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Mechanical characteristics and structural performance of rubberized concrete: Experimental and analytical analysis

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ABSTRACT

Rubberized concrete is referred to as "green concrete" by replacing fine aggregate with used tire rubber. However, although significantly increasing ductility, rubber particles lowered compressive strength. The study aimed to find the optimum ratio of crumb rubber (C-Ru) to employ in large scale elements. Firstly, the effect of C-Ru treatment and content on concrete mechanical behavior is examined. The experimental program contains 96 cubes and 78 cylinders using different percentages of untreated/treated C-Ru with portions from 5 % to 30 % replacing the sand. Then, four beams were produced with 5, 10, and 15 % sand volume substitution by C-Ru to investigate the effects of rubber content on structural performance and compared with conventional beam. It is found that C-Ru treatment has less enhancement for concrete fresh properties (workability) for using small ratios of rubber and this enhancement increases to reach 20 % for higher rubber content ratio while the comparable enhancement for hardened properties (compressive strength). In addition, well washing of the C-Ru after treatment did not affect the fresh RuC properties, while the improved the hardened properties of RuC (compressive and tensile strengths). Increasing the C-Ru content ratio decreased concrete fresh and hardened properties. Untreated C-Ru not more than 15 % as a replacement of fine aggregates is preferred to avoid large strength reductions while benefiting workability, economy, and safety. While the addition of C-Ru to the concrete mix increased the ductility, toughness, and self-weight of the beams, it also decreased their flexural capacity. Finally, the finite element analysis using ANSYS is used to compare with experimental results and thus it could accurately model behavior of rubberized concrete as a complex material that recommended for further studies.

1. Introduction

The use of waste rubber in concrete as a substitute for traditional fine and coarse aggregates has been the focus of extensive

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investigation in recent years. The primary objective of this research is to provide an environmentally acceptable substitute for the millions of waste tires that have accumulated [1,2]. Therefore, using such a strategy can help minimize the number of natural aggregates that are consumed while also significantly lowering the major environmental issues that arise from burning or piling scrap tires in landfills. As a result, using waste rubber in the construction sector supports the creation of green buildings and the application of the sustainable manufacturing idea [3].

The feasibility of producing rubberized concrete (RuC) with crumb rubber (C-Ru) particles in place of natural aggregates has been investigated by several researchers. Previous studies examined concrete properties by replacing C-Ru with fine and coarse aggregate, utilizing small-scale testing on cubes, cylinders, and prisms. Nouran et al.[4] tested the durability of concrete made with 5–20 % C-Ru from scrap tires replacing fine aggregates. They measured water absorption, chloride permeability, and corrosion resistance as indicators of concrete durability. Bu et al.[5] studied the properties of sustainable concrete made with recycled tire rubber. It discussed rubber content impact on mechanical characteristics and durability of fresh concrete. They found that higher rubber content reduced compressive strength but enhanced toughness and durability. Ataria et al.[6] studied the mechanical characteristics and durability of recycled aggregate concrete with 0–30 %. Increasing rubber content decreased compressive strength and elastic modulus but improved ductility. Durability also improved with more rubber. Assaggaf et al.[7] examined the effects of C-Ru characteristics and treatments on various properties of RC. The higher rubber content lowers compressive strength but improves ductility, toughness and durability. Elshazly et al.[8] studied the properties of rubberized concrete like strength, ductility, sound/water absorption, and acid/sulfate resistance. They revealed that increased rubber content lowers compressive strength but enhances ductility, abrasion resistance, water absorption, and freeze-thaw resistance while reducing sound transmission. Strukar et al.[9] tested concrete with 0–30 % coarse aggregate replaced by C-Ru under compression. Higher rubber lowered compressive strength and elastic modulus, but increased strain ability and ductility. Nevertheless, the majority of earlier studies showed that adding C-Ru negatively affected the generated RuC's workability, modulus of elasticity, split tensile strength, and compressive strength, this might be as a result of the cement paste and CR particles' poor bond.

Several rubber pre-treatment techniques have been developed in the past to enhance C-Ru's properties. Assaggaf et al.[10] investigated sustainable concrete made with treated C-Ru particles. The rubber was treated with sodium hydroxide, silane, and polyvinyl acetate to improve bonding with the concrete. Treating the rubber improved concrete properties like workability, strength, and abrasion resistance compared to concrete with untreated rubber. He et.al [11] studied concrete with surface-treated C-Ru powders. Treating the rubber powders with NaOH and silane solutions improved their bond with cement paste. Concrete made with the treated rubber showed enhanced workability, strength, and flexural capacity compared to untreated ones. Najim and Hall [12] looked at how different C-Ru treatments—such as water-washed, cement-precoated, mortar-precoated, and NaOH-pretreated C-Ru particles—affect the compressive strength of RuC. According to the findings, rubber that had been pre-treated with NaOH and water only marginally improved—by 3.1 % and 4.7 %, respectively. Pre-coated rubber particles in mortar and cement showed considerable improvements of 40.6 % and 15.6 %, respectively. According to Balaha et al. [13], the compressive strength of the RuC that had received a pre-treatment with NaOH increased by around 13 %. The impacts of C-Ru treatment techniques including NaOH, KMnO4, and cement coating on the RuC properties were described by Assaggaf et al. [14] KMnO4 and NaOH treatments significantly improved RuC's mechanical characteristics. RuC's flexural strength and compressive strength both rose by 33 % and 64 %, respectively; the cement treatment method is the most successful approach.

Despite a significant amount of prior research on the mechanical characteristics of RuC, it is clear that there are not enough investigations on the response of structural RuC elements. AL-Azzawi et.al. [15] tested reinforced concrete beams with 25 % and 50 % fine aggregate replaced by crumb rubber. Increasing rubber content enhanced beam ductility and energy absorption capacity but lowered cracking and load capacity, demonstrating. Ismail and Hassan.[16] Replaced the fine aggregate with up to 20 % C-Ru in reinforced self-consolidating concrete beams enhanced ductility, deformability and energy absorption while reducing cracking though lowering strength; added steel fibers recovered strength loss while further improving ductility. Ismail and Hassan [17] examined the impact of crumb rubber (C-Ru) on the flexural behavior of twelve large-scale beams through testing. The percentage of C-Ru (0–35 % by volume of sand) is considered. They demonstrated that raising the C-Ru seems to lower concrete self-weight, narrow fracture widths, and enhance deformability at a given load. In contrast, the ductility, toughness, initial crack moment, and ultimate flexural capacity of the tested beams were significantly reduced upon the addition of large percentages of C-Ru (over 15 %). Sayed Ahmed et.al [18] examined fourteen beams with various rubberized concrete (RuC) in flexure in order to evaluate the impact of various factors, such as rubber content, treatment materials, and the type of internal reinforcement, on the overall performance and characteristics of the beams. Different amounts of CR (5 %, 10 %, and 20 %) by volume of the sand used in the mixtures were included in the study. Cement or fly ash slurry (CTR and FATR) coating the C-Ru particles enhances their bond with the surrounding concrete components. The findings were predicated on the assumption that, in comparison to the similar mixes cast with UR, the compressive strength increased by 6.0–11.0 % and 13.0–22.0 % for the mixes cast with CTR and FATR, respectively. As a result, as compared to the mixes incorporating uncoating CR, the tensile strength of the RuC-integrated CTR and FATR increased by 5.9–11.0 % and 14.0–22.0 %, respectively. Furthermore, out of all the steel RC beams, the beams cast using FATR concrete had the greatest flexural capabilities.

Upon reviewing the literature, it becomes evident that further elaboration and clarity are required on the performance of structural elements constructed using rubberized concrete that has varying percentages of crumb rubber substituted for aggregate.

2. Research Significance and Scope

In order to achieve the ideal ratio of C-Ru in the concrete mixture, current research attempts to investigate the impact of rubber content and its treatment conditions on the mechanical characteristics of concrete. Investigations were conducted on several RuC mixtures with different C-Ru % and treatments. Additionally, research is done on how rubber content affects the flexural behaviour of RC beams. Then, a comparison was made between the analytical and experimental results to ensure that the finite element analysis could correctly represent the behaviour of rubberized concrete as a complex material for extending the studies in future.

3. Methods

The experimental program contains 96 cubes with dimensions 150×150×150 mm, 78 cylinders having dimensions 150*300 mm and 4 beams 150×300×1650 mm. Using different percentages of C-Ru with portions 5 %, 10 %, 15 %, 20 %, and 30 % replacing the sand in the concrete mixture.

3.1. Materials

This section provides an illustration of the experiment's material properties. Tests were carried out to obtain the properties based on Egyptian Standard Specifications (ESS) No. 1109/2002. The Materials employed in the experimental program were aggregates, cement, rubber, water, reinforcing steel and sodium hydroxide solution.

Ordinary Portland Cement (OPC) was provided with Grade 42.5 N as binding material. The coarse aggregates, which had a fineness modulus of 4.8 and a maximum size of 10 mm, were made from crushed dolomite. Natural sand made of siliceous minerals with a fineness modulus of 2.9 is employed in this work as fine aggregate. They were clean, impurity-free, and free of organic components.

The crumb rubber was used in place of the sand. Scrap tyre rubber powder with a maximum particle size of 4.75 mm and a specific gravity of 0.95 are employed. Fig. 1 shows the rubberized concrete components used in exprimental program. Refer to Fig. 2 for the grading schemes for fine and coarse aggregates as well as the Crumb rubber.

To change the surface of the rubber particles as curing material, a saturated sodium hydroxide solution was created. First, a sodium hydroxide solution was prepared by placing pure sodium hydroxide flakes in water, with 100 g of sodium hydroxide for every 100 g of water. Second, the rubber particles were thoroughly washed with water before beginning the treatment to remove dust present on the particle surfaces. Then, the rubber particles were placed in the sodium hydroxide solution and submerged for 24 hours. After that, the rubber particles were extracted from the solution. Half of the particles were washed with water once, while the other half was thoroughly washed with water for 3 cycles.

3.2. Rubber Treatment

This part illustrated the methods of the rubber crumbs treatment with sodium hydroxide solution and water washing. The untreated/washed rubber in addition the treated rubber washed initially and well washed were used in different concrete mixes. Six concrete mixes were cast with rubber replacement ratios of 0, 5, 10, 15, 20 and 30 %. For each mix, 3 cylinders and 6 cubes were cast.

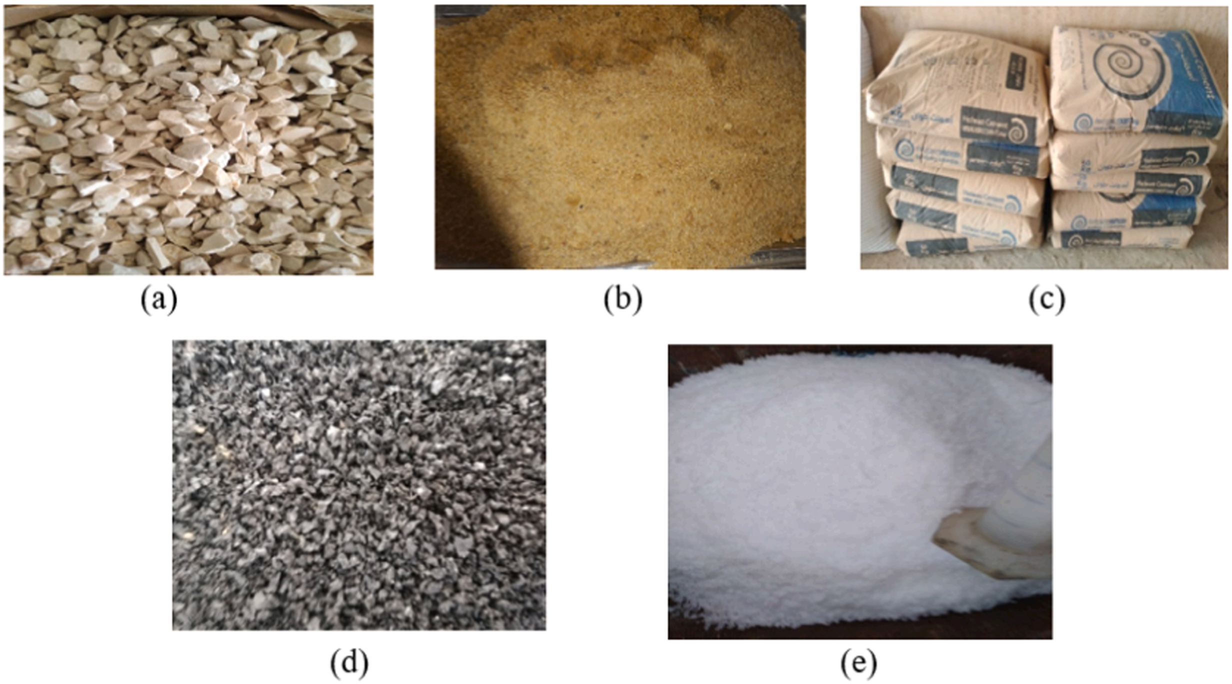


Fig. 1. Concrete materials (a)coarse aggregate, (b) fine aggregate, (c) cement, (d) crumb rubber and (e) Sodium hydroxide.

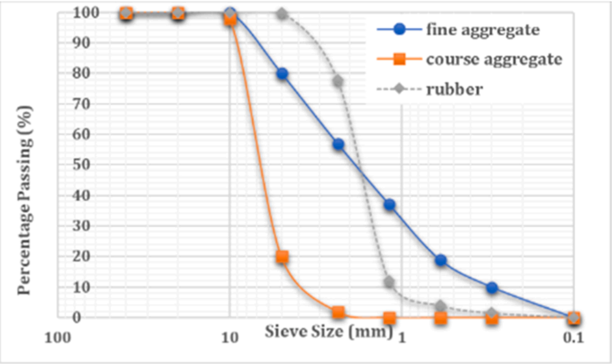


Fig. 2. Fine aggregate and coarse aggregate and C-Ru grading curves.

3.2.1. *Untreated Rubber*

The untreated rubber was only washed well with tap water and left for 24 hours before use in the concrete casting process (see Fig. 3a).

3.2.2. *Treated Rubber*

a. Treated and Initially Washed (**1 Cycle**): Under ambient circumstances, the rubber particle was treated for 24 hours with a saturated sodium hydroxide solution. They were then rinsed once with tap water and stored in the laboratory for 24 hours before usage (see Fig. 3b).
b. Treated and Well Washed (**3 Cycles**): After treating the rubber particles with a saturated sodium hydroxide solution for 24 hours under ambient conditions, they were washed three times with tap water and kept in the laboratory for two hours after the first and second cycles, then for 24 hours before use (see Fig. 3c).

3.3. *Mix Design*

According to Egyptian code, a concrete mix of coarse aggregate, sand, cement, and water was designed. All concrete mixes had a water cement ratio (w/c%) of 0.47. Table (1) shows six concrete mixes with varying amounts of C-Ru component ranging from 0 % to 30 % of sand volume. The compressive strength of all concrete mixtures was designed to be 40 MPa. Controlled samples are referred to as CC without employing the crumb rubber as substituting sand in concrete mix. Rubberized concrete samples are referred to as (-) % C-Ru, with these ratios varied as 5 %, 10 %, 15 %, 20 %, and 30 % as the replacement of crumb rubber of sand volume in concrete mix.

The procedure used to prepare the control specimen was to mix the fine and coarse aggregate for one minute, let it rest for one minute, then add the cement and a portion of the total water and mix for another minute. For mixes including crumb rubber, the same procedure was followed; however, in order to improve bond, it was first combined with cement before being added to the mixture.

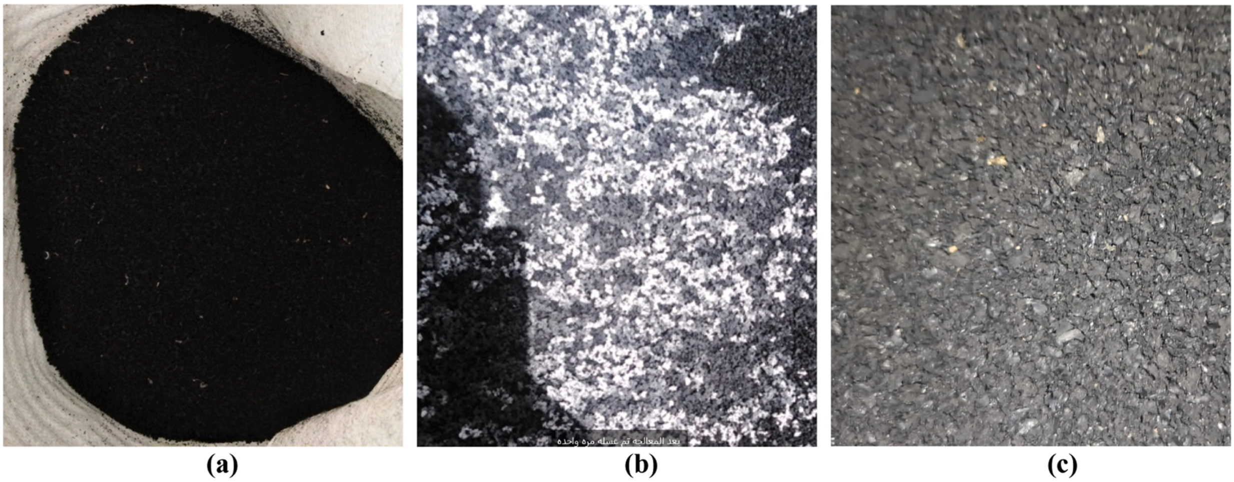


Fig. 3. Crumb rubber treatment procedure (a) Untreated, (b) Treated and Initially Washed (1 Cycle), and (c) Treated and well Washed (3 Cycles).

Table 1
Mix Proportions of the concrete mixes (kg/m^3).

Mix Name	Cement (kg)	Water (kg)	w/c ratio	Aggregate (kg)		Rubber (kg)
				Coarse	Fine	
CC	436	205	0.47	992	779	0
5 % C-Ru	436	205	0.47	992	740	39
10 % C-Ru	436	205	0.47	992	701	78
15 % C-Ru	436	205	0.47	992	662	117
20 % C-Ru	436	205	0.47	992	623	156
30 % C-Ru	436	205	0.47	992	545	234

3.4. Mechanical Properties

The percentage of slump, weight, compressive, and tensile strengths resulting from the use of untreated and treated crumb rubber (C-Ru) in concrete mix is listed in Table (2), which refers to the control case without crumb rubber in concrete mix.

3.4.1. Workability

Many studies [6,11,12] have found that rubberized concrete are with lower workability than conventional concrete. This is because the C-Ru ’s increased water absorption capacity when compared to other aggregates. Moreover, compared to normal aggregate and non-uniform forms, which require a significant amount of water, C-Ru has a larger service area. This is one of the main causes of the significant design problems with RC mixtures’ workability. The value of slump indicates the workability of the concrete mix. Higher slump values correspond to more workable concrete. As the results,see in Fig. 4, treatment of the rubber improves the workability.

3.4.2. Unit Weight

The unit weight of concrete is an important factor in structural design. As shown by various studies [3,7,13,14], using rubber can lower the weight of concrete, requiring less reinforcing and resulting in an efficient design, see Fig. 5. This is caused by two things: first, rubber has a much lower specific gravity than aggregate [15], and second, there is inadequate cement paste adhesion between rubber and concrete, which makes rubber act as a void in the concrete matrix, increasing porosity and lowering unit weight [3].

3.4.3. Tensile Strength and Compressive Strength Test

The results,see Fig. 6.and 7, indicated that the use crumb rubber decreases the compressive strength as reported by many investigations [4,11,15–18] and decreases the tensile strength as reported in [11,19–21].

Table 2
Percentage of slump, weight, compressive and tensile strengths as a result of using crumb rubber (C-Ru) referred to the control case.

C-Ru ratio	0 %	5 %	10 %	15 %	20 %	30 %
Percentage of Slump	Untreated rubber					
	-	100 %	93 %	87 %	80 %	70 %
	Treated and initially washed (1 Cycle)					
	-	103 %	103 %	100 %	100 %	93 %
	Treated and well washed (3 Cycle)					
	-	100 %	100 %	97 %	93 %	90 %
Percentage of Weight	Untreated rubber					
	-	99 %	96 %	94 %	90 %	88 %
	Treated and initially washed (1 Cycle)					
	-	98 %	96 %	93 %	90 %	88 %
	Treated and well washed (3 Cycle)					
	-	99 %	96 %	94 %	90 %	88 %
Percentage of Compressive Strength	Untreated rubber					
	-	86 %	69 %	51 %	37 %	28 %
	Treated and initially washed (1 Cycle)					
	-	46 %	39 %	31 %	24 %	18 %
	Treated and well washed (3 Cycle)					
	-	87 %	69 %	52 %	38 %	29 %
Percentage of Tensile Strength	Untreated rubber					
	-	100 %	98 %	90 %	84 %	77 %
	Treated and initially washed (1 Cycle)					
	-	51 %	35 %	37 %	33 %	27 %
	Treated and well washed (3 Cycle)					
	-	91 %	89 %	79 %	68 %	59 %

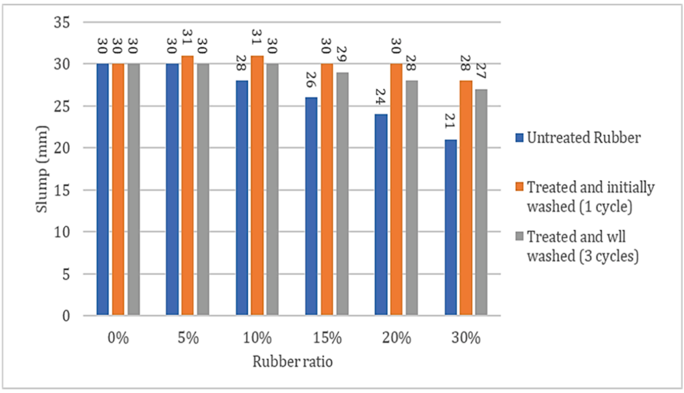


Fig. 4. Slump test results.

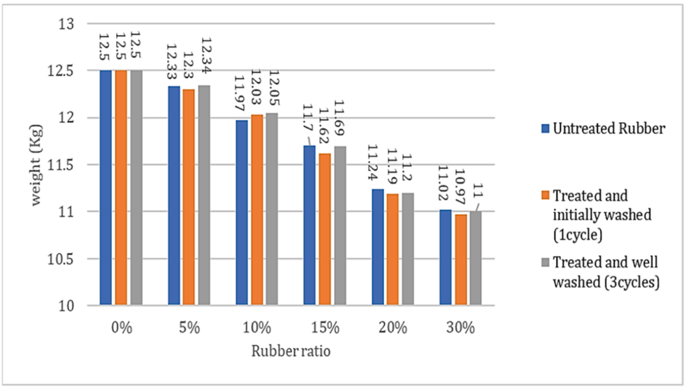


Fig. 5. Weight results.

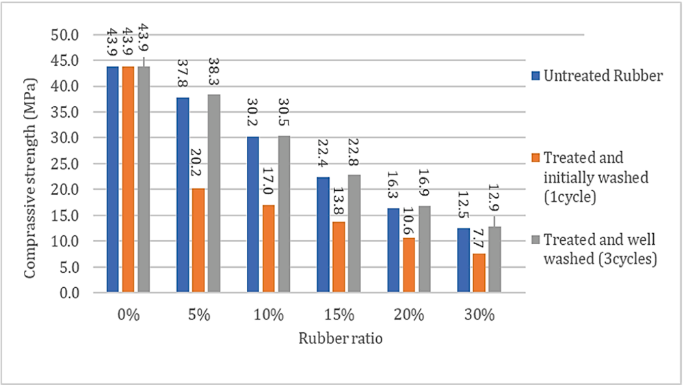


Fig. 6. Compressive strength after 28 days.

3.5. Findings from the Mechanical Characteristics of Rubbered Concrete Mixtures

3.5.1. Rubber Treatment's Impact

The mechanical characteristics of concrete were investigated using untreated and treated C-Ru. The workability of RC with treated rubber, either initial or well cleaned, is 1.03, 1.1, 1.15, 1.25, and 1.33 times that of untreated rubber for rubber ratios of 5, 10, 15, 20, and 30 %.

Ru-C with treated rubber, either initial or well washed, weighs almost the same as untreated rubber. As a result, the rubber treatment has no effect on weight.

The compressive strength of concrete employing treated-well washed rubber is 1.02 higher than that of untreated rubber. The tensile strength of concrete using untreated rubber is higher than that utilising treated-well washed rubber by 1.1–1.3.

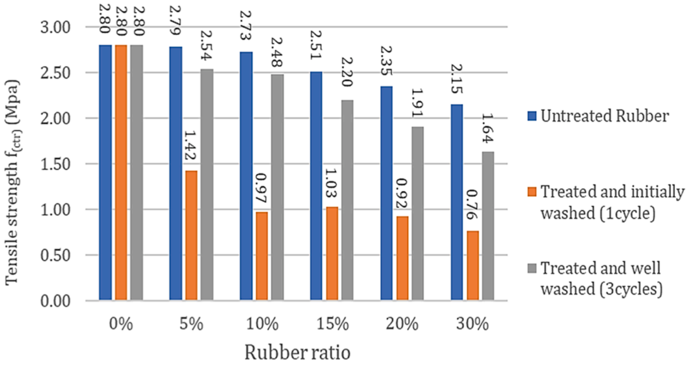


Fig. 7. Tensile stress results.

3.5.2. *Rubber Washing (after treatment) Impact*

The mechanical properties of concrete were examined in relation to unwashed C-Ru, initial washing (one cycle), and well washing (three cycles). The workability of RC with treated rubber initially washed is slightly larger than well washed treated rubber by 1.03.

The weight of RC with treated rubber initially washed is approximately similar to well washed ones. Therefore, the washing cycle's number has negligible effect on concrete workability and weight.

The compressive and tensile strengths when using well washed CR was doubled those when using initially washed C-Ru.

3.5.3. *Rubber Content Ratio Impact*

The impact on the mechanical properties of concrete by adding C-Ru at 5 % to 30 % of the sand volume, either before or after treatment, or after initial/well washing after treatment, was assessed. By increasing the rubber content ratio in concrete mix from 5–30 %, the workability of concrete is reduced when using untreated C-Ru by 7–30 % by increasing the rubber content ratio in concrete mix from 5 % to 30 %. In the other hand, using treated C-Ru in mix, and the workability has negligible affected by increasing the rubber content.

With the increase in rubber percentage, the weight of the samples decreased by 1.2–12 % with increasing the rubber content ratio (either untreated or treated) in concrete mix from 5 % to 30 %. This allows the use of rubber in lightweight concrete.

The increase in rubber percentage in concrete mix led to a reduction in both compressive and tensile strengths. The compressive strength was reduced by 14 %, 32 %, 49 %, 63 % and 72 % when using untreated rubber or using treated/well washed rubber with ratios 5, 10, 15, 20 and 30 %. For the tensile strength the more reduction is observed when using treated/well washed rubber rather than the case when using untreated rubber. The reduction in tensile strength is 1 %, 2 %, 10 %, 16 % and 23 % when using untreated rubbr but 9 %, 11 %, 21 %, 32 % and 41 % when using treated/well washed with increasing the rubber ratios from 5–30 %.

While the worst case is observed for treated/initial washed rubber, more reduction in both compressive and tensile strengths are recorded. When treated/well-washed rubber with ratios of 5, 10, 15, 20, and 30 % was used, the compressive strength was lowered by 54 %, 61 %, 69 %, 76 %, and 82 %, while the tensile strength was reduced by 49 %, 65 %, 63 %, 67 %, and 73 %.

Using over 15 % of untreated C-Ru in concrete mix caused significant decreases in tensile and compressive strengths. Hence, it was reached to extend the works on beams in this study by using untreated C-Ru instead treated ones with ratios did not exceed 15 % as partial replacements of fine aggregate to avoid extensive decreases in concrete strengths. As using either untreated or treated rubber in concrete mix was get an approximately converged concrete strengths, so it is preferred to use untreated rubber for saving the cost and for safety precautions.

4. Details of the Test Specimens

Four rubberized concrete (Ru-C) beams and one reference CC beam were tested. All beams were 1650 mm long, 1500 mm wide, 300 mm deep, 150 mm wide, and 20 mm concrete covered. Concrete beams were built from each combination (CC, 5 % C-Ru, 10 % C-Ru, 15 % C-Ru).

4.1. *Reinforcement Details*

Fig. 8 shows the reinforcing details for all tested beams. The principal reinforcement in all test specimens was the same: two steel

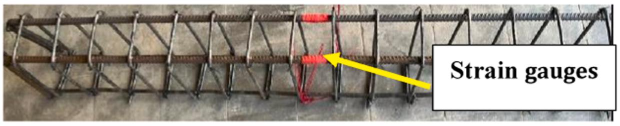


Fig. 8. Reinforcement details and Locations of the strain gauges (at main steel).

bars with 12 mm as diameter (T12). Because steel reinforcement yields, all beams were under-reinforced to guarantee ductile failure. For all tested beams, two steel bars with a diameter of 8 mm (T8) are employed as top reinforcement. To prevent shear failure, T8 stirrups spaced with 100 mm were employed along the beam span. At the extremities of all reinforcing bars, adequate anchorage lengths were given. The clear concrete cover was 20 mm thick for all beams.

4.2. Test Setup and Procedure

Glue was used to attach mid-span steel reinforcement gauges to the beam's bottom reinforcing bars as strain gauges (Fig. 8). The beam flexure was tested using a four-point symmetric loading test. To assure pure bending and zero shear area, two-point loadings were 500 mm apart (Fig. 9). Testing utilized digital load cells. The 500 kN load cell in the beam's midsection exhibited 10 kN accuracy. Three LVDTs—two on each side and one in the middle—measured beam deflection. At specific points, strain gauges recorded strain components.Data was collected on deflections and stresses. Data loggers recorded load cell and other measuring device readings.

4.3. Results

4.3.1. Cracks Patterns

The failure fracture pattern for each tested beam is shown in Fig. 10. The cracking behaviour of reinforced concrete beams was observed. All beams failed gradually due to many tiny vertical fractures at midspan during early loading phases, with more cracks spreading as loads rose. Higher loads caused more flexural and diagonal inclined shear fractures in shear spans. Branching expanded

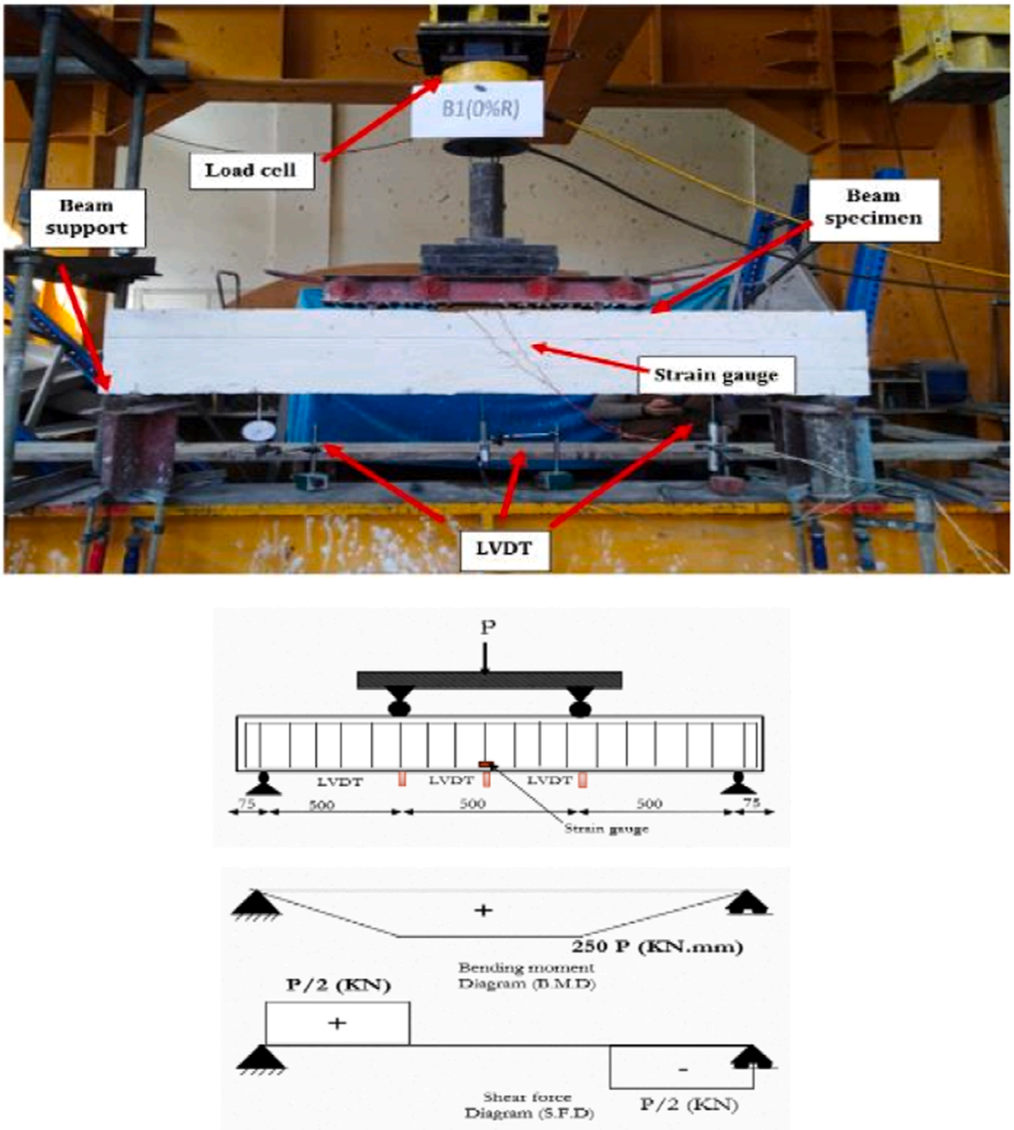
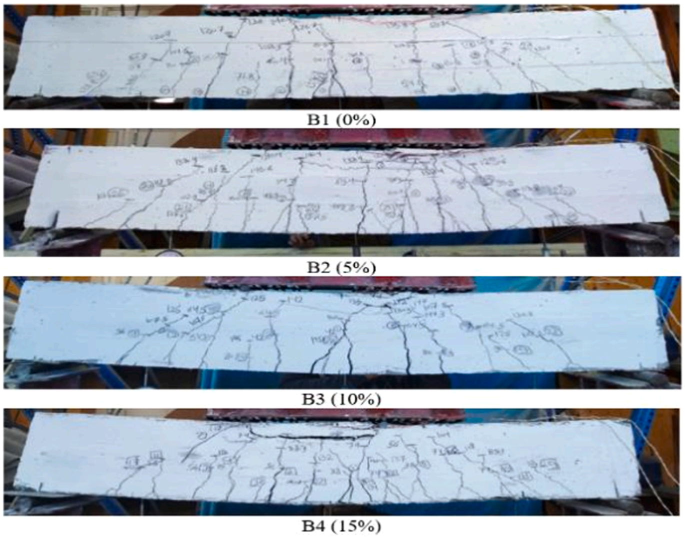


Fig. 9. (a) Beam four-point bending test setup and location of LVDTs, (b) Statically loaded system (loading, bending moment, and shear force).


B1 (0%)

B2 (5%)

B3 (10%)

B4 (15%)

Fig. 10. Patterns of crack distribution for all tested beams (B1) CC, (B2) 5 %RC, (B3) 10 % RC and (B4)15 % RC.

fissures before concrete crushing, near collapse.

It can be observed that all tested beams failed ductile flexurally, according to crack patterns. As reported by many investigations [22–24].

It can observed that he inclusion of C-Ru led to an increase in the number of cracks in CC from 12 cracks to 20 cracks in the 15 % C-Ru concrete beam [15,16,18]. In the 5 % C-Ru beam the cracks number increased to 14 cracks and there was extension in the cracks and some cracks connected with each other but the increase was minor and negligible. In the 10 % C-Ru beam the cracks number are increased to 16 cracks and the extension increased until the cracks from both sides under the beam met and there was widening in the cracks which branched, and the curvature shape increased noticeably.

In the 15 % C-Ru beam the number of cracks reached 20 cracks and all the cracks branched and met with each other as the widening of the cracks greatly increased until the reinforcement steel appeared, and the beam curvature was very large and appeared to the naked eye. This indicates enhanced deformability with increasing the crumb rubber portions in concrete mix.

4.3.2. Load–Deflection Relationship

Fig. 11 shows the load-deflection curve for reinforced concrete beams with 0 %, 5 % C-Ru, 10 % C-Ru, and 15 % C-Ru fine aggregate replacement. It can be observed that the typical load-deflection response was exhibited, with an initial linear behavior transitioning to rapidly increasing curvature and slight deflection increase up to failure as reported by many investigations [9,14,25]. The 5 % and 10 % R-C beams showed yield load increases of 9 % and 6.7 %, respectively, versus the control beam. While, with increasing C-Ru content from 5 % to 15 %, the ultimate load capacity decreased from 98 % to 85 % when compared with control case. At the end of tests, the failure load decreased to 89 % and 62 % for the 10 % and 15 % of C-Ru content. On the other hand, with increasing C-Ru content from 5 % to 15 %, the deformation at ultimate stage increased from 146 % to 242 % when compared with control case. Increasing the C-Ru content from 5 % to 15 % exhibited increases in deflection at failure from 23 % to 93 %, indicating greater deformability. The results demonstrate that higher C-Ru replacement leads to increased deflections, providing enhanced

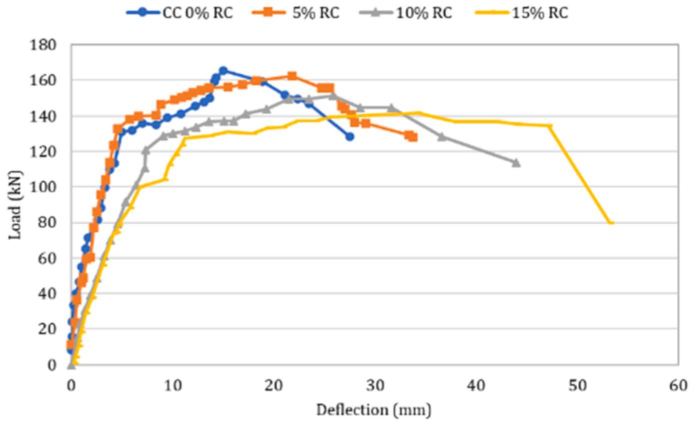


Fig. 11. Load–deflection relations for beams.

ductility although reducing flexural capacity.

4.3.3. Load – Strain Curve

Load-strain curves determined yield load and deflection, used for ductility and stiffness, Fig. 12. show steel tensile strain at beam midspan; load-strain behavior of reinforced concrete beams with 0 %, 5 %, 10 % and 15 % C-Ru fine aggregate replacement under four-point bending tests. It can be noted that the rubberized and controlled concrete beams exhibited similar initial linear load-strain trends. At yield and ultimate loads, the 15 % C-Ru beam showed 18 % and 12.8 % increases in steel tensile strain versus control, indicating greater curvature. The results demonstrate that higher C-Ru replacement leads to increased steel strains for a given load condition, providing enhanced ductility despite concrete fracture at peak strains causing strain gauge failures. Increasing C-Ru replacement resulted in greater steel strains prior to failure, improving ductility although reducing ultimate strength.

Table (3) summarized the beams test results showing the load, deflection, and steel reinforcement strain at yield, ultimate, and failure stages were listed.

4.3.4. Stiffness, ductility and Toughness

Beam stiffness, defined as the load-deflection curve slope, is an important structural property. It is noted (see Fig. 13) that increasing rubber generally decreased initial and post-yield stiffness. Overall, the rubber particles reduced initial and effective stiffness compared to conventional concrete. The 5 % rubber beam showed a 10.3 % increase in initial stiffness versus the control beam, indicating potential stiffness optimization at low contents of rubber.

A material’s ductility is determined by how much plastic deformation it can withstand before failing or rupturing [26]. It is quantified as the ratio of maximum displacement to yield displacement (μ). When compared to the reference specimen, the 5 % C-Ru specimen showed a 47.5 % increase in ductility factor, the 10 % C-Ru beam showed a 7.6 % improvement, and the 15 % C-Ru beam showed a 6.2 % improvement (see Fig. 14). This indicates the advantageous effect of incorporating C-Ru particles in concrete, since the low stiffness of rubber particles can improve deformability and strain capacity of the rubber-cement composite, hence boosting beam ductility. While increasing the C-Ru content in the concrete mix, the ductility index of the beam decreased. The ductility values reported in this paper are consistent with prior research on similar composite beams [10,17,26,27].

In engineering, toughness is a material’s capacity to absorb energy and bend plastically without fracture, proportional to its stress-strain curve area up to failure. It observed that (see Fig. 15) the rubber increased deformability and energy absorption at a given load. The 5 %, 10 % and 15 % rubber beams exhibited respective toughness increases of 49.3 %, 68.8 % and 114.4 % versus the control, demonstrating enhanced load capacity and potential for improved seismic/impact resistance. as reported by many investigation [3,17,27–31].

5. Finite Element Analysis

Complex geometry and nonlinear material behaviour are difficulties that can be solved with the finite element approach. The ANSYS 19 software was utilized for the following finite element work [32,33] in order to verify the software’s ability to simulate the behaviour of rubberized concrete with varying rubber content ratios as a complex material.

In pre-processing step, the Element Types, Material Properties, Modeling and Meshing, Boundary conditions and loading, and analysis type and solver were defined. The concrete and Steel reinforcement were modelled using the SOLID 65 and LINK180 elements, respectively. For the solid 65 element, real constant Set 1 is employed. Furthermore, the sections with cross section areas of 50.24 mm^2 and 113.04 mm^2 for Φ8 and Φ12 define the steel reinforced bars and stirrups.

In the material definition step, the linear isotropic and multi-linear isotropic material attributes are defined for the Solid65 element in order to mimic concrete. Since all the steel reinforcement in the beams is made of Link180 elements, it is presumable that the elements are multilinear isotropic. Tables 4 and 5 display the Material Models for Link 180 and Solid 65,.

Volumes were used to represent the supports, plates, and beams as displayed in Fig. 16 (a). It is advised to utilize a rectangular mesh in order to get the best performance out of the Solid65 element. command. As seen in Fig. 16 (b), the meshing of reinforcement is divided based on size such that its nodes match the mesh nodes of volumes. When a model has an appropriate amount of components, the results converge, and this can happen when increasing the mesh density has little to no impact on the outcomes. Thus, it was determined that using an element mesh size of 25 mm is appropriate since it saves analysis time and yields reliable findings.

For hinged support, constraints were applied to all nodes under the bottom plate in the UX, UY, and UZ directions, as well as to all nodes for the loading plate in the UX and UZ directions. The force, P, as shown in Fig. 16 (c), applies at every node on the steel loading plates.

Table 6 shows a comparison of finite element analysis and experimentation. The load-deflection relationship for the tested beams was displayed in Fig. 17. Fig. 18 compares the failure modes of experimentally tested beams with analytically analyzed beams with concrete and steel reinforcing stresses. As can be seen, the position of failure in the FE models, as indicated by the maximum Von Mises stress values, matched the findings of the experiments. With an average difference of 2 % in ultimate load and 5 % in maximum deflection, the results are in good agreement. As a result, the analytical model can be used to simulate the rubberized concrete having different rubber content ratios as a complex material and can be represent the failure mechanism of this kind of concrete.

6. Conclusions

Initially, the impact of the rubber content and treatment parameters on the mechanical properties of the concrete mix are assessed.

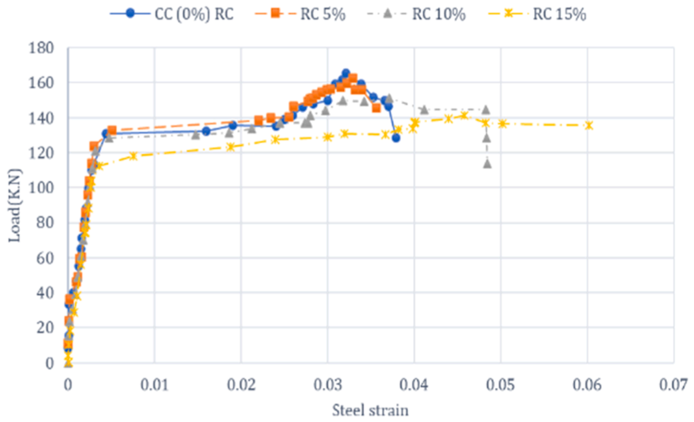


Fig. 12. Load - strain relations for beams.

Table 3

Results of flexural test of tested beams.

`	Yield point			Ultimate point			Failure point		
	Load (kN)	Def (mm)	Steel strain(με)	Load (kN)	Def (mm)	Steel strain(με)	Load (kN)	Def (mm)	Steel strain(με)
B1 (0 %)	113.4	4.23	3000	165.4	14.94	32100	128.5	27.518	37870
B2 (5 %)	123.6	4.18	3000	162.4	21.84	32900	128	33.8	-
B3 (10 %)	121	7.314	3190	151.3	27.9	33750	113.8	43.96	48454
B4 (15 %)	112.4	9.635	3550	141.4	36.221	45800	80	53.22	-

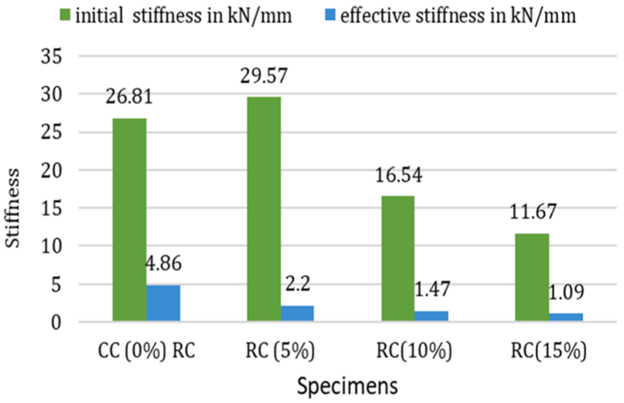


Fig. 13. Initial and effective stiffnesses for the rubber tested beams.

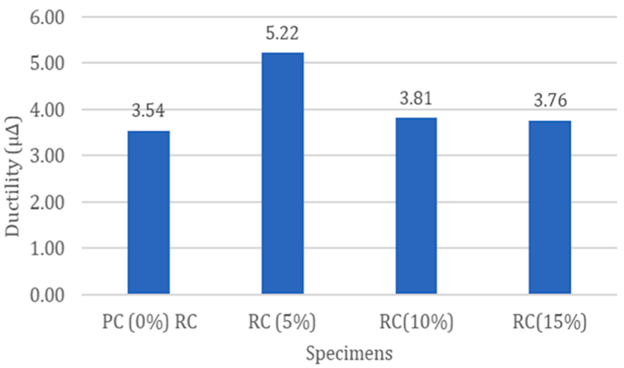


Fig. 14. Ductility of the tested beams.

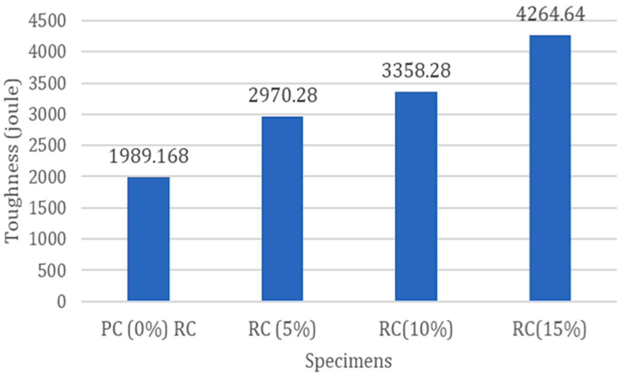


Fig. 15. Toughness of the rubber tested beams.

Table 4
Material models SOLID 65 for concrete.

Linear isotropic								
	C-Ru −0 %		C-Ru −5 %		C-Ru −10 %		C-Ru −15 %	
Modulus of elasticity	29153.1 Mpa		27051.95 Mpa		24179.99 Mpa		20824.6 Mpa	
Passion ratio	0.2							
Multi-linear isotropic	*Strain*	Stress	*Strain*	Stress	*Strain*	Stress	*Strain*	Stress
(Stress in Mpa unit)	0.000451	13.17	0.00041	11.34	0.000374	9.06	0.00032	6.72
	0.000651	18.150	0.00061	15.966	0.000574	13.19	0.00052	10.278
	0.001051	27.328	0.00101	24.334	0.000974	20.453	0.00092	16.229
	0.001451	34.343	0.00141	30.520	0.001374	25.513	0.00132	19.988
	0.001651	37.018	0.00161	32.793	0.001574	27.247	0.00152	21.125
	0.002051	40.853	0.00201	35.887	0.001974	29.384	0.00192	22.259
	0.002251	42.107	0.00221	36.817	0.002174	29.912	0.00212	22.397
	0.003011	43.9	0.00279	37.8	0.002497	30.2	0.003	22.4
Concrete								
Open shear transfer		0.4						
Open shear transfer		0.9						
Cracking stress Mpa		3.975	3.689		3.297		2.839	
Crushing stress Mpa		43.9	37.8		30.2		22.4	

Table 5
Material models LINK 180 for steel reinforcements.

Linear isotropic			
Modulus of elasticity Ex			200000 Mpa
Passion ratio PRxy			0.3
Multi-linear isotropic			
Φ8		Φ12	
Stress Mpa	Strain	Stress Mpa	Strain
280	0.0014	420	0.0021
360	0.0414	620	0.1021

Next, in order to examine the impact of rubber content on structural performance, four reinforced concrete beam specimens were created using rubberized concrete (R-C) and compared to conventional beam specimens. The followings can be obtained:

1) Treating the rubber particles with sodium hydroxide slightly improved concrete workability and compressive strength but decreased tensile strength compared to untreated rubber concrete.
2) Increasing the number of washing cycles after sodium hydroxide treatment for the C-Ru did not significantly affect the fresh RC properties, while the hardened properties of RC (including the compressive and tensile strengths) were doubled.
3) Increasing the C-Ru content ratio decreased workability and weight, also reduced compressive and tensile strengths substantially due to the lower stiffness of rubber particles.
4) Using over 15 % untreated C-Ru caused excessive decreases in concrete strength.
5) Using C-Ru in place of sand up to 15 % can increase ductility, toughness, deformability, and sustainability of concrete beams despite reduced flexural strength.

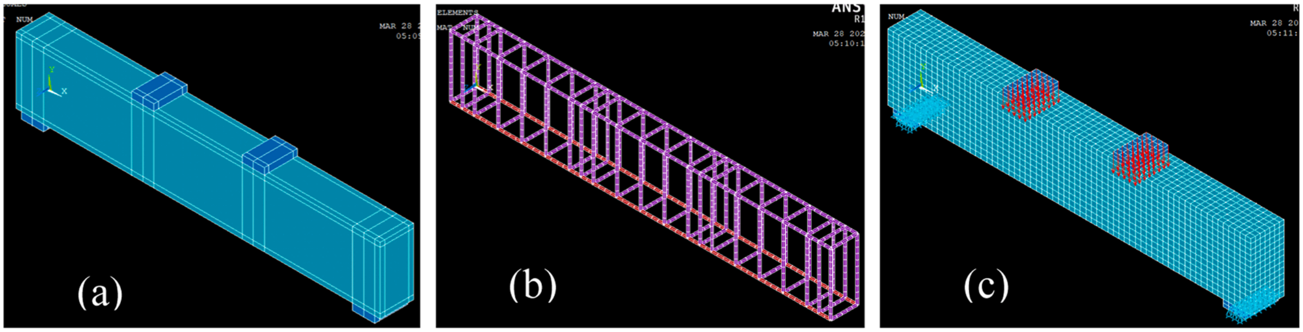


Fig. 16. FEM of tested beams (a) Volumes Created in ANSYS, (b) (c) meshing of Steel reinforcement, and (c) Boundary Conditions for supports and applied load.

Table 6
Comparison between experimental and analytical analysis.

	EXP		ANSYS		Ansys/Exp Ratio%	
	Max. load kN	**Max. deflection mm**	**Max. load kN**	**Max. deflection mm**	**Max. load**	**Max. deflection**
C-Ru −0 %	165.4	24.518	180.9	23.564	**109 %**	**96 %**
C-Ru−5 %	162.4	33.8	160.9	31.149	**99 %**	**92 %**
C-Ru −10 %	149.7	43.96	134.32	37.429	**90 %**	**85 %**
C-Ru −15 %	141.4	53.22	130.4	57.103	**92 %**	**107 %**

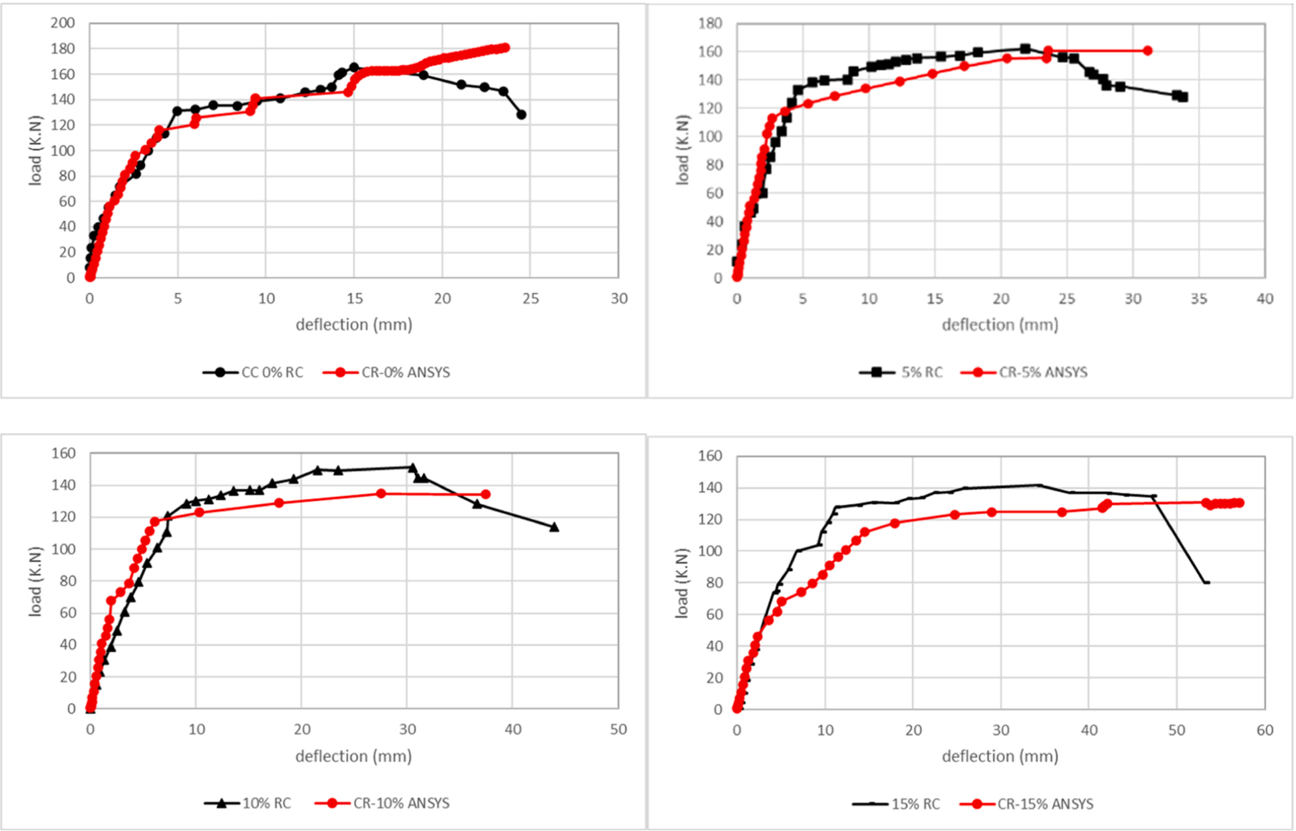
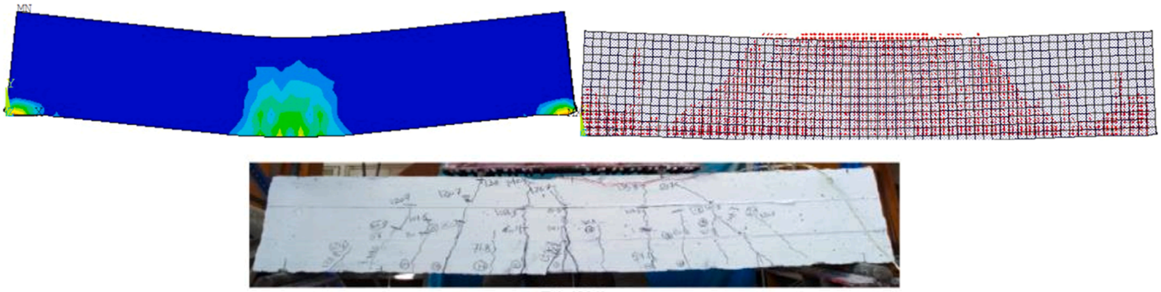
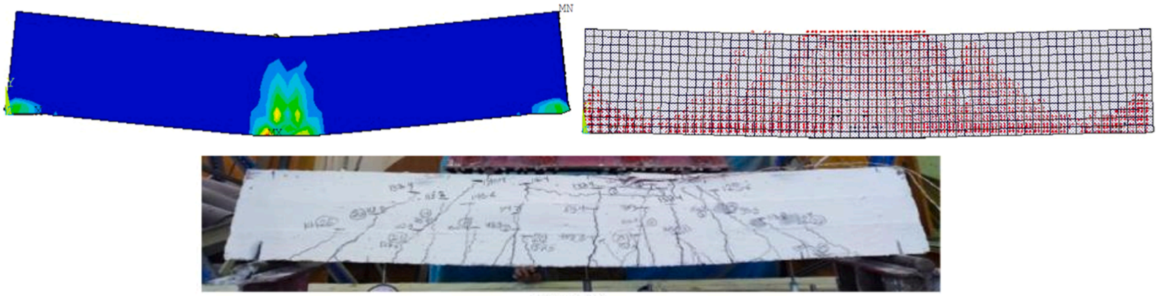


Fig. 17. Load-Deflection relationships for beams experimentally and analytically.

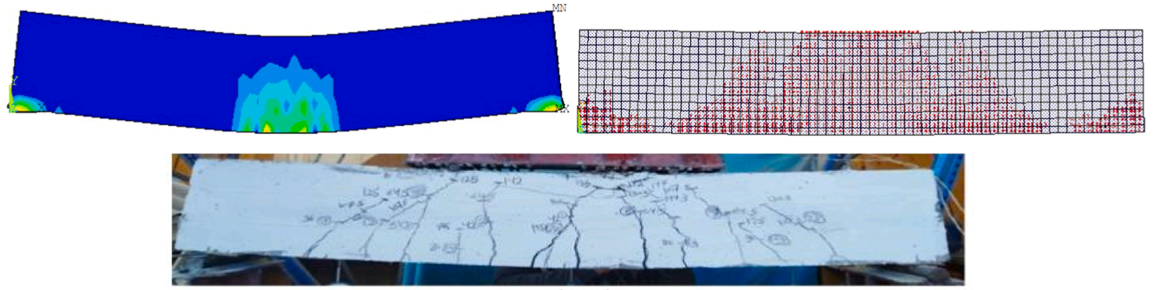
6) RC exhibited improved ductility, toughness, and deformability in flexure compared to conventional concrete.
7) The flexural capacity decreased with increasing C-Ru content, but curvature ductility, deflections, crack widths, and energy absorption increased substantially.



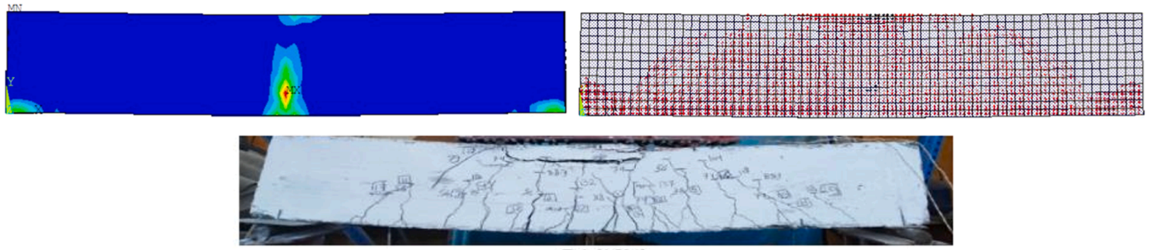
B1 (0%)



B2 (5%)



B3 (10%)



B4 (15%)

Fig. 18. crack patterns and concrete stresses for tested beams.

8) The analytical model can be used to simulate the rubberized concrete having different rubber content ratios as a complicated material and can represent the failure mechanism of this kind of concrete.

CRediT authorship contribution statement

Samy Elbialy: Writing – review & editing, Funding acquisition. **Nehal Ayash:** Writing – review & editing, Validation, Supervision, Software, Methodology, Investigation, Conceptualization. **Hala Mamdouh:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Wael Ibrahim:** Writing – review & editing, Supervision, Resources, Methodology, Investigation, Conceptualization. **Shimaa Mahmoud:** Writing – original draft, Resources, Methodology, Investigation, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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