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Behavior of Rubberized Reinforced Concrete Columns under Axial Loading

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Axial strength, Crumb rubber, Rubberized concrete, Failure, Ductility, Toughness Modulus.

Abstract: Utilizing waste rubber in concrete enhances its ductility, toughness, and impact resistance while reducing the structural members' weight. Additionally, incorporating waste rubber supports the creation of environmentally friendly concrete and promotes sustainable production, which is increasingly emphasized nowadays. This research examines the behavior of full-scale rubberized reinforced concrete (RC) columns under concentric loading. Eight reinforced concrete columns with dimensions of 300×300×1200 mm was constructed and subjected to concentric loading until failure. The primary variables in this study were concrete type and stirrup configuration and spacing. Two columns, cast with normal concrete, served as references for comparison with six rubberized RC columns. The rubberized concrete mix had crumb rubber (CR) at 20% volume substitution for sand, ensuring admissible fresh properties and minimal strength depletion. Key design considerations, including damage progression, ultimate strength, ductility, and toughness, were analyzed. The findings indicate that rubberized concrete can achieve comparable performance to traditional concrete, with improvements in ductility. An increase in strength and ductility were recorded for the concrete cores of well-confined columns.

1. Introduction

The global production of tires has surged alongside economic and industrial growth, generating substantial amounts of waste tires annually. Traditional disposal methods, such as landfilling and burning, have reached hazardous levels. Since waste tires are non-biodegradable and have a prolonged lifespan, their improper disposal results in severe environmental and aesthetic problems. Burning tires emit toxic gases harmful to humans, animals, and soil fertility while contributing to global warming. Therefore, there is an urgent need for environmentally and economically beneficial disposal solutions for waste tires. Recycling waste tires by incorporating rubber particles into concrete mixtures offers an eco-friendly and economically viable approach [1-2]. Research has shown that adding ductile materials like rubber to concrete mixtures partially replacing fine or coarse aggregates

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improves ductility, energy absorption, sound insulation, and reduces unit weight [3-5]. Applications include railway sleepers, sidewalks, green building roofs, sports courts, and skid-resistant ramps [6]. However, rubberized concrete generally exhibits significant lower mechanical strength compared to conventional concrete, primarily due to the lower stiffness of rubber particles and the weak interfacial bond with the cement paste. Various studies have investigated treatments and coatings for crumb rubber and additive inclusions to improve these properties [7]. Additionally, lots of research has been focused on rubberized concrete taking into consideration its different mechanical characteristics [8-17]. While significant research has explored the mechanical properties of rubberized concrete, limited studies focus on its impact on large-scale structural elements like RC columns, where ductility plays a critical design role [18]. Liu et al. [19] reported an investigation that included analyses of steel tube columns filled with rubberized concrete under cyclic loading. The findings indicated a substantial reduction in strength as the crumb rubber content increased, while stiffness showed only a moderate decline. Elchalakani et al. [20] conducted an experimental investigation on short double-skin circular steel columns filled with rubberized concrete containing varying levels of rubber. Their study revealed that the ultimate compressive strength decreased by 50% and 79% for rubberized contents of 15% and 30%, respectively, compared to conventional concrete. However, the inclusion of rubber significantly enhanced the ductility of the concrete-filled steel tubes, increasing it by up to 250%. Similarly, Son et al. [21] explored the impact of crumb rubber concrete on energy absorption and deformability in RC columns subjected to axial loads. Their tests, conducted on six column specimens measuring 200 mm × 300 mm × 1600 mm, evaluated parameters such as rubber content (2.7% and 5.4% of total aggregate volume), compressive strength (24 MPa and 28 MPa), and particle size (0.6 mm and 1.0 mm). The results showed that curvature ductility improved by 45% to 90%, depending on the rubber content and particle size. Additionally, Mohamed et al. [22] examined twelve large-scale columns with square and circular cross-sections, replacing fine aggregate with crumb rubber at rates of 0%, 10%, and 15%. The axial strength reduction ranged from 14.95% to 20%. Although the earlier reported studies consistently report significant reductions in axial strength when crumb rubber partially replaces fine or coarse aggregates, this study focuses on identifying an optimal crumb rubber ratio with minimal strength loss for use in large-scale RC columns [23]. With the utilizing 20% treated fine crumb rubber with NaOH and silica fume, this study presents promising results for rubberized concrete mixtures in structural applications.

2. Experimental program

2.1. Specimens’ description

The experimental program included testing of eight square reinforced concrete columns under concentric axial loading. All tested columns were 300×300 mm in cross section with 1200 mm height. **Fig. 1** shows the specimens geometry and reinforcement details. Two specimens were cast with normal concrete and served as reference specimens, while the other six specimens were cast with rubberized concrete. Two stirrup configurations were tested, with spacing of 100 mm, 150 mm, and 200 mm labeled as configurations I and II. The specimens were divided into three groups as listed in **Table 1**. For ease of identification, the columns are labeled based on their concrete type (NC for normal concrete and RC for rubberized concrete), followed by subscript showing the stirrup configuration (I or II). This is followed with superscript identifying the stirrups spacing.

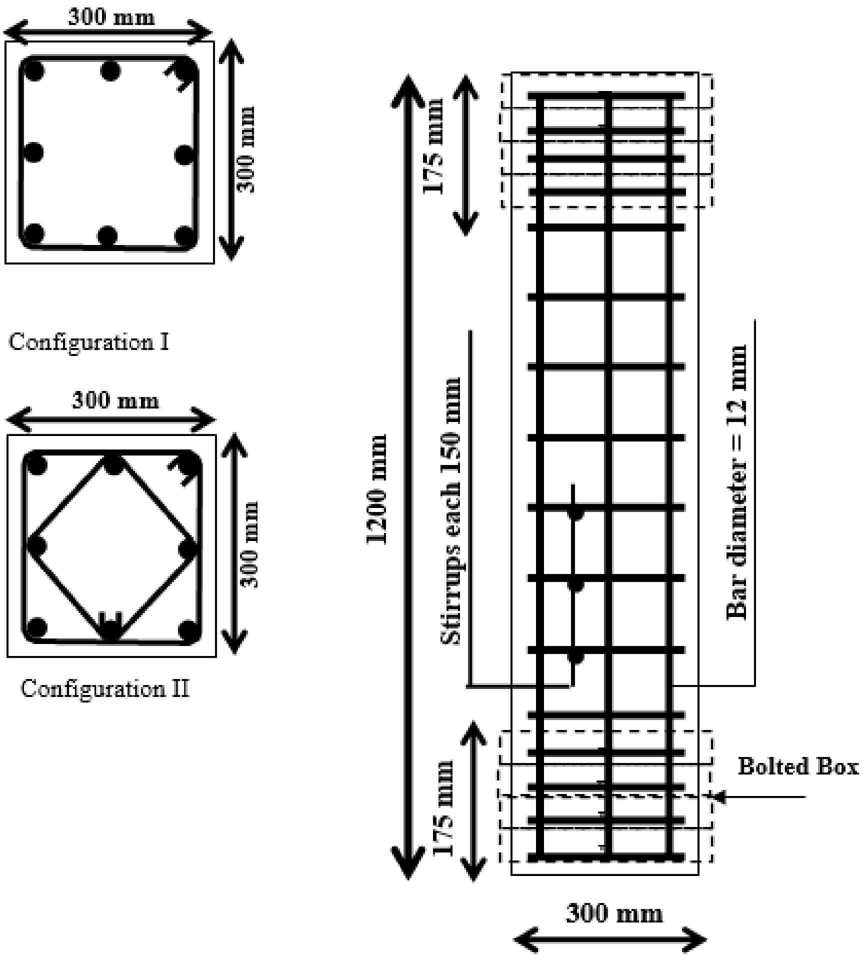


Fig. 1: Specimens details

Table 1: Columns geometry, reinforcement details and study parameters

Group	Specimen	Concrete type	Stirrups	
			Configuration	Spacing
A	NC_{I}^{150}	Normal concrete	I	150
	NC_{II}^{150}		II	150
B	RC_{I}^{100}	Rubberized Concrete	I	100
	RC_{I}^{150}		I	150
	RC_{I}^{200}		I	200
C	RC_{II}^{100}		II	100
	RC_{II}^{150}		II	150
	RC_{II}^{200}		II	200

2.2. Material properties

2.2.1. Concrete

The concrete mix used contained 20% treated fine crumb rubber combined with silica fume, selected based on the findings from the initial phase of the study, which focused on determining the optimal crumb rubber ratio that would minimize strength loss for the column mix [23]. The mixing proportions for both normal and rubberized concrete are outlined in **Table 2**.

Table 2: Concrete mixing proportion of each batch of concrete, kg/m^3

Mix designation	Mix. proportions (kg/m^3)					
	Cement	Silica fume	Coarse aggregate	Fine aggregate	Rubber	Sp.
Normal concrete	400	--	1127	624	--	9.5
Rubberized concrete	300	100	1127	499.2	41.43	9.5
Sp.: Superplasticizer dosage						

Locally sourced aggregates, including sand and crushed gravel, were employed. The physical and chemical properties of the aggregates complied with the ECP 203-2020 [24] standards. River sand was utilized as the fine aggregate, while the coarse aggregate was natural gravel, with a maximum size of 10 mm. The sieve analysis results are shown in **Fig. 2**, and the physical properties of the aggregates are listed in **Table 3**.

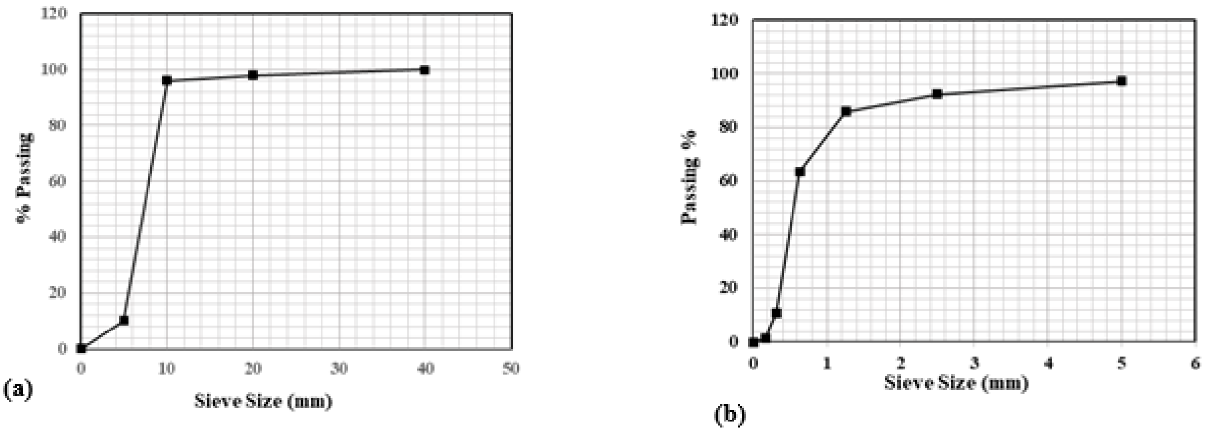


Fig. 2: Sieve analysis test results for a) sand, b) gravel

Portland cement of grade 32.5 N, commonly used in construction, was utilized. Its physical properties met the ECP 203-2020 [24] specifications, as detailed in **Table 4**. Silica fume, with a specific gravity of 2.0, was used as a supplementary cementitious material (SCM), and its chemical and physical properties met the ASTM C1240-03a [25] standards. To address workability issues, Sikament-NN, a superplasticizer, was incorporated. Portable drinking water was used for both mixing and curing the specimens throughout the experimental process. The crumb rubber aggregate, sourced from Hana-Masr Factory in Egypt, contained no steel wires and had a maximum particle size of 4.65 mm. According to the manufacturer's data, the crumb rubber had a specific gravity of 0.83 as well as negligible absorption. **Fig. 3** illustrates the crumb rubber used. The rubber was immersed in a 10% NaOH solution for 30 minutes, then vigorously washed to remove the NaOH until the rubber's pH is back to 7, as tested with a pH meter. After washing, the rubber was air-dried on trays lined with paper towels.

Table 3: Concrete mixing proportion of each batch of concrete, kg/m^3

Property	Sand	Gravel	Code limitation (E.S.S)	
			Sand	Gravel
Maximum nominal size (mm)	----	10	----	≤ 10 mm
Volume weight (t/m^3)	1.68	1.58	----	----
Fineness modulus	2.88	6.95	2~3.75	5~8
Specific gravity	2.5	2.5	2.5~2.75	2.5~2.75
Water absorption %	1	0.8	< 2%	< 2.5%
Fine materials %	1.8	0.6	< 2.5%	< 1%
Sulphate content %	0.0145	0.13	< 0.4%	< 0.4%
Chloride content %	0.042	0.019	< 0.06%	< 0.04%
PH	7.6	7.5	> 7	> 7

Table 4: Physical properties of the used cement.

	Average Results	Egyptian Specifications
Specific surface area (cm^2/gm)	3200	More than 2750
Setting time Initial setting time (min)	150	Not less than 75 min.
Soundness (mm)	5	Not more than 10 mm
Compression Strength N/mm^2		
After 7 days	25.5	Not less than 16 N/mm^2
After 28 days	36	Not less than 32.5 N/mm^2 and not more than 52.5 N/mm^2

2.2.2. Steel reinforcement

High tensile steel (B400DWR, 12 mm diameter) was used for longitudinal reinforcement, while mild steel (B240C-P, 8 mm diameter) was utilized for stirrups. In accordance with ECP 203-2020 [24], three samples from each type of steel bar were selected, and their mechanical properties, including yield stress, elastic modulus, tensile strength, and ultimate strain, were determined through a direct tensile test. The average values of these properties are presented in **Table 5**.

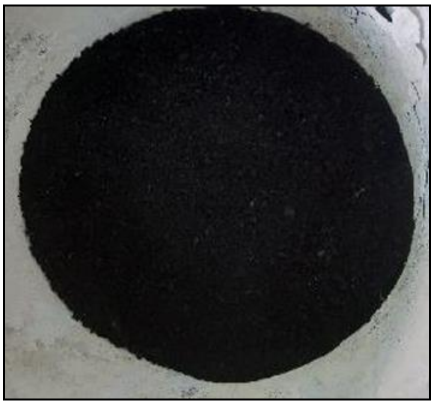


Fig. 3: The used fine crumb rubber

Table 5: Mechanical Properties of used steel

Steel Type	Diameter (mm)	Yield or Proof Strength (N/mm^2)	Ultimate Strength (N/mm^2)	Elongation%
M.S (B240C-P)	8	340	480	25%
Specification limits (E.S.S)	-----	More than 240	-----	More than 20%
H.T.S (B400DWR)	12	419	690	18.2%
Specification limits (E.S.S)	-----	More than 400	-----	More than 17%

2.3. Mixing and casting of columns

The samples were prepared and tested at the concrete laboratory of the civil engineering department in Assiut University. A 0.15 m³ capacity concrete mixer was used for mixing. Initially, the dry aggregates, including any crumb rubber, were blended for three minutes. Next, the binders (cement and silica fume) were added and mixed for an additional two minutes to achieve uniformity. Half of the water was then added and mixed for another two minutes. The remaining water, along with the superplasticizer, was incorporated and mixed for three more minutes until a uniform mixture was achieved. All columns were put in steel plate molds of dimensions 300×300×1200 mm. The molds were surfaced with oil, and steel reinforcement cages were positioned at the centre of the forms. The concrete mix was transported and placed into the molds using a bowl. The concrete was molded in layers, with each layer being compacted using an internal rod vibrator. The columns were demolded 24 hours after casting. They were then covered with sackcloth and sprayed with fresh water twice daily until 14 days after casting. **Fig. 4** shows the cross-section of the columns with reinforcement details, concrete casting, curing process, and the columns are ready for testing.

Fig. 4: cross-section of the columns with reinforcement details, concrete casting, curing process, and the columns are ready for testing.

3. Test setup and instrumentation

Fig. 5 illustrates the study test setup as well as instrumentations. The specimens were tested using a 500-ton compression testing machine. The load was applied at the center of the columns, transmitted through a steel plate from the loading piston to ensure even distribution of the applied load. A concrete strain gauge was attached at the mid-height of the column to measure compressive strain. Additionally, two linear variable differential transducers (LVDTs) were mounted vertically at heights of 500 mm and 700 mm to measure longitudinal shortening.

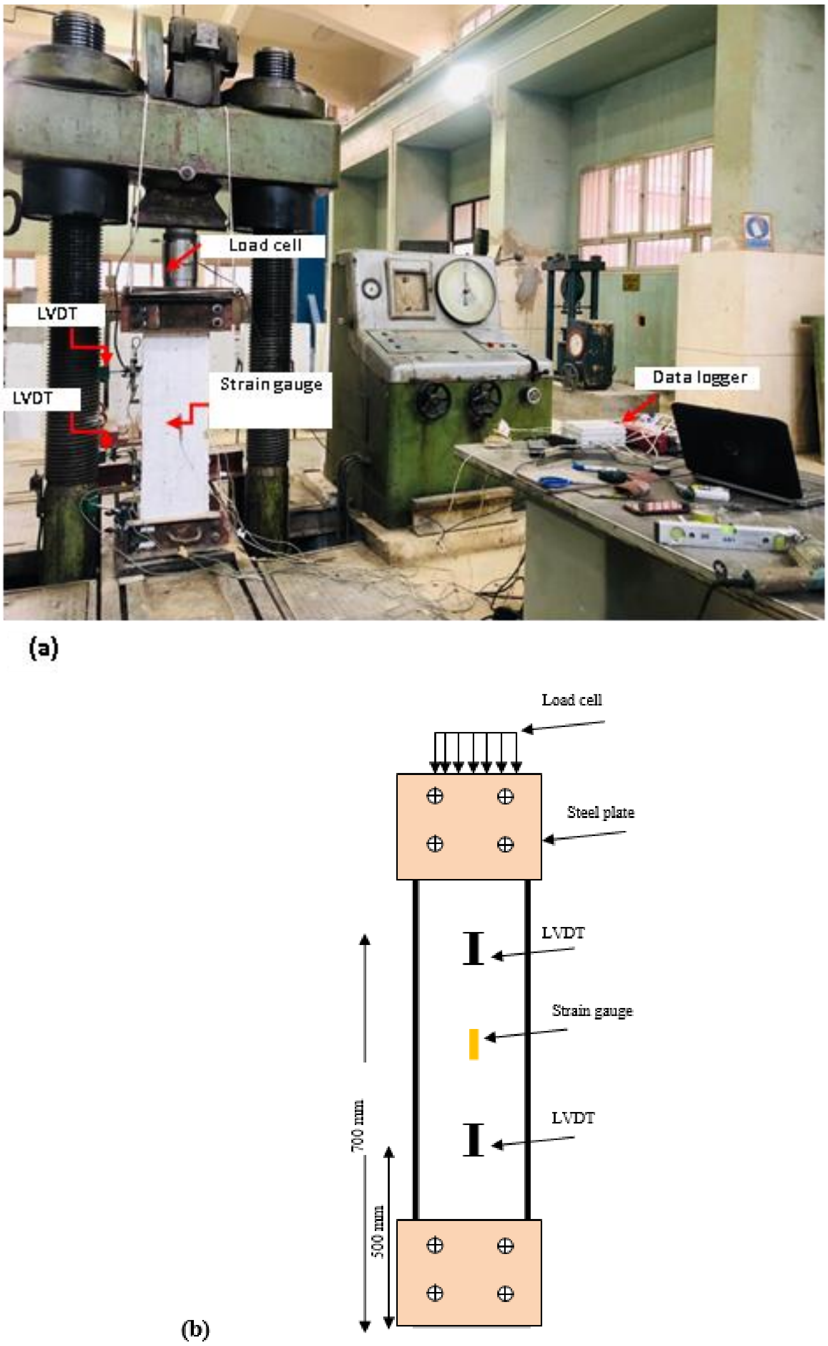
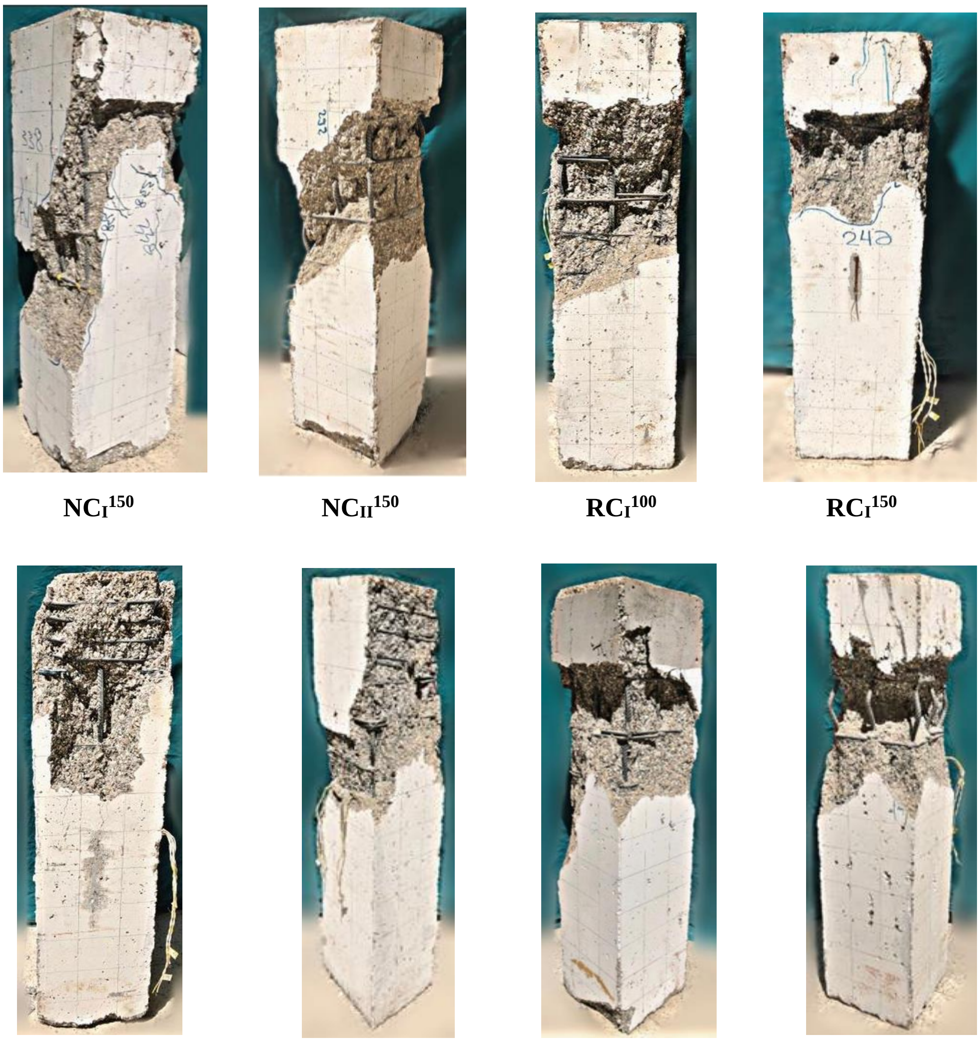


Fig. 5: Test setup and instrumentations: a) photo, b) schematic drawing

4. Test Results and discussion

4.1. Cracks pattern and failure mode

Fig. 6 compares the specimens at failure. All columns failed in compression failure mode. The progression of damage started with vertical cracks. Damage progression began with vertical cracks, which gradually increased in number and width until the concrete cover spalled off. It was followed by buckling of the vertical steel bars as well as crushing of the concrete core. A key difference between the failure modes of normal and rubberized RC columns was observed. In rubberized RC columns, failure began with a noticeable and gradual lateral dilation of the concrete core before the final failure. This was significantly enhanced as function of the stirrup's configuration and the spacing. The best behaviour was attained in case of stirrups configuration type II and spacing 100 mm. In contrast, failure in normal RC columns occurred suddenly, with concrete fragments scattering widely, and the collapse did a sound that can be listen everywhere in the laboratory. It should be noted that the decrease in the stirrups spacing enhanced the confinement of the concrete core and delayed the longitudinal bars buckling with no significant kinked bars at failure. As can be seen from **Fig. 6**, the bars buckling is prominent at failure in case of specimen RCI200, and RCII200, while it is controlled in the other specimens especially for those with stirrups spacing equals to 100 mm.



NC$_{I}^{150}$ **NC$_{II}^{150}$** **RC$_{I}^{100}$** **RC$_{I}^{150}$**

RC$_{I}^{200}$ **RC$_{II}^{100}$** **RC$_{II}^{150}$** **RC$_{II}^{200}$**

Fig. 6: Failure in tested columns.

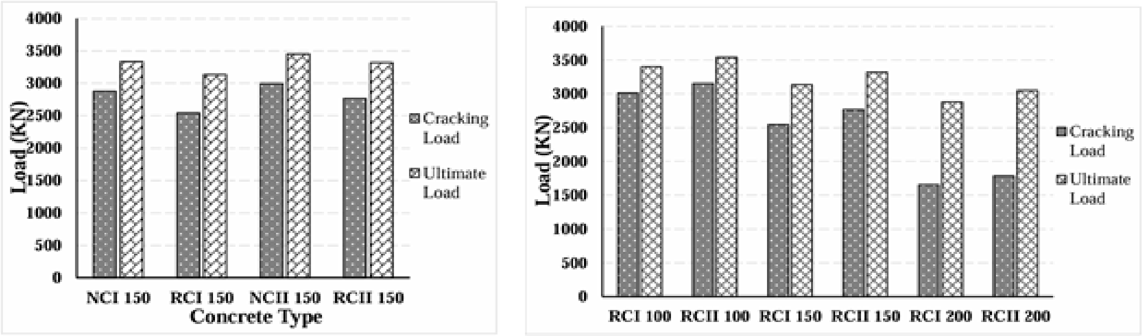
4.2. Cracking and ultimate loads

Table 6 lists the results of tested columns in term of cracking load, ultimate load, concrete compressive strength, nominal axial stress, nominal axial strain, shortening, and modulus of toughness. **Fig. 7a** compares the cracking and ultimate load for the rubberized RC columns with their companions. It can be seen that a reduction in the cracking load occurred by 13% in specimen RC_I compared with NC_I, while 9% reduction was recorded in specimen RC_{II} compared with $NC_{II.}$ The reduction ratios were 6% and 4% when the ultimate load was considered. **Fig. 7b** shows the effect of the stirrups configuration and spacing on the cracking and ultimate loads for the rubberized RC columns. The data reveals that the stirrups had a significant effect on the cracking and ultimate load compared to the stirrup's configurations. For instance, specimen RC_{II}^{100} achieved ultimate load, and cracking load 20%, and 67% higher than specimen RC_{II}^{200}, respectively. The enhancement, however, noticeably changed when the comparison between RC_{II}^{100} and RC_I^{100} where the enhancement were 4%, and 8% with respect to the ultimate, and cracking load, respectively. So, it can be inferred that the stirrups spacing is more effective in enhancing the concrete core confinement. Furthermore, it can be found that the decrease in strength that associated with the use of rubberized concrete, albeit it was insignificant, can be offset by decreasing the stirrups spacing. This is clear, when specimen RC_I^{100} is compared with specimen NC_I^{150} where both specimens exhibited similar cracking and ultimate load.

Table 6: Test results of tested columns.

Group	f_c	Specimen	P_{cr}	$p_u^{exp.}$	σ_n	$p_u^{pred.}$	$p_u^{exp.}/p_u^{pred.}$
A	31.0	NC_I^{150}	2879	3335	37.06	2248.98	1.48
	31.2	NC_{II}^{150}	3025	3454	38.38	2261.04	1.53
B	28.5	RC_I^{100}	3011	3400	37.78	2098.23	1.62
	27.6	RC_I^{150}	2543	3137	34.86	2043.96	1.53
	29.3	RC_I^{200}	1654	2879	31.99	2146.47	1.34
C	29.3	RC_{II}^{100}	3154	3542	39.36	2146.47	1.65
	28.9	RC_{II}^{150}	2768	3317	36.86	2122.35	1.56
	28.9	RC_{II}^{200}	1785	3049	33.88	2122.35	1.44
SD	1.80						
COV	6%						

P_{cr} = cracking load (kN), $P_u^{exp.}$ = ultimate experimental load (kN), σ_n= nominal stress f_c = the concrete compressive strength, ε_{VI} = nominal axial strain, (N/mm^2), $P_u^{exp.}$ = ultimate predicted load (kN) following **Eq. 1**.



a)

b)

Fig. 7: Cracking and ultimate load of tested columns

4.3. Nominal stress strain curves

Fig. 8 compares the nominal axial stress versus axial strain curves for the tested specimens. Initially, the curves showed a very stiff behaviour that is representative for the elastic stage. Once vertical cracks appeared, significant softening occurred, marking the elastic-plastic stage. This was followed with degradation of strength up to failure occurred due to concrete crushing. The failure was considered at 25% loss of strength. The rubberized RC columns showed improved deformation with similar stiffness compared to the reference samples as shown in **Fig. 8a**. Notably, the strength reduction was abrupt in specimen $NC_{I}^{١٥0}$, and $NC_{II}^{١٥0}$, while it was relatively more gradual in the other rubberized RC specimens. **Figs. 8b-e** reveals that the stirrups configuration also had a role in the ultimate strain enhancement regardless the concrete type. The stirrups configuration, however, had no effect on the column's stiffness. In contrast, the stirrups spacing showed pronounced effect on both strength, stiffness, and strain capacity. For example, the difference in case of reducing the stirrups spacing from 200 mm to 150 mm showed 10% increase in ultimate strength and 25% increase in the ultimate strain, while the stiffness slightly enhanced. The image was quite difference when the stirrups spacing changed from 200 mm to 100 mm; where 22 % strength gain was achieved, and 40% gain in the ultimate strain with substantial enhancement in the stiffness as can be seen from **Figs. 8f**, and **8g**.

4.4. Toughness Modulus

The toughness modulus index measures the strain energy needed for material failure, represented by the area under the stress-strain curve that is represented in **Fig. 8**. Following this method, the modulus of toughness were quantified and plotted in **Fig. 9**. It is evident that the use of rubberized concrete generally improved the toughness modulus of the tested columns compared to those made with normal concrete (**Fig. 9a**). The best occurred in specimen RCII150 compared with NCI150, where the 29% gain in the modulus of toughness was achieved. This is due to the enhancement combined from the concrete type and the stirrups configuration. Fig. 9b shows the modulus of toughness of specimens with different stirrups configurations as well as different stirrups spacing. Clearly, the stirrups spacing showed the best improvement. This is clear when specimen RC_{II}^{100} is compared with specimen RC_{II}^{200}; 78% improvement in the modulus of toughness achieved. Meanwhile, the enhancement was 11% when specimen RC_{II}^{100} is compared with RC_{I}^{100}.

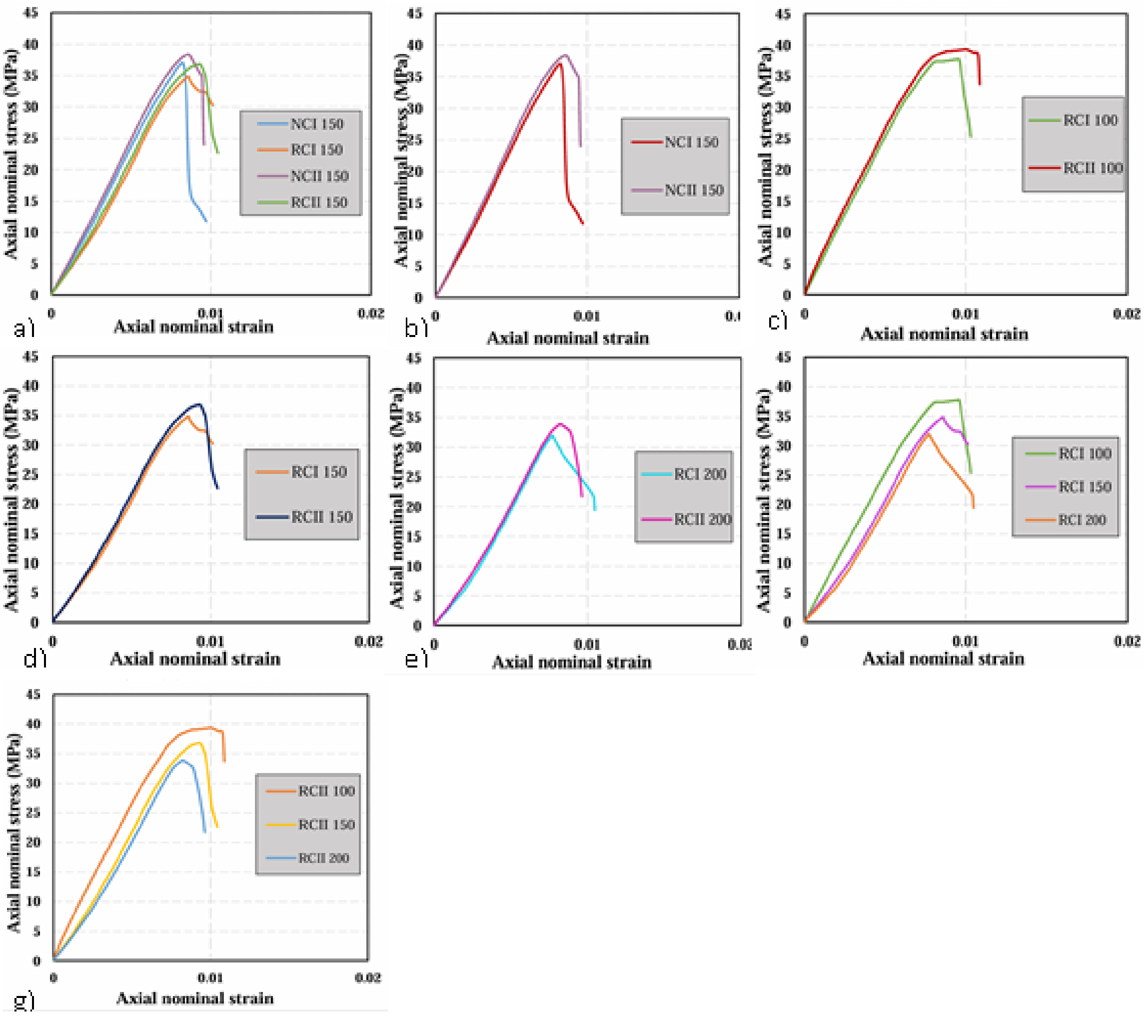


Fig. 8: Axial nominal stress versus axial nominal shortening.

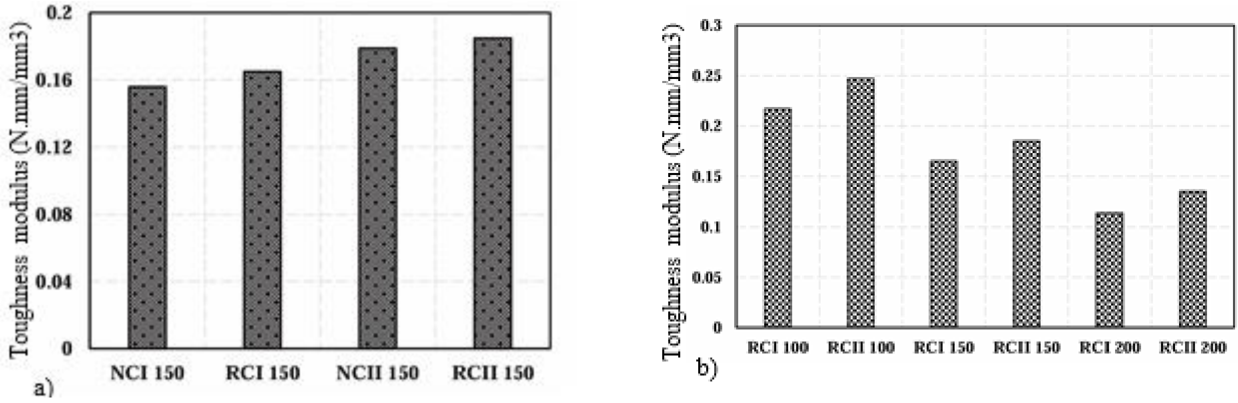


Fig. 9: Recorded toughness modulus for the test specimens: a) effect of concrete type, b) effect of stirrups configuration and spacing

5. Ultimate capacity and code provision

The plain concrete strength of full-scale columns tested under concentric compression loading is generally lower than the concrete compressive strength measured on standard 150 ×150 ×150 mm cubes. The 0.67 reduction factor suggested by the ECP 203-2018 [24] is mainly attributed to the differences in size and shape of RC columns and the concrete cubes. The nominal capacity of an axially loaded RC column P_n was defined as the sum of the forces carried by the concrete and the steel, as given by the following equation.

$$P_n = 0.85 f_c^{'}(A_g - A_s) + f_y A_s \qquad \text{Eq. 1}$$

where A_g is the total cross-section area of the column; A_s is the cross-section area of longitudinal reinforcement; fc′ is the concrete compressive strength; and f_y is the yielding strength of steel reinforcement. The ultimate capacities were predicted and compared with the experimental results as listed in **Table 6**. It is worth mentioning that all material reduction factors in the design equations were set to unity. It can be observed that the ECP 203-2018 [24] predictions of the ultimate axial loads returned conservative values. The difference is attributed to the negligence of the stirrups spacing and configuration. Overall, it can be concluded that the ultimate strength for rubberized concrete columns can be conservatively predicted using the equation specified by the ECP 203-2018 [24].

6. Conclusions

Tire rubber waste is a significant environmental concern that requires urgent attention from the scientific community. This study focused on evaluating the use of rubberized concrete in reinforced concrete columns subjected to axial loading. eight square reinforced concrete columns were constructed and tested under axial loading, with two columns made of rubberized concrete and the other two using normal concrete as reference specimens. Two stirrup configurations were tested with spacing of 100 mm, 150 mm, and 200 mm. The results are promising and can be summarized as follows:

- The rubberized RC columns exhibited similar strength and stiffness to the normal concrete columns, with no signs of premature or instability failure.
- The failure progress in the rubberized RC columns was highly preferred and more gradual, with noticeable lateral dilation and a gradual decrease in strength before failure. In contrast, the normal concrete samples failed suddenly with a rapid loss of strength.
- Rubberized concrete enhanced the modulus of toughness and ductility of the tested columns compared to those made with normal concrete.
- The configuration of the stirrups played important role in confining the concrete core, which in turn improved the ultimate strength and deformation. However, the stirrups spacing showed much high improved enhancement in the behaviour.

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