while the ultimate load of control beam for flexural group was 50 kN. It was observed the cracking and failure loads have been increased by 43% and 66 %, respectively when beams were strengthened by CFRP strips. Similarly, the ultimate load of control beam for the shear group was 90 kN and when they strengthened by CFRP strips the ultimate load has increased by 18%. Khatib et al. [5], studied the workability of rubberized concrete and reported that was a decrease in slump with increasing rubber content as a percentage of total aggregate volume. They further noted that at rubber contents of 40%, slump was almost zero and concrete was not workable. It was also observed that mixtures made with fine crumb rubber were more workable than those with coarse tire chips or a combination of tire chips and crumb rubber. Because of low specific gravity of rubber particles, unit weight of mixtures containing rubber decreases with the increase in the percentage of rubber content. Moreover, increasing rubber content increased the air demand, which in turn reduced the unit weight of the mixtures. The decrease in unit weight of rubber concrete was negligible when rubber content was lower than 10 – 20% of the total aggregate volume.

The flexural strength of full-scale rubberized concrete beams have been investigated by Ismail et al. [12]. The study has included 12 self-consolidated beams made with crumb rubber and with and with steel fibers (0%, 0.35%, and 1% volume fraction). The authors have found that increasing the percentage of crumb rubber has increased ductility and decreased crack widths with a significant reduction in toughness when crumb rubber percentage exceeded 15%. The authors reported that ACI 318 [13] underestimated the ultimate flexural capacity of the tested beams. In addition, the crumb rubber inclusion has decreased the first cracking moment.

The flexural strength of crumb rubber of 12 beams has been reported by Mendis et al. [14]. The study results have been compared with three different design guidelines (ACI 318, AS 3600, and Eurocode 2). All the codes have shown a very good prediction of the cracking and ultimate moment capacities with a main conclusion of that both conventional concrete and rubberized concrete have the same flexural behavior with the same strength [14].

Most of the published research have focused on the flexural behavior of crumb rubber beams, with Ismail et al. [12] have reported the shear strength of large-scale rubberized self-compacting concrete beams reinforced with steel fibres. The crumb rubber replacement has been introduced as (0% to 35%) as fine aggregate replacements. The higher the crumb rubber percentage, the higher negative impact on mechanical properties and shear strength with noticeable improvements in the ductility and toughness. The study showed reductions in shear strength of 30.5% for crumb rubber replacement up to 25% with more reduction in strength when including higher percentages of crumb rubber.

As seen from the literature, most of the research that has been done was mainly related to the flexural and shear behavior of conventional and self-consolidating concrete made with crumb rubber as a fine aggregate replacement. The main conclusions were that crumb rubber decreases the mechanical properties and strength and increases the ductility and toughness. Very few literature has dived into the capacity, ductility and toughness of crumb rubber beams strengthened with CFRPs. The next sections describe the results of testing ten (10) high strength concrete beams made with crumb rubber and strengthened with various CFRP configurations.

II. Experimental Testing

A. Materials

Aggregate used was one size of crushed dolomite (10 mm) was used in casting of all beams. The crushed dolomite was found more suitable to be used as coarse aggregates than gravel because it has a rougher angular texture and its surface is irregular. Also, the surface area to volume ratio for the dolomite aggregate is greater than gravel and its mineralogical compatibility with the cement matrix is helping in producing high strength concrete.

The silica fume used in this work was locally produced by Ferro Alloys Factory in Edfu, Egypt. Table 1 shows the physical and chemical properties of silica fume.

Crumb rubber used in this study was an industrial product that produced from two main feed stocks, tire buffing's, consequence of tire retreated and scrap of tire rubber. Indeed, a classic scrap tire consists of 70 % recoverable rubber (by weight), 15 % steel, 3 % fiber and minor materials (e.g. inert fillers). Crumb rubber of 2 mm size was used to replace 15 % of the sand weight in all mixtures. Fig. 1 shows crumb rubber used in this research.

Two types of reinforcing bars were used in this work. The first was high strength deformed steel bars (f_y/f_{ult}=250/410 MPa) used as longitudinal reinforcement, and the second one was ordinary plain mild steel used for stirrups (web reinforcement).

Sikament®-NN was used as a high-range water-reducing admixture. It complies with ASTM C494 type A&F and EN934-2:2001. It was used in preparing medium and high strength concrete mixes. After many trails, the dosage of superplasticizer was kept constant at a value of 4% by weight of cement where it showed acceptable workability.

TABLE I. Chemical Properties of Silica Fume

Property	Measured Value	Limitations
Physical Properties		
Color	Light Grey	
Specific gravity	2.15	
Bulk Density (kg/m^3)	340	250-450
Chemical Properties		
SiO_2	97%	90% min.
C	0.5%	1% max
Fe_2O_3	0.5%	1.5% max
Al_2O_3	0.2%	1% max
Cao	0.2%	1% max
MgO	0.5%	1.5 % max
K_2O	0.5%	1.5 % max
Na_2O	0.2%	0.5% max
SO_3	0.15%	0.2 % max
Cl	< 0.01%	0.05 % max
H_2O	0.5%	0.8%

Figure 1. Crumb rubber

B. Specimens Preparation and Testing Program

In the experimental program, full-scale tests were carried out on ten (10) concrete beams with nominal cross-sectional dimensions of 100 x 200 mm with a total length of 1650 mm. All tested beams have 1500 mm clear span. All beams were simply supported and subjected to two concentrated static loads (four-point bending) and were tested at a shear span-to-depth ratio (a/d) of 2.5 as shown in Fig. 2. The beams were divided into two groups, each group consisted of five beams. Beams designed to fail in flexure had 2#10 mm lower reinforcement, 2#10 upper reinforcement, and 10 #8 stirrups as shown in Fig. 3. For beams designed to fail in shear had 4#12 lower reinforcement, 2#10 upper reinforcement, and 4#8 stirrups as shown in Fig. 3. Table II shows all CFRP strengthening details for all beams. The strain in the main reinforcements have been observed through two strain gages that were attached to the main bottom reinforcement and the concrete strain at the tension side has been recorded as well at the mid-span.

TABLE II. Illustrated the Experimental Program of the Research Study and the Schemes of Strengthening of Beams in Flexural

	Beams under Flexural		Beams under Shear
BF 1	Control beam without strengthening and without crumb rubber	BS 1	Control beam without strengthening and without crumb rubber.
BF 2	Control beam (without strengthening and with crumb rubber)	BS 2	Control beam (without strengthening and with crumb rubber)
BF 3	Single flat layer (width=10 mm at tension face)	BS 3	Single vertical side with strip (width=250 mm)
BF 4	U- shape layer (width=250 mm)	BS 4	Two vertical side strip one layer (width 100 mm)
BF 5	Double flat layers (width=100 mm at tension face)	BS 5	Double vertical side strips (width=250 mm)

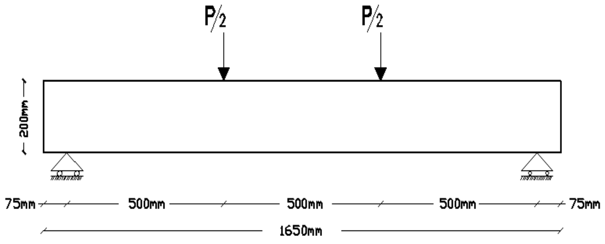


Figure 2. Beam dimensions and loading protocol

The workability of fresh concrete has been tested during mixing, where slump test was carried out to control the plastic consistency of each mix as shown in Fig. 3. Twelve standard concrete cubes (150 * 150 *150 mm) were used to determine the compressive strength (f'_c) at 28-days. The metal cube was filled with concrete in three layers and each layer received 25 blows of the standard tamping rod to be compacted according to ASTM standards as shown in Fig. 4. Table III shows the concrete mix ingredients required for 1 m^3 fresh concrete and the average compressive strength obtained at 28 days. Table III shows the mix proportions for the control and strengthened beams, respectively, and shows mix proportions for the control and strengthened beams, respectively.

TABLE III. MIXTURE PROPORTIONS OF BEAMS MADE WITH AND WITHOUT CRUMB RUBBER

Cement (kg/m^3)	Water (L/m^3)	Dolomite Aggrgate (kg/m^3)	Sand (kg/m^3)	Crumb rubber (kg/m^3)	Silica Fume (kg/m^3)	Admixtures (kg/m^3)
Mix Proportions for Control Beams (without crumb rubber)						
46	12	79	44	0.0	4.6	1.85
Mix Proportions for Control Beams (with crumb rubber)						
185	48	318	149	26	18.5	7.40

Concrete was poured in layers and compacted with a mechanical vibrator. Twenty cubes (two per each beam) were taken during the pour and compacted with a tamping rod as per the ASTM standards. Specimens were left 24 hours in the forms after which the sides of the forms were stripped away and also, the same for the standard cubes, then all beams were covered by wet towels for 28 days while the concrete cubes were cured by submerging them in clean tab water for 28 days. After 28 days of curing, Carbon fiber reinforced polymer (CFRP) was applied to all beams as will be discussed next.

C. *Carbon FRP Wraps Installation*

The CFRP (SkisaWrap Hex-230C) fabric was acquired from Sika Inc. and cut as per the designed size. The sikadur®-330 resin and hardener was mixed with a ratio of 4:1, respectively. The mixed sikadur®-330 was applied to surface of the beam which would be strengthened, where the carbon fiber sheets were applied to the area where the resin is and then pressure was applied to get rid of any air void between the CFRP sheets and the concrete surface. The thickness of the CFRP fabric layer was 0.128 mm, tensile strength of 3,450 MPa, and the elastic modulus was 230 GPa. Figs. 3 and 5 show all the CFRP strengthening configurations for beams tested under flexure and shear.

III. RESULTS AND DISSCUSSIONS

The concrete cubes have been tested before the application of the CFRP sheets (28-days) to ensure that all beams have reached the target compressive strength. It was found that the cubes made with no crumb rubber and with crumb rubber achieved 770 kg/cm^2 (75.5 MPa), and 500 kg/cm^2 (49.03 MPa), respectively.

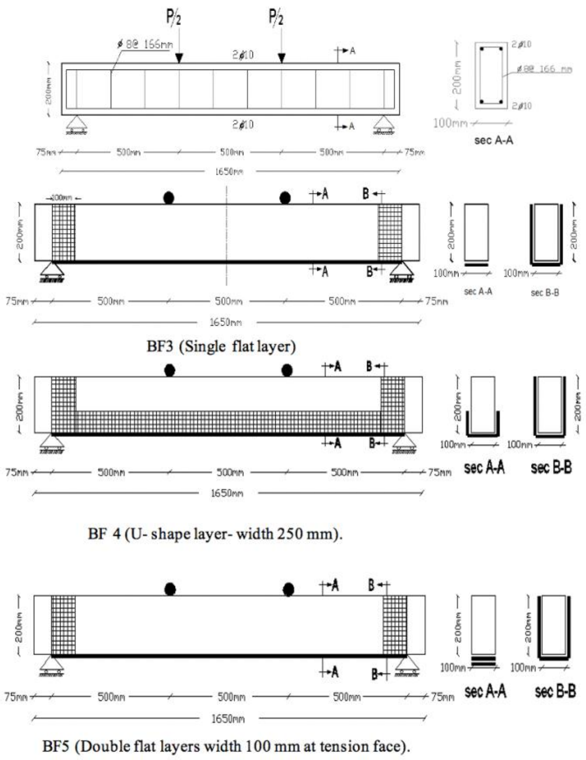


Figure 3. Schematic of strengthening of beams in flexural.

Figure 4. Slump test

A. *Flexural Strengthening Mode of Failure*

For all tested beams, the initial crack load, failure load, deflection at mid- span, strain at midspan (tension side for concrete and steel), crack pattern, and mode of failure were observed and recorded. Fig. 6 shows all beams tested under flexure which experienced flexural mode of failure. Table IV shows the cracking and failure loads for all beams. It was noticed from Table IV that the cracking and the failure loads for the beam made with crumb rubber (BF2) has decreased by 4% and 8%, respectively and the ultimate load for beams BF3, BF4, and BF5 were increased by 37.7%, 51%, and 42.8%, respectively. The highest increase in the ultimate load was for beam BF4 that has double layers of the CFRP incorporated with beam side strengthening.

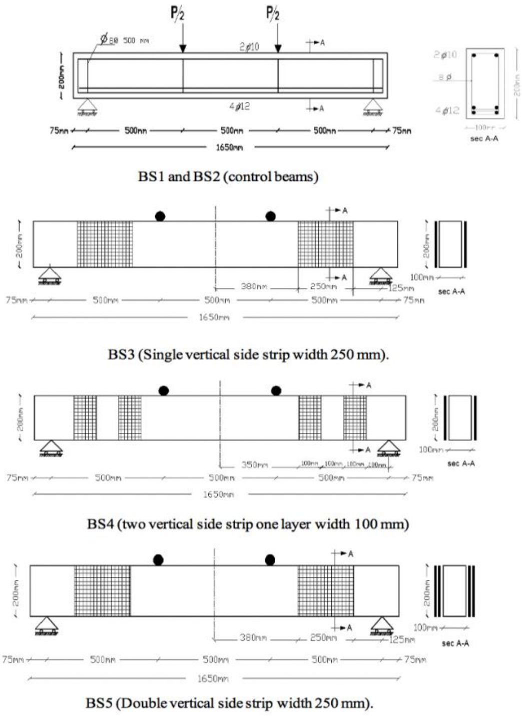


Figure 5. Schematic of strengthening of beams in Shear.

The load-deformation of all tested beams have been recorded at the midspan as shown in Figure 7. Overall, the deflections were decreased by applying CFRP sheets. The ultimate deflection for the control beam (BF1) was 18 mm while the ultimate deflection of the control beam (BF2) containing 15 % rubber was 20 mm, which indicates an increase of 11 % compared to the control beam BF1.

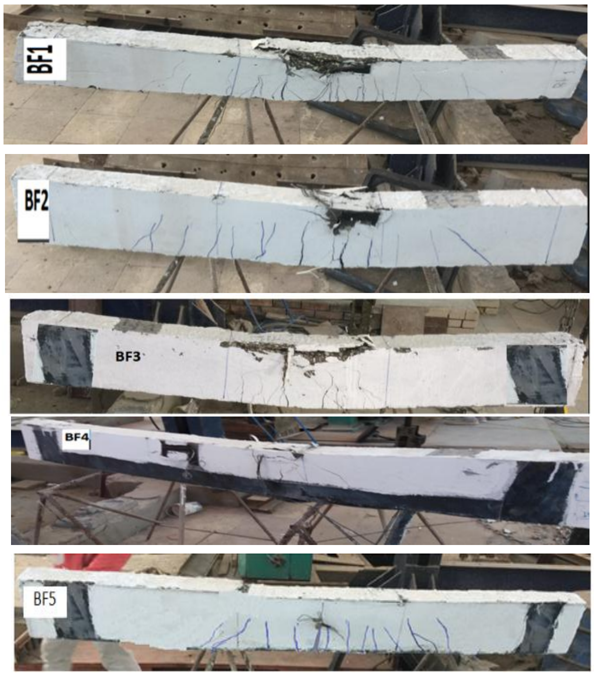


Figure 6. Crack pattern for beams tested under flexure

The strengthened beams' deflections have decreased by 20%, 50 % and 35 % for beams BF3, BF4, and BF5, respectively. All beams showed very similar initial stiffness except for beam BF4 that showed higher stiffness due to the high stiffness of the two added layers of CFRP at the tension side in addition to the longitudinal CFRP warps. Once the first crack has identified, all beams showed nonlinear behavior accompanied by strain hardening followed by reaching to the ultimate load and strain softening till failure. Ductility is defined as the energy absorbed by the material until complete failure occurs. The ductility was greatly affected by the various strengthening techniques. The beams with the highest ductility were BF1 and BF2 (no strengthening), followed by beam BF3 and lastly BF4, and BF5.

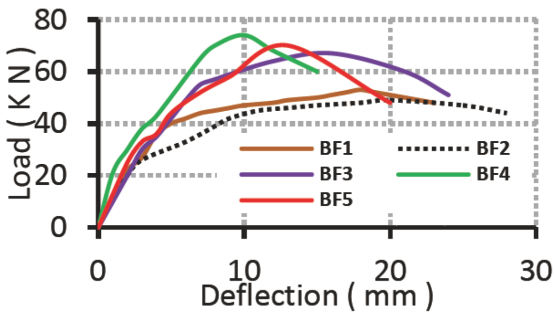


Figure 7. Load-deflection for tested beams under flexure

It can be seen from Table IV that the ductility index for reference specimen BF1 was 2.40 while for specimens BF1 and BF2, the ductility has increased by 38% and by using the CFRP, the ductility was increased by 33%, 18% and 20% for BF3, BF4 and BF5, respectively compared with beam BF1. Table 4 reveals that the toughness was increased by about 21% for control beam (BF2) compared to beam (BF1) and it can be seen that the toughness was decreased as a result of the various strengthening techniques by 43%, 46% and 45% for beams BF3, BF4 and BF5, respectively compared with (BF1).

In terms of the steel and concrete strain at the tension side. Figs. 8a and 8b show that the reinforcement in all beams have been yielded except beam BF5 which showed stiffer behavior with low ductility and toughness as outlined earlier. The concrete tensile strength has been significantly decreased when CFRP was applied as shown in Fig. 8b.

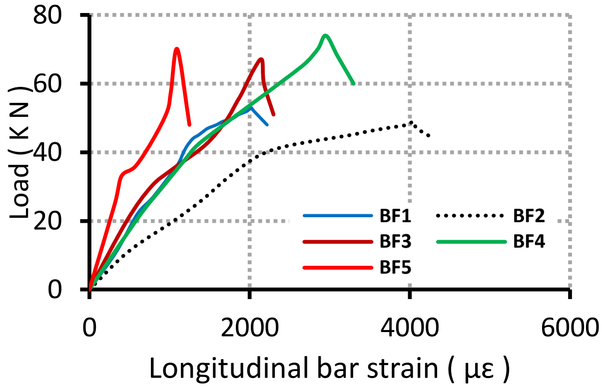


Figure 8a. Steel longitudinal strain at the mid-span.

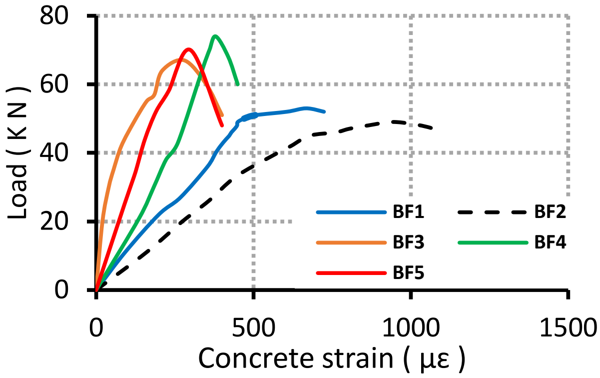


Figure 8b. Concrete longitudinal strain at the mid-span.

B. *Shear Strengthening*

Figure 8 shows the crack patterns and mode of failure of the tested beams under shear. The behavior of all tested beams under shear was very different as expected than the behavior under flexural failure. All beams experienced sudden diagonal typical unsymmetrical shear crack extended from one of the supports to the point of load application. This mode of failure was observed in the control and unstrengthen beams. It was observed also that the shear crack has extended through the carbon fiber layers for beams BS3 and BS4 and when two layers of CFRP were added to the shear span (BS5), the shear strength was greatly enhanced and the shear crack did not cross the CFRP layers as shown in Figure 9.

Generally, the experimental results exhibited that, externally CFRP bonded at the shear span of the beams were effective for shear strengthening. The deflections at the midspan were decreased by applying CFRP sheets. The ultimate deflection for control beam (BS1) was 10 mm while the ultimate deflection of control beam (BS2) containing 15 % rubber was increased by 20% compared to beam BS1. The deflections of (BS3, BS4 and BS5) were decreased by 58%, 42% and 75%, respectively, which explains that the externally reinforced bonded CFRP enhanced (increased) deflections for shear strengthening beams. Figure 10 shows tensile strain in steel reinforcements where bars for BS4 and BS5 have reached the yield strain.

TABLE IV. STRENGTH CHARACTERISTICS OF FLEXURAL TESTED SPECIMEN

Beam Number	P_c (kN)	P_c/P_{cr}*	P_y (kN)	P_u (kN)	P_u/P_{ur}*	Δ_y	Δ_y / Δ_{yr}*	Δ_u	Δ_u / Δ_{ur}*	Δ_u / Δ_y	Toughness (kN. m)
BF1	27.00	1.00	25.00	53.00	1.00	7.50	1.00	18.00	1.00	2.40	21,335
BF2	26.00	0.96	22.00	49.00	0.90	6.00	0.80	20.00	1.10	3.33	25,800
BF3	30.00	1.15	35.00	67.00	1.37	5.00	0.67	16.00	0.89	3.20	12,200
BF4	43.00	1.65	40.00	74.00	1.51	3.50	0.47	10.00	0.56	2.85	11,500
BF5	33.00	1.27	36.00	70.00	1.43	4.50	0.60	13.00	0.72	2.90	11,600

(P_{cr*} , P_{yr*} , P_{ur*}) : Cracking , yielding and ultimate loads for BF2 (reference beam).
(P_c , P_y, P_u) : Cracking , yielding and ultimate load for reubberized beams
Δu , Δy : Deflection at ultimate and yield load
Δu /Δy: Ductility index

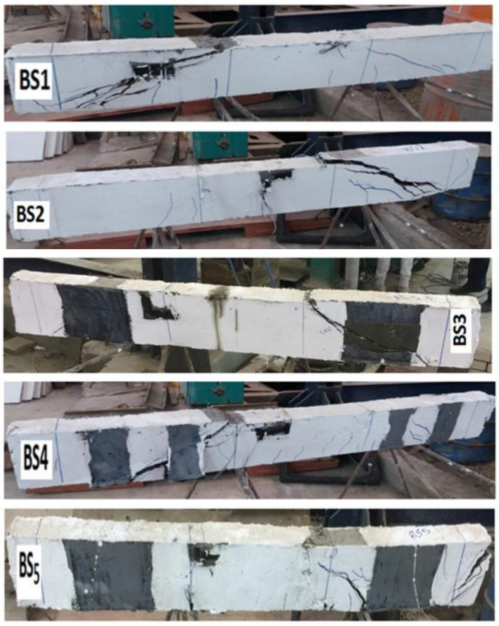
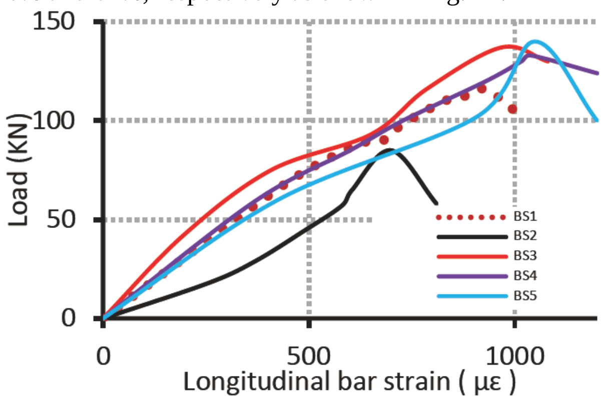


Figure 9. Crack pattern and mode of failure of beams strengthened under shear.

The ultimate failure loads were increased by applying CFRP sheets using the various configurations illustrated earlier. The ultimate failure load for the control beam (BS1) was 116 kN while the ultimate failure loads of control beam (BS2) was 85 kN with a percentage of decrease equals to 26 % compared to control beam BS1. All other beams (BS3, BS4, and BS5) experienced very good enhancement in the failure loads by about 61%, 56% and 64%, respectively as shown in Fig. 11.



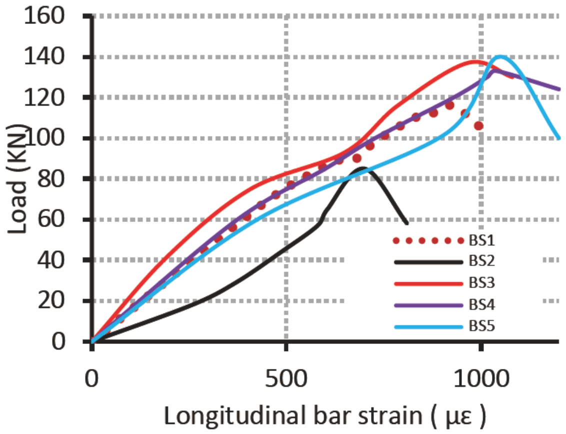


Figure 10. Load-strain for tested beams under shear

Table V shows that the experimental yield load was decreased by 7 % for specimen BS2 compared with BS1. However, the yield load has increased by (52%, 44% and 86%) for BS3, BS4 and BS5, respectively. In addition, the ductility index for the reference specimen BS1 was 3.30, while the ductility of BS2 with crumb rubber has increased by 21%. Finally, the ductility of BS3, BS4 and BS5 were decreased by 49%, 29% and 70 %, respectively compared with (BS1).

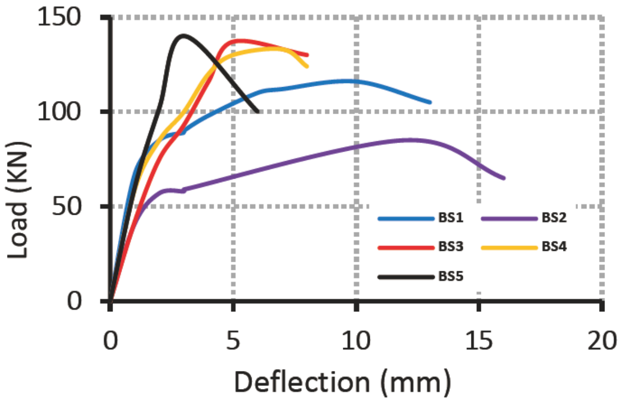


Figure 11. Load-deflection for tested beams under shear

Table V also reveals that the toughness of beam BS2 has decreased by 19% compared to BS1 with the highest increase in toughness was observed for beams BS3 and BS4 (19 % and 32%) compared to BS1.

C. Theoretical and Experimental Cracking Moment

The theoretical cracking moment was calculated based on the ACI 318-19 as shown in Equation 1 and compared to the experimental results.

$$M_{cr-ACI} = f_r \frac{I_g}{y_t} \tag{1}$$

where f_r is the modulus of rupture = $0.62\sqrt{f_c'}$, y_t is the distance form the neutral axis to the extreme tension fiber, and I_g is the gross moment of inertia. ACI 318 and AASHTO LRFD has recommended to use the previous equation in calculating the modulus of rupture for concrete strength up to 124 MPa, Logan et al. [15].

TABLE V. STRENGTH CHARACTERISTICS OF SHEAR TESTED SPECIMEN

Beam	P_c (kN)	Pc/Pcr*	Py (kN)	Py / Pyr*	Pu (kN)	Pu / Pur*	Δy	ΔY / Δyr*	Δ u	Δu / Δur*	Δu / Δy	Toughness kN. m
BS1	89.00	1.00	85	1.00	116	1.00	3.00	1.00	10.00	1.00	3.30	20,400
BS2	57.00	0.64	59	0.69	85	0.73	3.00	1.00	12.00	1.20	4.00	16,450
BS3	93.00	1.04	90	1.60	137	1.61	3.00	1.00	5.00	0.50	1.66	24,300
BS4	85.00	0.96	85	1.00	133	1.56	3.00	1.00	7.00	0.70	2.33	18,600
BS5	102.0	1.15	110	1.29	140	1.64	3.00	1.00	3.00	0.30	1.00	27,000

Fig. 12 shows that ACI 318-19 significantly underestimated the cracking moment for beams made without crumb rubber (BF1 and BS1). However the implementation of CFRP has increased the cracking moment for all beams tested under flexure and significantly has increased for beams tested under shear. The cracking moment for beam BF4 showed an increase of 27.1% compared to theoretical ACI 318 cracking moment for beams made with rubber. On the other hand, beam BS5 has showed an increase of 78.5% in cracking moment to the ACI 318-19 value.

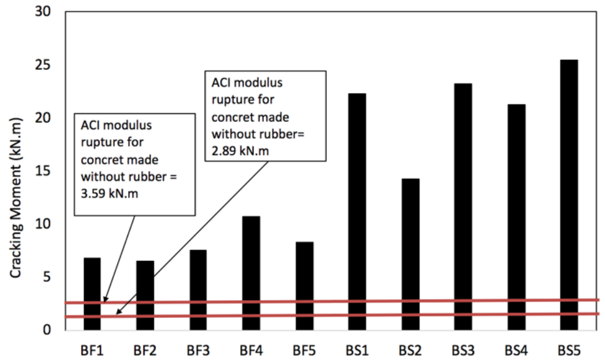


Figure 12. Theoretical and experimental cracking moments for all tested beams.

IV. CONCLUSIONS

This paper presents an experimental investigation to study the felxural and shear behavior of rubberized high strength concrete beams strengthened with various CFRP configurations. The goal was to quantify the enhancement in craking load, ultimate load, ductility and toughness of the strengthened rubberized high strength concrete beams. The results were compared to conventional high strength concrete beams that were considered cas ontrol specimens. A series of ten high strength reinforced concrete beams were fabricated and tested up to failure. All beams were divided into two groups, each group had five beams. The first group was designed and tested to fail under flexure and the second group was tested to fail due to shear. In each group, two control beams were considered; one beam was a conventional high strength concrete beam and the second was a rubberized (15% of the sand was replaced by 2 mm crumb rubber) concrete. Three beams in each group were then strengthened with externally bonded CFRP sheets. The following conclusions were drawn:

A. Beams Tested under Flexure

1. The compressive strength of rubberized high strength reinforced concrete has reduced by 35%, and the

weight was decreased by 3% on the average when 15% of sand has been replaced by 2 mm crumb rubber.

2. Beams strengthened by CFRP have shown a decrease of 35% in deflection on average.

3. The flexural cracking load of the strengthened beams have been significantly improved by15%, 65% and 27% for beams strengthened by single flat layer, U-shape single layer and double flat layers, respectively with an average increase in the flexural cracking load of 36%.

4. The flexural yield load of the strengthened beams has increased by 60%, 80% and 64% using single flat layer, U- shape single layer and double flat layers, respectively. In addition, the ultimate flexural failure load was increased by 37%, 51% and 43% for the same beams.

5. The ductility of rubberized high strength concrete beams tested in flexure has increased by 38% on average. While for beams strengthened using CFRP, the ductility was improved and increased by 24% on average.

6. By using 15% of 2 mm crumb rubber, the toughness has increased by 21%. While using the CFRP, the toughness was decreased by 45% on the average.

B. Beams Tested under Shear

7. Midspan deflection was decreased by 58%, 41% and 75% for beams strengthened in the shear span using single vertical side strips, two vertical side strips and double vertical side strips, respectively. In addition, It was observed that the shear cracking load of the strengthened beams has increased by 63%, 49% and 79% for beams BS3, BS4, and BS5, respectively.

8. The ultimate load has increased by 61%, 56% and 64% for beams BS3, BS4, and BS5, respectively.

9. Finally, the ductility of the control rubberized beam has increased by about 21% on average. While for the strengthened beams, the ductility was decreased by 23 % on the average.

10. Overall, it is feasible to produce HSC with crumb rubber without compromising the structural integrity of the concrete.

Conflict of Interest

All authors have no conflict of interest

Author Contributions

All authors contributed equally producing this manuscript.

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Ahmed S. Eisa is a Professor of Structural Engineering at Zagazig University, Egypt. His area of research is focused on structural concrete members and their behavior under various loading conditions.

Ahmed Gab Allah is a former graduate student at the department of structural engineering at Zagazig University, Egypt.

Ragab Shaker Mahmoud is a lecture at the at the department of structural engineering at Zagazig University, Egypt. His research interests are in the behavior of structural engineering.

Ahmed Ibrahim is the corresponding author and he is an Associate Professor at the Department of Civil and Environmental Engineering at the University of Idaho. His research interests are focused on the dynamic behavior of structural elements and under extreme loading conditions, and the behavior of composite members and its applications in the field of structural engineering.