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Research Article

Behavior of rubberized concrete deep beams reinforced with GFRP bars

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Abstract

Recently, glass fiber-reinforced polymer (GFRP) bars have been considered are emerging as a potential alternative to steel rebars due to their durability and resistance to corrosion. However, investigations on shear behavior of rubberized RC beams modified with GFRP bars have not been well established. On the other side, it is possible to reduce the dangerous materials found in tires and generate sustainable crumb rubberized concrete. In this study, the static performance of rubberized concrete deep beams reinforced with GFRP bars was evaluated. Rubber crumbs are substituted with fine sand aggregate in volumetric replacement ratios to create rubberized concrete. The primary factors were the amount of crumb rubber (0%, 10%, and 20%) and the main ratio of reinforcement ($\rho 1 = 0.0085$ *and* $\rho 2 = 0.0113$). Six RC deep beams having dimensions of (1400×300×150) (Length×Depth×Width) subjected to a 4-point loading up to failure. The mixture strength properties, load-midspan deflection curves, first crack, the effect of GFRP reinforcement ratio, and ductility index were the parameters examined. The results showed that increasing the volumetric percentage of rubber aggregate declined the compressive and splitting strengths of concrete mix. It was revealed that the behavior of the rubberized concrete deep beams influenced the load-deflection performance, the ultimate load, the increase in the deflection and ductility index. The test results reveal the significance of the GFRP bars, which are found to effectively improve the ultimate load and deflection of RC beams and increase the load before initiating cracking. The deep beams with 10% rubber and a higher reinforcement ratio showed the highest ultimate load and deflection and improved ductility, with an increase of 61%, 147.6%, and 25%, respectively, in comparison to the reference samples.

1. Introduction

Recently, concrete can be considered as the most widely used material around the world, and its production requires continuous natural resources. There is a need to find alternatives using recycled solid waste to produce sustainable concrete. On the other hand, many countries suffer from the problem of car tires accumulating as solid waste. Over the next 30 years, the amount of rubbish generated worldwide is expected to increase to be 3.4 billion tons in the year 2025[1]. Therefore, a significant profit can be attained by re-utilizing these discarded tires in civil engineering sector in the future. According to Kordoghli et al. [2], tire dumping in the ground causes environmental and economic problems, as it can lead to fires and emissions that are difficult to control. One of the inventive ideas was to make rubberized concrete with rubber crumbs. Rubber crumbs having size ranged between (4.75 and 75 mm) are produced by cutting, shredding, and grinding rubber tires. With fine aggregate, volumetric replacement is employed at ratios of 5%, 10%, 15%, etc.[3, 4]. Limited studies (small and medium-sized samples) have been published. The

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use of crumb rubber particles as a substitute for sand aggregates at various ratios was the main focus of these investigations. The results demonstrated limited workability and a decline in concrete's mechanical qualities, which is proportional to crumb rubber aggregate volume[5]. Nonetheless, several results illustrated that inclusion of rubber aggregate decreased the self-weight, enhanced concrete toughness, strain capacity, and ductility index[6]. According to[7], the results of the study indicated a 12.7%, 21.7%, and 26.0% decrease in compressive strength at 5%, 10%, and 15%, rubber aggregate ratio, respectively. Comparable to the deterioration in the compressive strength, the elastic modulus decreased by 9.4%, 13.9%, and 18.5%, respectively. Alasmari et al. [8] evaluated the flexural performance of rubberized RC beams under four-point load. Crumb rubber aggregate was substituted with 10%, 12.5%, and 15% of sand (volume). The initial cracking load of the rubberized RC beams dropped by approximately 9% when compared to the control and 16% when 15% rubber crumb was included. The inclusion of crumb rubber, which ranged from 0% to 15%, increased the hardness of the rubberized concrete beams by an average of 24.1%. Moreover, to evaluate the influence of rubber aggregate on deformability, the ductility index of rubberized RC beams increased by 111% and 35%, respectively. In a recent study[9], fourteen rubberized reinforced concrete continuous RC deep beam of steel reinforcement bars and plain RC (ORC) as a reference was investigated and designed to fail in shear. One of the study parameters crumb and chips tire rubber that utilized by replacing of fine and coarse aggregates, respectively, with varied volumes (5% to 20% for each type). The results showed that the ultimate load of continuous RC rubberized deep beams decreased by 32% and 33% at 20% replacing of fine and coarse aggregates, respectively. However, a significant decrease in the max. deflection by 83.1% and 106.3% was obtained at same aggregate replacement of 20%. Moreover, the ductility of the continuous rubberized RC deep beams increased up to 37% at 20% rubber crumb ratio. Sandeep et al.[10] conducted a research, in a pilot study, described improving the performance of shear deep beams using concrete containing rubber crumbs. Rubber content (0%, 10%, and 20%) was the primary factor. Except for the reference sample, which failed due to a combination of flexure and shear (flexure-shear failure), all the beams failed under diagonal stress. It was noted from the results that the addition of 10% of processed crumbled rubber increased the strength of the deep beams and enhanced the load of the first crack, and is recommended in structural applications. The results approved that ductility index at shear is directly proportional to crumb rubber content. The increases in ductility index were observed to be 18%, 21%, and 22% at rubber ratio of 10%, 15%, and 20%, respectively.

The shear response of rubberized concrete deep beams reinforced with glass fiber-reinforced polymer (GFRP) bars is scarce, whereas the behavior of concrete steel bar-reinforced deep beams has been well studied in previous research. On the other hand, glass fiber-reinforced polymer (GFRP) is a potential non-corrosive substitute for steel[11]. In concrete structures, steel rebar corrosion weakens the concrete and obscures structural performance, safety, and serviceability, all of which are expensive to maintain and repair. This makes GFRP rods suitable for structures exposed to harsh environments, thus imparting desirable properties when using GFRP bars, such as higher stress resistance, higher tensile-to-weight ratio, crack width control, and non-magnetic properties[12]. According to [13], their study investigated the synergistic effect of steel fibers and rubber aggregate on the shear behavior of high-strength RC beams supported with glass FRP (GFRP) bars. Among the variables investigated, the GFRP reinforcement ratio (ρ_f = 0.89 and ρ_f = 0.34) and rubber aggregate content (0%, 5%, 10%). The results showed that the beam shear capacity increased as the GFRP reinforcement ratio increased, the crack number increased by 10% with a 10% increase in CR concentration. The use of CR may be responsible for this decrease in fracture width. In general, it was found that the measured load-mid-span deflection associated with the beam failure load decreased for specimens containing 5% and 10% CR.

The above reviews show that the behavior of deep beams of rubberized concrete reinforced with GFRP bars is not well understood, due to which a recent study has highlighted the need for more research in this direction. On the other side, ACI 440 [14]does not provide design guidelines for GFRP-RC deep beams due to a lack of published research on this subject. The importance of this study was to bridge the gap in part by evaluating the behavior of deep rubberized concrete beams reinforced with GFRP bars. The proportions of rubber crumb (10% ,20%) were selected based on previous reviews that show the possibility of using them in the production of recycled rubber concrete, that can be developed in the manufacturing of green structural concrete in the future. Additionally, this study evaluates the prospect of rubberized concrete with GFRP bars as a solution to the problem of critical shear behavior of deep beams and the associated ductility problems with GFRP bars.

2. Experimental Program

Six deep beams that are intended to fail under shear are being tested as part of the experimental program. For all deep beams considered in the study, the total length is 1400 mm, depth of 300 mm, and 150 mm wide. Two variables were considered in this study: the first variable is the effect of crumb rubber percentage (0%, 10%, and 20%) and the second variable is the ratio of the main reinforcement (ρ) which were (ρ_1=0.0085 and ρ_2=0.0113). The selection of the sample size and criterion was based on the minimum requirements of the deep threshold core according to the conditions in the American Code[15] . In the sections that follow, mixture proportioning, sample preparation, and testing is discussed in further detail, along with the characteristics of the various constituent elements.

2.1. Materials

2.1.1 Cement

Type I, OPC was utilized in this experiment for sample casting, as presented in Fig.1. The chemical composition of the main ingredients of this type of cement are presented in Table 1. The OPC physical properties are listed in Table 2.

2.1.2 Aggregates (Fine and Coarse)

The max. size of the crushed coarse aggregate used in this study is 12 mm. Natural river sand of max. size 4.75 mm was utilized as fine aggregate. Both adhere to Iraqi Specification No. 45 [16]. The PSD of sand and coarse aggregates is presented in Tables 3 and 4, respectively.

2.1.3 Crumb Rubber

Crumb rubber was utilized with a relative density = 1.1 according to ASTM D854 [17]. The particle size ranged between 4.75 and 0.075 mm. The rubber aggregate was utilized as a volumetric replacement ratio (10%and 20%) by the natural sand aggregate (Vol.). It had little absorption. The PSD of the crumb rubber aggregate was carried out following ASTM C136 [18].

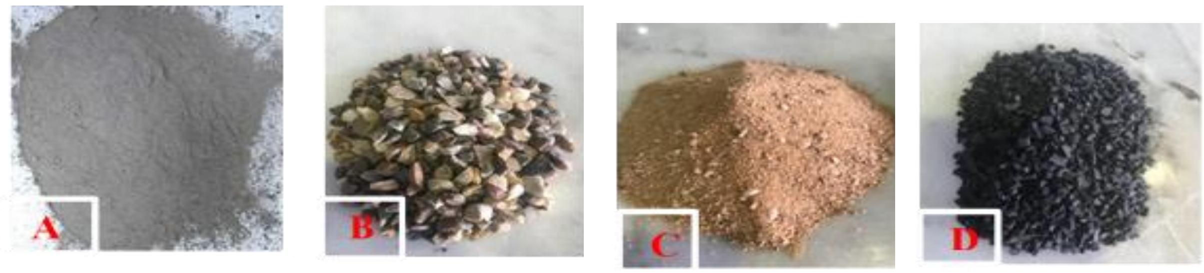


Fig. 1. (A) OPC, (B) crushed coarse aggregate, (C) sand, and (D) rubber aggregate

2.1.4 Reinforcement Bars

Reinforcement bars regular ordinary steel bars and glass fiber reinforced polymer (GFRP) bars were used to reinforce beams. GFRP serves as the primary longitudinal reinforcement in this investigation and has a diam. of 12 mm. Steel reinforcement diam. is 6 mm. Table 5 shows the mechanical characteristics of the reinforcements utilized in this work.

Table 1. The cement's chemical composition

Chemical Compound	% Weight	The Iraqi standard's limit. (No. 5/2019)
CaO	64.2	-
Fe_2O_3	3.4	-
SiO_2	21.1	-
Al_2O_3	3.81	≤ 3.5
MgO	2.2	A max of 5%
Main compounds	Oxide% by Weight	Iraqi standard No. 5/2019 Limits
C3A	5.4	≤ 3.5%
C4AF	14.62	-
C3S	19.42	-
C2S	49.45	-

Table 2. Physical properties of OPC

Property	Values	Limits of Iraqi Standards IQS 5-2019
Setting time		
Initial	160	≥ 45 [min]
Final	246	Less than 600 [min]
Fineness (Blaine method) in cm^2/g	2531	≥ 2500 cm^2/g
Comp. strength (2 days) [MPa]	12.4	Not less than 10 MPa
Comp. strength (28 days) [MPa]	42.3	Not less than 32.5 [Mpa]

Table 3. Sieve analysis of natural sand

Size of the mesh [mm]	% Passing	Limits of IOS (NO. 45-1984)[16]
10	100	100
4.75	99	90-100
2.36	85	75-100
1.18	72	55-90
600 mics	55	35-59
300 mics	16	8-30
150 mics	3	0-10

Table 4. Sieve analysis for coarse aggregates

Size of the mesh [mm]	% Passing	Limits of IOS (NO. 45-1984)[16]
20	100	100
14	100	90-100
10	81	50-85
5	10	0-10

Table 5. Physical properties of the steel reinforcements and GFRP bars

Type	Diam. [mm]	Area [mm^2]	Yield stress [MPa]	Ult. strength [MPa]
Steel bar	6	28.27	596	613
GFRP bar	12	113	-----	822

2.2 Mixing Proportions

To achieve the necessary compressive strength and workability, trial mixes using ACI 211 method was adopted in this study. Th w/c ratio was selected to be 0.47. A 35 MPa compressive strength was adopted as a design strength criterion. The amount of crumb rubber added to each batch of concrete resulted in three different compositions. Table 6 lists the ingredients for each blend. Each group contains a different rubber ratio.

Table 6. Mixing percentages (kg/m^3)

Mix Type	Cement	Coarse Agg.	Fine Agg.	Water	Crumb rubber	w/c
REF.(Rub0%)	420	1015	800	210	0	0.47
Rub10%	420	1015	720	210	36.4	0.47
Rub20%	420	1015	640	210	72.4	0.47

2.3 Mixing Method

In order to make sure that every mixture experienced the same conditions, the same mixing method was generally applied throughout the experiment. The inside surface of the 0.07 m3 rotary mixer had been cleaned and lubricated before to use. Preparing the weights of the materials required and utilized for every sample was the first stage. Initially the coarse aggregate was added and then the fine aggregate was well mixed for four minutes and then the cement and mixing were added for four minutes. Meanwhile, the rubber crumbs and dry mixing were added for four minutes, after making a consistent combination, the water was gradually added and mixing with an approximate time of about 10 minutes (total). Later, after the mixture being homogenized, the concrete was poured to the molds. All deep beam molds were prepared and lightly greased. In this experiment, a rod vibrator was employed. Twenty-four hours after casting, the molds were taken out. During the 28-day curing phase, the burlap covering was kept damp.

2.4 Sample Descriptions and Test Setup

As illustrated in Fig. 2, six simply supported RC deep beams were built for this investigation and tested until they failed under the influence of two-point symmetric stress. The rectangular cross-section of each beam was the same, with fixed dimensions (b=150×h=300 mm). The total length of the tested beam was 1400 mm, and the tested span (clear) was 1200 mm. The deep beams were grouped into two categories, (R1 and R2), the first category (R1) representing three samples with the same main reinforcement ratio (ρ1) with the difference in the content of rubber, which stands for (0%,10% and 20%) and second category (R2) representing three samples with the same main reinforcement ratio (ρ2) with the difference in the content of rubber, which stands for (0%,10% and 20%). Additionally, longitudinal and transverse steel rebars having diameter of 6 mm are utilized as the beam web reinforcement. Loads were applied to each beam at two symmetrical locations to produce a constant moment zone spanning 400 mm to investigate the flexural performance of RC deep beams with selected various rubber content.

A hydraulic jack and plate spaced 400 mm apart were used to apply two concentrated loads on the deep beam. In the middle of the sample and beneath the loading points, three LVDTs were employed. The hydraulic machine in Fig.3 shows the load increments until the maximum load is attained. All samples' fracture propagation both during loading and at the point of failure was noted. Show Tab.7 rubber content and the number of GFRP for each deep beam.

Table 7. Details of samples

Sample	Rubber content (%)	Reinforcement ratio (ρ)	No. of GFRP	Diameter of GFRP	Shear span	Width mm	Length mm	Depth mm
R1-0%	0	0.0085	3	12	400	150	300	1400
R1-10%	10	0.0085	3	12	400	150	300	1400
R1-20%	20	0.0085	3	12	400	150	300	1400
R2-0%	0	0.0113	4	12	400	150	300	1400
R2-10%	10	0.0113	4	12	400	150	300	1400
R2-20%	20	0.0113	4	12	400	150	300	1400

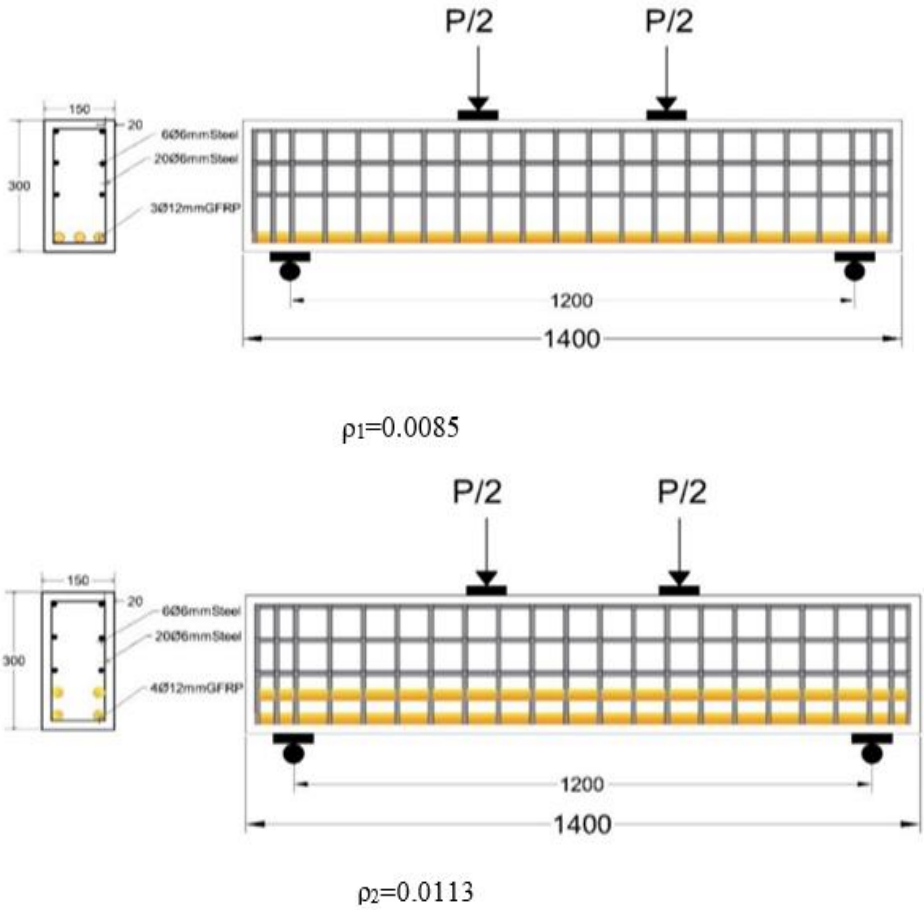


Fig. 2. Details of dimensions and reinforcement

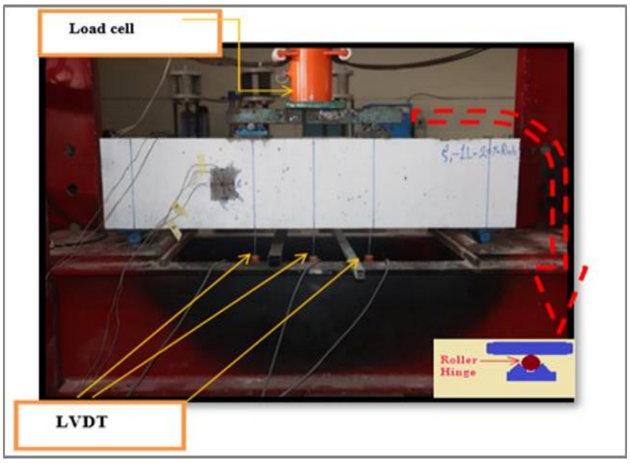


Fig. 3. Deep beams test details

3. Result and Discussion

A brief summary of the results and conclusions derived from the analysis of these results is given in the following sections.

3.1 Mechanical Properties of Rubberized Concrete

3.1.1 Workability (Slump) test

Fig. 4 displays the slump test results for both rubberized and regular concrete. Slump values were shown to decrease with an increase of crumb rubber (10%, 20%). This study examined different ratios of freshly mixed concrete to crumb rubber (0%, 10%, and 20%). The mixture with 0% rubber had a 90 mm slump, 10% rubber produced an 80 mm slump, and 20% rubber produced a 70 mm. Rubber particles have a rougher surface with heterogeneous shape compared to the natural sand particles, which is the cause of the decline[19]. As a result, inter-particle frictional resistance rises and work capacity falls[20].

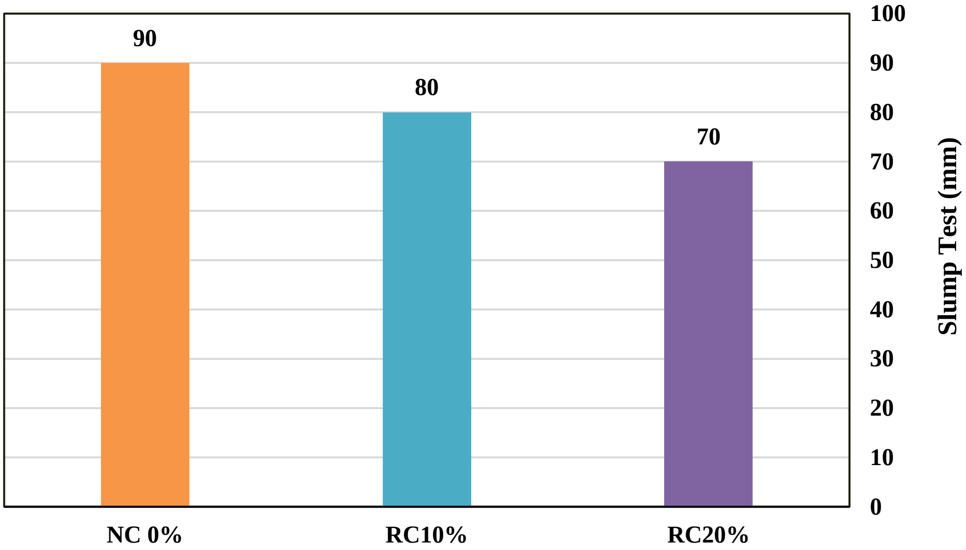
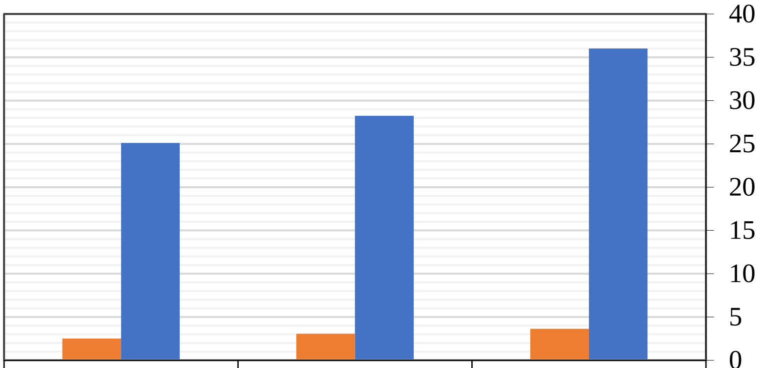


Fig. 4. The results of the slump test for both regular and rubberized concrete mixtures with varying rubber contents

3.1.2 Test of Compressive Strength

One of the most important factors taken into consideration is the concrete's compressive strength. Samples are inspected according to the approved specification ASTM C39 [21]. Rubberized concrete mixes were prepared considering two replacement ratios of 10% and 20%. In addition, a reference mixture of normal concrete was prepared for purpose of comparison. Samples were cast under standard conditions. Samples were tested at 28 days of age. Each concrete mixture's compressive strength was measured using three cylinders with a dimension of (300 mm depth and 150 mm diam.). Fig. 5 shows the failure modes for normal and rubberized concrete cylinders after the compression strength test. Based on the results in Fig.6, which is attached. It is demonstrated that rubber concrete loses more strength with respect to rubber aggregate volumetric percentage. The concrete compressive strength showed a decline by 21.57% at 10% and 30.31% at 20% rubber aggregate percentage in comparison to normal concrete. The cause for this decline in strength is ascribed to deficient bond exists in around cement matrix surrounding rubber particles[22, 23]. In addition, the entrapped air inside the matrix resulted from rubber hydrophobicity [24].

Fig. 5. Failure mechanisms of concrete cylinders following a test for compressive strength



	RUB (20%)	RUB (10%)	RUB (0%)
Compressive	25,1	28,25	36,02
Splitting	2,504	3,056	3,642

Fig. 6. Results of compressive and splitting tensile strength

3.1.3 Splitting Tensile Strength

This property represents an important property of concrete as it reflects the capacity of concrete to sustain loads causing cracks. In this study, according to the approved specifications for tensile inspection (ASTM C496)[25]. Three mixtures of rubber concrete having various two percentages of 10% and 20% in addition to plain concrete mix were prepared. Samples were cast under standard conditions. Samples were tested at 28 days of age. Each concrete mixture's splitting tensile strength was measured using three cylinders with a dimension of (150 mm diam. and 300 mm height). Figure 6 explains the results of the splitting tensile strength test. As shown in Fig. 6 , the results exhibited a decline of 19% and 31% in tensile strength for rubber concrete specimens at percentages (10% and 20%), respectively, in comparison to OPC mix specimens. The primary reason behind this decline in splitting strength is resulted from defect in bonding between the surrounding cement paste and the adjacent elastic rubber aggregate particles[26]. Additionally, the weaker boundary layer and increased water demand in the cement paste surrounding the crumb rubber aggregate particles due to the rubber's inability to absorb the trapped water[27, 28].

3.2 Structural Performance of Deep Beams

3.2.1 Load-Deflection

Table 8 presents the results from flexural test of RC deep beams. Load at initial crack, deflection at mid-span during the initial crack, the ultimate load, deflection at mid-span during maximum or ultimate load were measured. Ductility and failure mode were also evaluated. At initial cracking, the stiffness drop rate reduced significantly with inclusion of crumb rubber aggregate. Fig. 7 shows the load –deflection curves for the tested RC deep beams. Clearly, the load-deflection curve for all samples often climbs upward as the ratio of crumb rubber increases resulting in increased load-carrying capability due to the tendency of crumb rubber aggregate to absorb more energy. The ultimate load (Pu) increased by 32%, 41%, 61%, and 44%, for specimens (R1-10%, R1-20%, R2-10%, and R2-20%), respectively, in comparison to the plain RC beam. The sample's peak load was found to have marginally dropped (R2-0%). The load of the first crack of the samples containing rubber crumbs decreased compared to the reference due to the weakness of the interfacial bonding of the soft rubber particles adhered to the surrounding paste, which led to occurrence of small cracks on the surface of the rubber concrete.

The deviation in the middle of the deep beam extension at the first crack was reduced by (6.6%, 2.4%, 30.9%, 22.2%) for the deep beam specimens (R1-10%, R1-20%, R2-10%, and R2-20%), respectively, compared to the reference sample (R1-0%). In samples containing rubber crumbs, the first cracking appeared more clearly and spread until the shear span[29]. Fig. 11 illustrates modes of failure of the RC deep specimens tested in this study. As shown, rubberized RC deep beams exhibited increased number of cracks in comparison to reference beam. This is evidence on the crumb rubber tendency to improve and enhance the ductile behavior of RC deep beams.

3.2.2 Effect of GFRP reinforcement ratio

Figures 8 – 10 show the effect of reinforcement ratio on load-deflection of RC deep beams at constant crumb rubber ratio. To elaborate the effect of rubber aggregate particles, a comparison between the specimens (R1-10%) and (R1-20%) is presented. As shown in Fig. 10, the first crack generally dropped by 11.1% and 4.2% for (R2-10%) and (R2-20%), respectively, as the reinforcement ratio percentage increased. In comparison to (R1-10%) and (R1-20%), an increase in the ultimate load value of RC deep beams by 22% for (R2-10%) and 3% for (R2-20%). Despite being regarded as a material with brittle behavior[29], using GFRP rebars instead of steel rebars enhanced the tensile strength and, consequently, the load capacity of the deep beams. Deep beams may undergo a substantial internal force reorientation upon cracking, which tends to cause forces to flow straight starting from the loading point towards the support's region. In this arch action, compression struts are formed to immediately transfer the stress to the supports, and the longitudinal reinforcement serves as a tie to keep the arch's base together. Generally, the main longitudinal bars could enhance the control of the crack width and increase the ultimate load capacity.

3.2.3 Ductility Index

Ductility is regarded as one of the most crucial safety parameters as it exhibits the structural member's capacity to tolerate cracking and significant plastic deformations before failure and losing its capacity to support loads. According to Table 8, the rubberized concrete samples exhibited higher ductility than the normal concrete sample. The results showed an increase of (23.38%, 27.4%, 25.0%, 42.7%) for the deep beam specimens (R1-10%, R1-20%, R2-10%, and R2-20%), respectively, compared to (R1-0%).

Table 8. Results of the first crack, final load, deflection, ductility index, and failure mode.

Sample	Pcr, [kN]	D.P% Pcr, %	Peak load, Pu, [kN]	D.P% Pu	Mid-span defection [mm]	D.P% Mid-span defect.	Ductility Index µE	Mode of failure
R1-0%	48.2	------	221	----	5.41	-----	1.24	Flexure
R1-10%	45	-6.6	291	31.6	10.38	91.8	1.53	Shear-Flexure
R1-20%	47	-2.4	310	40.3	13.4	147.7	1.58	Shear–flexure
R2-0%	57.9	-20.0	219	-0.9	4.62	-14.6	1.29	Flexure
R2-10%	40	-30.9	356	61	13.9	147.6	1.55	Shear-flexure
R2-20%	45	-22.2	317	43.4	11.11	105.4	1.77	Shear–flexure

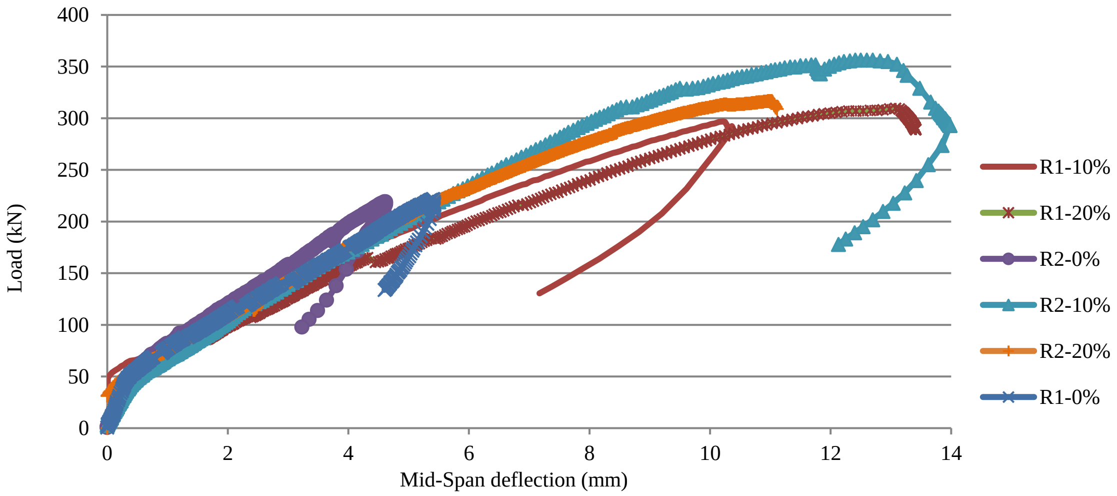
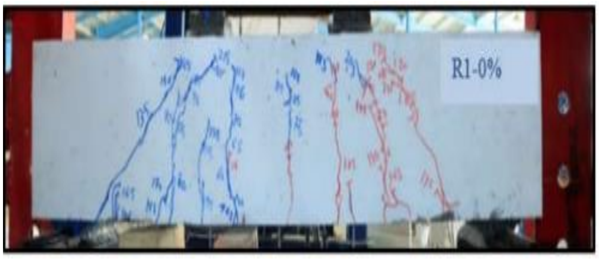


Fig. 7. Load-deflection response for all RC specimens

It is worth mentioning that the load deflection curve can indicate the beam performance in terms of ductility[11]. The increase in deflection led to an increase due to elastic performance of the elastic rubber particles which increase the deformations beyond the cracking [30]. This suggests that additional rubber crumbs with ratios of 10% and 20% may deform and contribute significantly to improved ductility. In general, deep beams reinforced with GFRP were more ductile when rubber aggregate was added.



R1-0%

R1-10%

R2-0%

R2-10%

R1-20%

R2-20%

Fig. 8. Failure modes for specimens

4. Conclusions

In this study, the feasibility of recycling end-of-life tires' crumb rubber to create rubberized concrete is investigated experimentally. The impact of this process on the mechanical strength, including slump, compressive and tensile strengths were being assessed. RC deep beam reinforced with GFRP load-deflection curves were determined. The impact rubber aggregate percentages (0%, 10%, and 20%) and primary reinforcement ratio were the two main factors that were adopted analyze the flexural performance of the RC rubberized deep beams reinforced with GFRP bars. In this regard, the main conclusions obtained from the investigation's findings are:

- The concrete workability was significantly altered as the percentage of rubber aggregate increased from 0% up to 20% in comparison to normal concrete. This decrease is proportionate to crumb rubber content.
- In comparison to plain concrete mix, the rubberized concrete mixture's compressive strength dropped by roughly 19% and 31%, respectively, for crumb rubber contents of 10% and 20%. On the other hand, when the rubber content was raised to 10%, the splitting tensile strength dropped by 19%, and it declined by 45% at 20%, rubber content, compared to reference mix.

- The deflection load curve revealed that as the first-crack load dropped when cracks in the rubberized concrete emerged more quickly, increasing the crumb rubber content increased the final load before complete failure occurred.
- For the beams that failed in shear and flexure, the ultimate load of rubberized concrete GFRP beams containing 10% and 20% improved by 34% and 43%, respectively, compared to control concrete. The improvement occurred due to the adequate bond interaction between the GFRP bars and the bounded rubberized concrete texture.
- Clearly, the increase in the reinforcement ratio led to an increase in the final load of the samples, as it enhanced control over the crack width and it developed the capacity of the final load. This is due to the properties of GFRP bars in withstanding tension three times that of steel bars.
- The 10% and 20% crumb rubber samples were more ductile than the normal concrete sample. Comparing the samples R2-10% and R2-20% to the reference sample, the use of GFRP with10% and 20% rubber can be recommended for shear-critical deep beams where ductility is desirable

This research presents the result discussing the shear behavior of deep rubber concrete sills reinforced with GFRP bars. A proposed model for use in future real-world civil engineering applications, where rubber concrete provides a model for sustainable concrete and GFRP bars provide a new generation model in reinforcement. Based on the current study's experimental findings, the following suggestions are given for further research: Using different proportions of processed crumb rubber to powder rubber. Further research using different FRP types is required, reinforcements as CFRP.

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