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Research Paper

An Experimental Study on the Structural Behavior of RC Columns when Using Crumb Rubber Concrete Combined with Recycled Steel Fibers

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Abstract

The growing demand for vehicles has spurred an increase in tire production. However, the improper disposal of these waste tires poses a significant environmental and health hazard. To address this, recent research has explored the integration of recycled steel fibers (RSF) and crumb rubber (Cr) from used tires into concrete formulations to create innovative rubberized and fibrous concrete. A notable study specifically examined the impact of adding RSF of varying lengths and a fixed volume fraction into rubberized concrete containing different proportions of Cr, where Cr partially replaced natural sand. Through the fabrication and testing of 18 reinforced concrete columns under axial compression, the findings demonstrated that RSF alone significantly enhanced the concrete's properties, including density, compressive strength, and tensile strength, by remarkable percentages of 100.27%, 116.84%, and 107.25%, respectively. Conversely, the exclusive use of Cr resulted in a decline in these properties as its content increased. Notably, the "Co5" columns, which incorporated RSF into a concrete mix containing Cr, exhibited superior performance, showing improved displacement and ductility by a degree of approximately 44.67% and 15.65%, respectively, alongside a significant reduction in crack widths by about 29.45% compared to standard rubberized concrete (Co1&Co2). The properties and attributes of columns display promising performance as well as displacement and ductility when RSF is incorporated into concrete mix that includes Cr compared to rubberized concrete.

Keywords: *axial compression; columns; Cr; RSF; several ratios.*

Introduction

Concrete's technological and financial benefits have made it the most widely used structural material in the construction industry. The growing demand for concrete is depleting natural resources and consuming aggregate (Hossain et al., 2019). Incorporating waste and recyclable materials into the concrete mixture can promote sustainability and environmentally friendly "green" concrete, thereby conserving natural resources. The growth in the automotive industry has resulted in an increase in damaged and old tires, causing environmental impacts due to the slow and time-consuming disposal process. Around 1 billion tires are discarded each year, and this number is projected to reach 5 billion by 2030 (Xu et al., 2020). The use of recycled steel fiber (RSF) can increase the strength of concrete, while partially replacing natural aggregate with crumb rubber (Cr) can decrease the cost and environmental impact without compromising the strength of the concrete when using both. This could enable a 25% decline in excavation and a storage area for Cr, which will reduce the environmental impact (Gravina and Xie, 2022). Scrap tires are a significant waste resource in modern society due to their high durability and volume. Some of these tires have already been repurposed, while the remainder are stored or buried (Savas et al., 1997).

To address the environmental impact of tires, crumb rubber has been utilized to partially replace natural sand or gravel in concrete ingredients, producing new green or rubberized concrete products (Alwi Assaggaf et al., 2022; Bisht & Ramana, 2019; Gesoğlu et al., 2011; Khaloo et al., 2008; Naito et al., 2014; Najim & Hall, 2010). Several studies have demonstrated that replacing Cr with natural sand in concrete leads to a decrease in compressive strength of up to 85%, accompanied by concurrent reductions in tensile strength and modulus of elasticity (Bisht & Ramana, 2019; Li et al., 2019; Liu et al., 2012; Zhu et al., 2019). In contrast, incorporating Cr into concrete could improve earthquake endurance and ductility (Xue et al., 2013). Numerous researchers have employed a partial replacement approach involving sand or gravel to address the partial impact of Cr on concrete strength. Gesoğlu and Güneyisi (2011) indicate that a partial

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replacement of a mixture component (gravel or sand) can help avoid the total collapse of concrete properties when Cr is used. In their investigation, rubberized concrete was generated by substituting a portion of the fine aggregate with Cr at four distinct percentages (0%, 5%, 15%, and 25%). The investigation demonstrated that the inclusion of Cr had a detrimental effect on the concrete properties, with the severity of the impact contingent upon the replacement ratio (Gesoğlu et al., 2011). Several studies have highlighted the limitations associated with incorporating Cr into concrete composites to mitigate potential issues (Alwi Assaggaf et al., 2022). Researchers have suggested that replacing less than 20% of the fine aggregate with Cr would lead to an acceptable reduction in some specific properties, such as compressive and flexural strengths (Naito et al., 2014). Furthermore, research by Khaloo, Dehestani, and Rahmatabadi (2008) revealed that incorporating no more than 25% of rubber content into the concrete composite was considered acceptable. However, as the rubber content increases, concrete workability decreases, and strength and durability diminish (Fawzy et al., 2020). Medine (2017) also reported that increasing the rubber content in concrete results in higher mass loss when exposed to sulfuric acid. Alwi Assaggaf et al. (2022) reported that the air gaps created by the Cr absorb less water than fine aggregate, causing additional stress in the specimens and resulting in the formation of further cracks.

To minimize this problem, several studies have indicated that steel fiber can be used to enhance post-cracking through the resistance of growing microcracks. Zhang (2015) conducted comparative investigations on the mechanical properties of concrete reinforced with tire-recycled steel fiber (RSF) versus industrial steel fibers, and it was determined that the tensile strength of the tire-recycled steel fiber-reinforced concrete was superior to that of the industrial steel fiber-reinforced concrete. Another study conducted by Wang (2000) examined the mechanical properties of (RSF) extracted from tire wires in combination with industrial fibers, finding that industrial fibers may similarly impact the mechanical characteristics of RSF. Additionally, Aiello et al. (2009) examined the mechanical properties of concrete reinforced with (RSF) and determined that the performance outcomes from utilizing waste fibers were analogous to those achieved with industrial steel fiber-reinforced concrete. In addition, the use of (RSF) can reduce the cost and environmental impact compared to industrial steel fibers. However, a greater dosage rate may be necessary to match the target or maintain the performance. Meddah et al.'s (2009) investigation found that incorporating waste metallic fibers of varying lengths into concrete led to improvements in the mechanical properties of the concrete, including increased load-bearing capacity. Moreover, according to Moghadam (2020), steel fiber (SF) outperformed in terms of improving the bending efficiency of concrete, which led to a delay in the collapse of the specimen. Elsayed et al. (2023) found that using 1% steel fiber had the optimum effect on the concrete properties compared to the reference one. According to Variegate (2015), there are a limited amount of steel fibers in the concrete, ranging from 0.1 to 3%, because increasing the percentage resulted in an inconsistent mixture due to the elevated viscosity of the cement matrix, which consequently led to poor workability. Rossli et al. (2012) reported that the highest compressive strength was observed at a tire fiber volume fraction of 0.4%. Another approach that yielded a promising performance and that was recommended by several researchers to minimize the impact and mitigate some obstacles imposed by crumb rubber was including steel fibers in these mixtures. These fibers have the potential to enhance the overall performance of concrete structures and have been the subject of extensive research in the field of civil engineering. The increased tensile strength and improved crack control provided by steel fibers have been proven to enhance the overall load-carrying capacity and ductility of concrete structures. An advanced composite material has been developed to improve the ductility and energy absorption of columns subjected to loading. This approach combines the advantages of steel fibers, which enhance shear strength and confinement, with rubberized concrete, which increases deformability and damping (Lee et al., 2006). The inclusion of steel fibers, specifically at volumes between 0.6% and 1.2%, significantly boosts the column's capacity and ductility, thereby preventing the brittle failure modes often seen in ultra-high-strength concrete applications (El-Attar et al., 2015; Lu et al., 2010; Shin et al., 2014).

Previous studies on the use of RSF and the incorporation of rubberized concrete in column structures have revealed limitations in the understanding of some characteristics. Therefore, the primary objective of this study is to investigate and comparatively analyze the behavior of a novel type of reinforced concrete column that incorporates rubberized concrete at 10% and 15% of the fine aggregate replaced with incorporated steel fibers at fixed volume fractions at 0.6% with three different lengths, namely 45 mm, 70 mm, and 85mm. The concrete columns were subjected to axial compression until failure, and the load capacity, displacement, ductility, and failure modes were recorded and compared. This research endeavors to contribute to the sustainability of environmentally friendly concrete (green concrete).

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Experimental Program

This study investigates the effects of utilizing RSF at varying lengths, with a consistent 0.6% volume fraction ratio and 10% or 15% Cr, as a partial substitute for natural sand aggregate in a novel structural design for columns, cubes, and cylinders. All samples were subjected to axial compression testing, including control concrete, rubberized concrete, fibrous concrete, and fibrous rubberized concrete.

Materials

The experimental work involved casting all concrete specimens using ordinary Portland cement (Type 1) with a specific gravity value of 3.15, as mentioned in the supplier's data sheet. Natural aggregates, including sand and stone, were employed as the fine and coarse aggregate constituents, respectively. The fine and the coarse constituents, with an approximate size of 14 mm for the fineness modulus, had a relative density of 3.0 and 2.64, respectively. The waste materials employed in the experiment were obtained from a local company in Saudi Arabia. The recycled steel fibers were extracted from the steel bead wires of tires, with straight shop fibers and varying aspect ratios based on lengths (45 mm, 70mm, and 85mm long) and diameters of 0.2–0.3 mm, as shown in Figure.1a and 1b. According to the supplier's data sheet, the strength of the RSF was found to be 2140 MPa, and the specific gravity was 2.08. Figure 2 depicts the crumb rubber extracted from damaged tire rubber, with a size of 4.75 mm and a fineness modulus, specific gravity, and water absorption, which were calculated as 4.5,1.26 and 1.03, respectively. Due to the impact of these materials on the workability of the concrete mixture, a superplasticizer, Conplast SP430, with a specific gravity of 1.06, was obtained from the supplier's data sheet and was used for a workability improvement. For the evaluation of mixture properties, stranded specimens with scale columns of 500 × 200 × 200 mm dimensions were utilized. For the reinforced columns, steel bars with a diameter of 10 mm, a yield strength and an ultimate strength of 460 MPa and 610 MPa, respectively, as well as a Young's modulus of 200 GPa (data sheet), were employed.

(a)

(b)

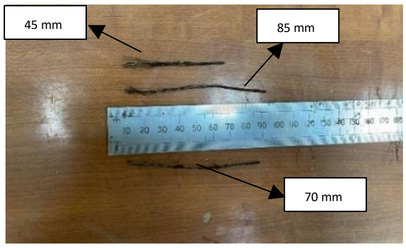

Figure 1 (a) Recycle steel Fibers (RSF), and (b) Length of RSF

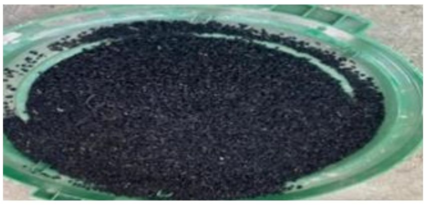

Figure 2 Crumb rubber (Cr)

Column Preparations and Details

Eighteen square columns with a 200 x 200 mm a cross-sectional size and 500 mm height were prepared and tested. Figure 3 shows four steel bars with 10 mm in diameter that were longitudinally reinforced in columns. To address shear resistance, link bars were employed with six 8-mm-diameter stirrups to provide lateral reinforcement for the reinforced concrete columns, which were designed with a longitudinal reinforcement ratio of at least 1% (ACI committee 211,1991). Additionally, 18 square columns and the 100-mm cube and cylinders (diameter = 150 mm; height = 300 mm) underwent a 28-day water curing process and were then maintained at ambient room temperature until testing.

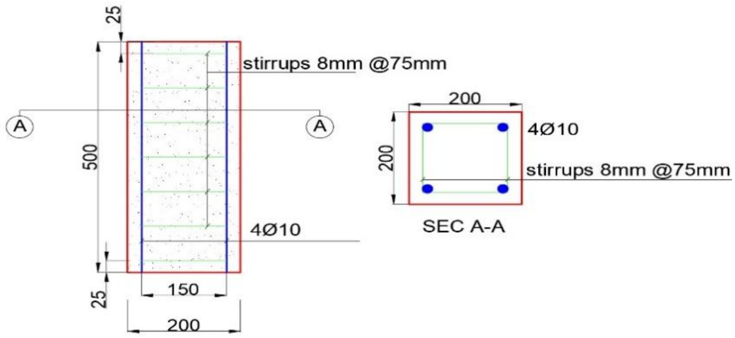

Figure 3 Reinforcement Column details

Mix and test variables for columns

The mixing controlling (Co0) were designed using the ACI method (AC1318M, 2015), with a targeted 40 MP of compressive strength, as shown in Table 1. Four mixes (Co1, Co2, Co4& Co5) in same table were prepared using Cr for column structure. The Cr was used for this mixture at two percentages, namely 10% and 15%, by partially substituting natural sand volume by calculating the weight of Cr from Eq. (1).

$$W_{Cr} = V_{sand} X\ Cr_{10\&15\%} X \frac{Cr_{S.g}}{F.A_{S.g}} \quad (1)$$

Where W_{Cr} equals crumb rubber weight in 1 m3 concrete, V_{sand} equals sand volume, $Cr_{10\&15\%}$ represents crumb rubber percentage, and $Cr_{S.g}$ and $F.A_{S.g}$ represent specific gravity of crumb rubber and fine aggregate, respectively.

Table 1 Mix proportion for controlled, rubberized, fibrous and rubberized fibrous concrete (1 m³)

Mix ID	Cr (%)	W/C (-)	F.A (kg)	C.A (kg)	RSF (%)	W (kg)	C (kg)	SP (kg)
Co0	0	0.47	701	1050	-	173.9	370	3.5
Co1	10	0.47	671	1050	-	173.9	370	4.3
Co2	15	0.47	656	1050		173.9	370	5.4
Co3	0	0.47	713	1050	0.6	173.9	370	9
Co4	10	0.47	671	1050	0.6	173.9	370	5.5
Co5	15	0.47	656	1050	0.6	173.9	370	7.5

Recycle steel fiber at a fixed volumetric ratio of 0.6% was incorporated into the conventional concrete and rubberized concrete mixtures to enhance the concrete properties for the column structure. The weight percentage of RSF is calculated from Eq. (2):

$$W_{RSF} = \frac{V_{RSF} \times D_{RSF}}{V_m \times D_m + V_{RSF} \times D_{RSF}} \quad (2)$$

where VRSF represents the recycled steel fiber's volume fraction, DRSF denotes the steel fiber's density, Dm signifies the matrix density, and Vm corresponds to the matrix volume fraction (calculated as Vm = 100 - VERSO), respectively. Columns were classified into six categories based on the testing variables, as shown in Table 2.

The study examined the performance of the conventional concrete (Co0), rubberized concrete, with 10% and 15% (Co1&Co2) as partial substitutes for natural sand aggregate, fibrous concrete (Co3), with 0.6% RSF, and fibrous rubberized concrete (Co4), with both additional materials (0.6% RSF and 10% Cr), The fibrous rubberized concrete (Co5; 0.6% RSF and 15% Cr) were the tested variables considered. The superplasticizer (SP) increased as Cr increased, while when using both materials (Cr and RSF), the SP increased more for workability.

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Table 2 The columns' test variables

Group ID	Columns ID	Concrete mix	Materials scheme	Test variables
CL0	CL01 CL02 CL03	Co0	Non	Control column
CL1	CL11 CL12 CL13	Co1	10%Cr	Crumb rubber content (Cr)
CL2	CL21 CL22 CL23	Co2	15%Cr	Crumb rubber content (Cr)
CL3	CL31 CL32 CL33	Co3	0.6%RSF At 45 mm,70mm and 85mm-long	Recycled steel fiber (RSF)
CL4	CL41 CL42 CL43	Co4	10%Cr&0.6%RSF At 45 mm,70mm and 85mm-long	Crumb rubber content (Cr) & Recycled steel fiber(RSF)
CL5	CL41 CL42 CL43	Co5	15%Cr&0.6%RSF At 45 mm,70mm and 85mm-long	Crumb rubber content (Cr) & Recycled steel fiber (RSF)

Test setup for columns

A 200-ton-capacity hydraulic universal testing machine was utilized to subject the column to compressive stress, as illustrated in Figure 4 (a & b). Axial forces were distributed uniformly across the columns by affixing steel plates to their upper and lower surfaces. Prior to the mechanical testing, the top surface of each reinforced concrete column was polished using a Gipson grinder. Eighteen RC columns were subjected to concentric axial compression loading at a displacement rate of 0.5 mm/min until they reached their ultimate axial capacities, resulting in the emergence of hairline cracks. The average values from three-column specimens were considered during the loading process. A computerized system connected to the testing apparatus recorded data on axial load and vertical displacement for all columns, enabling the plotting of a vertical load-displacement curve that facilitated the determination of three key mechanical properties: ultimate load, displacement, and ductility for each column. Furthermore, the experiment identified crack patterns and failure modes throughout the testing procedure.

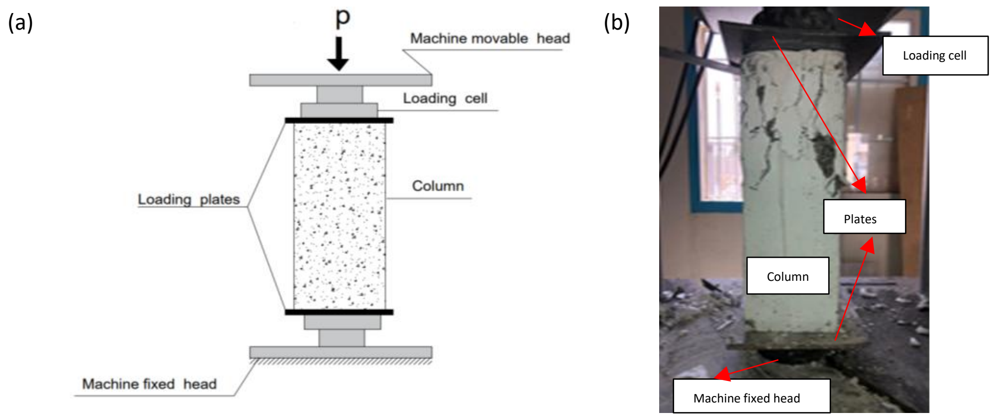

Figure 4 Concrete columns set-up by UTM load compression. (a) Schematic Columns test, and (b) Real Columns test.

Results

Concrete Properties

Figure 5 summarizes the concrete properties for each mixture, including measurements of split tensile strength, compressive strength, and density. In terms of the density of all specimen mixes when 10% of sand volume was replaced with Cr in the mixture (Co1), there was an average decrease in density of 2.18% compared to the control (Co0). When Cr increased to 15% replacement, the density in Co2 declined by 4.94% compared to the reference specimen. The fully fibrous concrete in Co3 had slightly higher density, with an average increase of 0.27% compared to Co0 mixing. On the other hand, when mixed with rubber at 10 and 15%, there was a slight decline of around 1.86% and 3.56% compared to reference specimens. However, there was a slight improvement in the density average of Co4 and Co5 when compared with Co1 and Co2, at 2378 kg/m³ and 2350, respectively, as shown in Figure 5a. The compressive strength was assessed through the examination of three samples from each mix design, with the objective of determining the mean strength at 28 days, as depicted in Figure6. A decrease in average compressive strength was observed in Co1 and Co2 compared to Co0, with a decline of 7.9% and 16.34%, attributed to the substitution of sand with 10% and 15% Cr, as shown in Figure 5b. Conversely, integrating a comprehensive fibrous component led to a considerable improvement in compressive strength, exhibiting an increase of approximately 16.84% compared to the control group. In contrast, the incorporation of RSF containing 10% Cr in the Co4 composition resulted in a modest increase of around 2.53% compared to the Co0 composition. The incorporation of Cr and RSF can be attributed to their capacity to absorb load cells, which in turn contributes to the control and delayed occurrence of cracking through the proportional involvement of RSF.

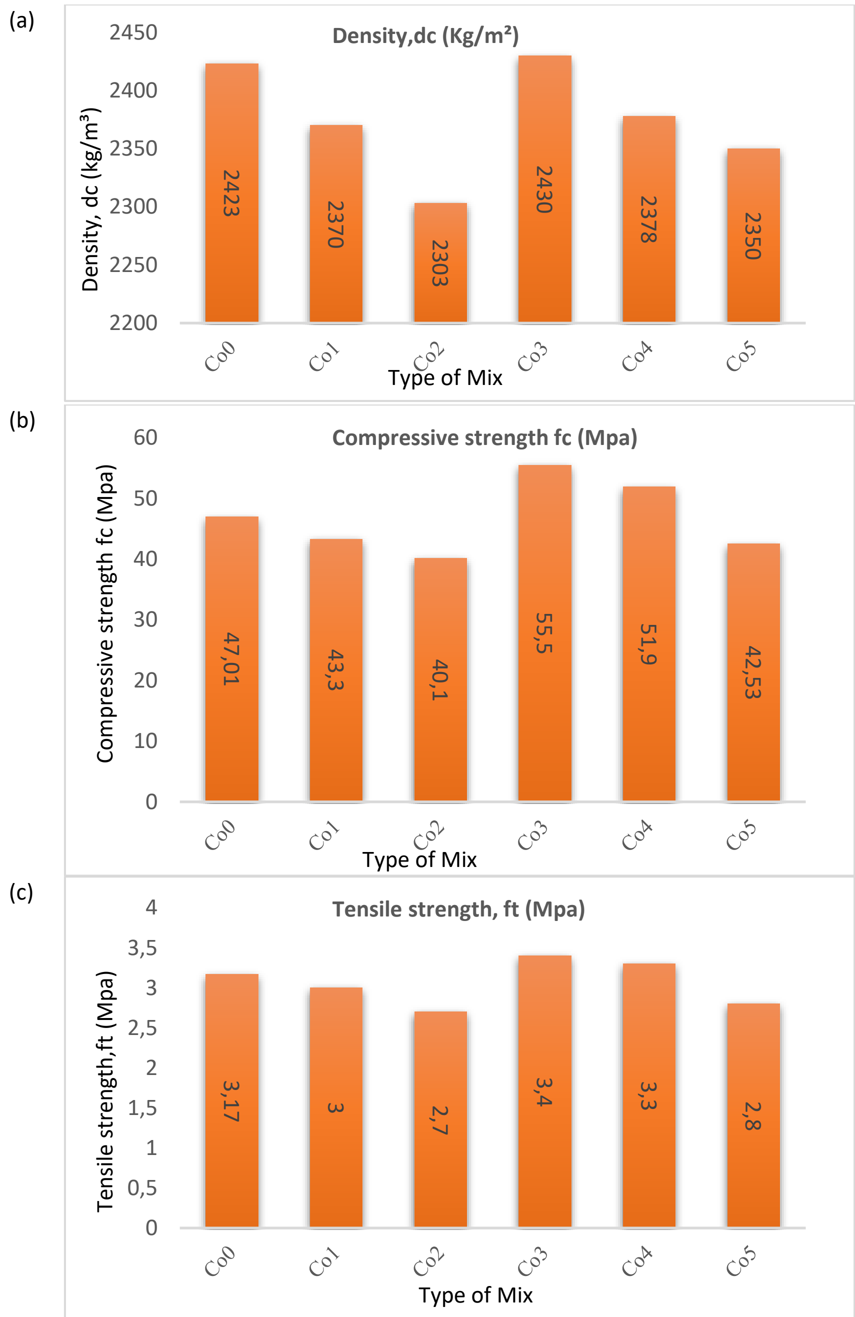

Figure 5 The properties of concrete for each mix. (a) Density, d_c (kg/m³), (b) Compressive strength f_c (Mpa), and (c) Tensile strength, f_t (Mpa)

The study revealed a modest decline in compressive strength of around 9.53% in the Co5 mixture, attributable to the increased rubber content.

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Figure 6 Cube compression test

Figure 7 Cylinders splitting tensile test

When analyzing the splitting tensile strength, each sample included an average of three cylindrical concrete specimens. As illustrated in Figure 7, the experimental evaluation of these test specimens was performed after a 28-day period. In Figure 5c,the splitting tensile test results indicate a decline due to the partial replacement of fine aggregates with Cr. Specifically, the average splitting strength value for Co0 was recorded at 3.17 MPa, which then decreased to 2.87 and 2.6 in Co1 and Co2 following a partial replacement with 10% and 15% CR, respectively. In Co3, the inclusion of only RSF resulted in an increase in splitting tensile strength to 7.20% compared to the reference specimens. However, this value decreased to 4.1% for Co4 when rubber content was 10% and 0.6% RSF, while it decreased to 11.68% for Co5 when the Cr replacement was increased to 15%, with a fixed ratio of RSF at 0.6 % compared to Co0.

Characteristics of The Columns

Table 3 outlines the axial properties of the columns, which were ascertained by testing the compressive load capacity of the columns from all mixture configurations. Each mixture abbreviation corresponds to the mean performance metrics of three column specimens (Co0, Co1, Co2, Co3, Co4, and Co5). Some properties were observed visually during the axial test and by analyzing the area under the displacement curve, while others were calculated using given formulas (Eqs. (3)and (4)).

$$(\mu = \frac{\Delta u}{\Delta yield}) \quad (3)$$

$$(K = \frac{Pu}{\Delta u}) \quad (4)$$

As shown in Table 3, the energy absorption capacity of each concrete mixture was quantified by integrating the area under the load-displacement curve for the reinforced concrete specimens tested under axial loading. According to ACI committee 211 (1991), the area under the load-displacement curves up to the ultimate load can be characterized as the energy absorbed (toughness), but even after this point is reached in reinforced columns, it is still possible to absorb more energy leading up to total failure (shear failure). The results of this study indicated an expansion in deformability for all tested columns, signifying an increase in toughness. For rubberized concrete columns (Co1), a 10% Cr resulted in an average increase in toughness of 21.88% compared to the reference (Co0). In Co2, after increasing the Cr percentage to 15%, the toughness increased to 24.87%.

The increased toughness observed highlights the potential applications of rubberized concrete as a sustainable construction material. The results showed that the concrete's toughness improved when 15% Cr was added, which aligns with the findings from a previous study. However, beyond this percentage, some studies have indicated that there was a decrease in toughness before the failure (Medine et al., 2017). It was also confirmed that specimens absorbed more energy for using RSF, whether alone or with Cr incorporated in concrete, demonstrating an average increase for Co3 and Co4 od around 82.93% and 80.33%, respectively, compared to Co0.

Total energy in Co5 increased by more than 96.33% compared to the reference specimens. The highest levels of secant stiffness (K), at around 11.30%, were observed in fibrous concrete Co3, with RSF only included compared to Co0. The stiffness of the columns decreased significantly with the incorporation of rubberized concrete in samples Co1 and Co2, demonstrating a reduction of approximately 51.34% and 65.91%, respectively, compared to the control sample Co0, as shown in Table 3.

The incorporation of Cr with RFS commonly led to an enhancement in the ductility index. The study found a notable enhancement in the ductility of the Co4 and Co5 columns when compared to the control group Co0. Specifically, their respective ductility values were 1.31 and 1.33, as opposed to 1.15 for Co0, representing increases of 13.91% and 15.65%, respectively, over that of Co0.

The highest ultimate load value (Pu) was observed in column Co3 (1287.10) with fibrous concrete only. Conversely, the introduction of rubberized concrete resulted in decreased Pu values, as indicated in Table 4. In Co0, the difference between the first cracking load (Pcr) and ultimate load (Pu) on average was a around 54.30%, while, in rubberized concrete specimens (Co1), it was around 40.50%, which means that Cr accelerated the appearance of the cracks faster compared to Co0. In Co3, with fibrous concrete, the Pu occurred after 241.62% from the first cracking load (Pcr) due to the fact that fiber helped to increase the capacity load and delay collops. Co4 shows that RSF helps to increase the Pu around 89.36% compared to Pcr even including the crumb rubber.

Table 3 Columns characteristic results

Mix.ID	Sp.ID	P_{cr} (KN)	Δ_{cr} (mm)	P_{yield} (KN)	Δ_{yield} (mm)	P_u (KN)	Δ_u (mm)	E_{total} (KN.mm)	K. (KN/mm)	(μ)
Co0	CL01	600.00	3.65	800.00	3.21	857.30	3.50	1186.02	244.94	1.09
	CL02	545.00	3.55	810.00	4.35	881.00	5.35	1333.55	164.67	1.23
	CL03	545.00	2.65	820.00	3.65	869.50	4.10	1239.67	241.00	1.12
	Average	563.33	3.28	810.00	3.74	869.27	4.32	1253.08	216.87	1.15
Co1	CL11	333.00	3.90	400.00	4.19	453.50	5.01	1187.54	90.51	1.20
	CL12	385.00	2.40	521.00	3.97	600.40	4.90	1462.28	120.10	1.23
	CL13	490.00	4.30	560.00	4.80	643.40	6.07	1932.14	105.96	1.26
	Average	402.67	3.53	493.67	4.32	565.77	5.33	1527.32	105.52	1.23
Co2	CL21	355.00	2.40	393.60	4.41	436.80	5.30	1585.70	81.97	1.20
	CL22	165.00	2.20	457.10	5.00	495.10	5.80	1444.36	85.55	1.16
	CL23	255.00	2.15	380.00	5.60	406.10	7.46	1664.30	54.28	1.33
	Average	258.33	2.25	410.23	5.00	446.00	6.19	1564.78	73.93	1.23
Co3	CL31	450.00	3.25	1393.00	6.25	1457.00	7.60	2011.00	191.71	1.22
	CL32	450.00	3.73	1120.00	4.35	1221.80	5.38	2448.00	225.00	1.24
	CL33	115.00	0.74	954.50	2.96	1182.50	3.85	2383.31	307.47	1.30
	Average	338.33	2.57	1155.83	4.52	1287.10	5.61	2280.77	241.39	1.25
Co4	CL41	390.00	1.68	1069.00	4.48	1106.00	5.68	2136.31	190.79	1.27
	CL42	600.00	3.20	1125.00	4.54	1128.00	6.17	2198.70	182.73	1.36
	CL43	675.00	3.10	960.00	4.16	1073.80	5.44	2444.26	197.50	1.31
	Average	555.00	2.66	1051.33	4.39	1102.60	5.76	2259.76	190.34	1.31
Co5	CL51	540.00	3.70	810.00	4.85	883.00	5.66	2869.88	156.01	1.17
	CL52	545.00	4.75	730.00	5.40	790.00	7.55	3110.29	105.36	1.40
	CL53	301.00	3.35	630.00	3.88	658.00	5.54	1400.62	119.07	1.43
	Average	462.00	3.93	723.33	4.71	777.00	6.25	2460.26	126.81	1.33

Cracking behavior and failure modes for columns tested

Figure 8 presents the observed patterns of crack propagation and widths for the rubberized, fibrous, and fibrous rubberized concrete specimens from the tested columns. The inclusion of 10% and 15% crumb rubber (Co1&Co2) resulted in an average increase of 17.04% and 31.67% in the frequency of crack formation, respectively, compared to the control sample. In contrast, fibrous columns (Co3) with widening cracks exhibited an average 19.53% decrease in the number of diagonal cracks compared to conventional concrete columns (Co0). The inclusion of RSF generally led to improved cracking patterns by controlling and minimizing the number of diagonal cracks and enhancing the resistance to collapse by increasing the cracks' widths, as shown in Figure 8. In the Co4 and Co5, there was improvement in the

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number diagonal around 12.5% and 16.66% compared to Co1 and Co2, respectively, due to the inclusion of the RSF in both mixtures. The incorporation of 10% Cr in the Co1 resulted in an average 11.8% reduction in the maximum spacing width between diagonal cracks compared to conventional concrete. Likewise, the maximum spacing width of diagonal cracks in the Co2 mixture exhibited a 23.6% decrease. The failure modes observed differed between the conventional concrete (Co0) and crumb rubber specimens. The conventional concrete specimens experienced crushing (CC), while the columns containing crumb rubber exhibited a sequence of concrete crushing (CC) followed by steel buckling (SB), as depicted in Figures 9b and 9c. The steel buckling of Co1 and Co2 was the most pronounced when the rubber replacement ratio of the concrete was high. This was because the rubber particles were concentrated in the upper portion of the specimen, reducing the strength and rigidity of the rubberized concrete in that area. As a result, the concrete column was unable to prevent steel buckling. Consequently, the column with a high rubber replacement ratio (Co2) was more susceptible to steel buckling. Conversely, when recycled steel fiber at a concentration of 0.6% was added, the failure modes in Figure 9(d) showed only crushing (CC). Additionally, inserting steel fibers with rubberized concrete (10%,15%) had minimal effects on the maximum column load; it reflected only crushed modes with last cracks, as shown in Figure 9e&f compared to Figure 9(b) and Figure 9(c), respectively. This is because steel fiber plays a major role in maintaining structural integrity by preventing complete collapse.

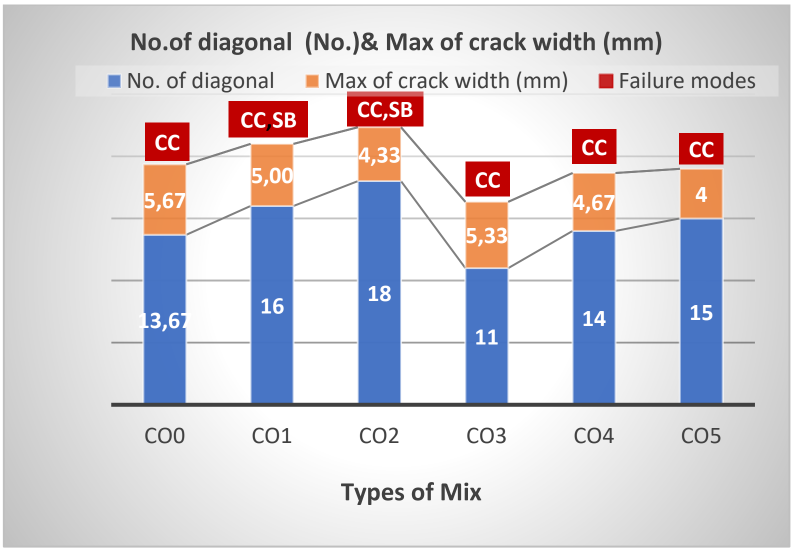

Figure 8 Characteristics of the columns cracking patterns (CC= concrete crushing, SB= steel buckling).

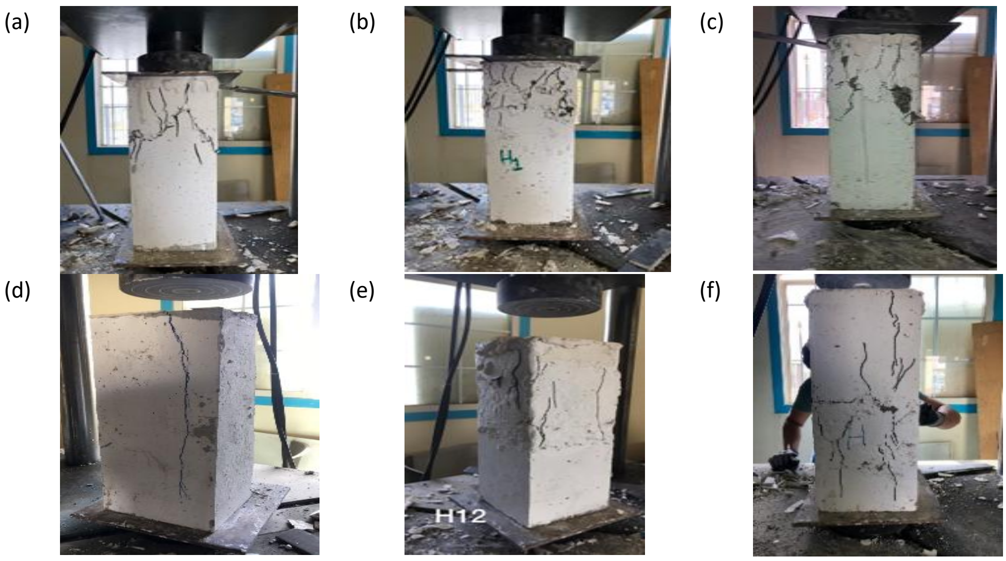

Figure 9 Failure mechanisms of the tested columns. (a) Co0, (b) Co1, (c) Co2, (d) Co3, (e) Co4, and (f) Co5.

Load-displacement behaviors

Figure 10 shows the load-displacement characteristics of the reinforced columns that were experimentally investigated, including those with and without Cr and RSF, across the concrete mix designs denoted as Co0, Co1, Co2, Co3, Co4, and Co5. It was observed that there was an increase in the slope before the appearance of initial cracks during displacement recording. Subsequently, a nonlinear slope began to gradually decrease after cracking occurred. This trend continued following the emergence of cracks until failure. The load-displacement response of the reinforced columns incorporating 10% Cr, 15% Cr, and 0.6% RSF displayed notable differences compared to the reference columns.

Previous research (Al-Tayeb et al., 2012; Noaman et al., 2017) has indicated that the cause of this occurrence was the steel bar undergoing yielding until it surpassed its yield point due to an added load. The significant decrease in the slope of the curves ultimately resulted in the attainment of the maximum load capacity through the crushing of the concrete. This resulted in a total collapse of the specimen, with significant cracks observed on the surface of the concrete. The Co1 column exhibited an average increase in ultimate displacement of 23.37% compared to Co0, while the ultimate load showed a reduction of 34.91% due to the inclusion of Cr, as depicted in Fig. 9a and 9b and Table 3. Increasing the Cr to 15% led to an increase in (Δ_u) to 43.28% and a reduction of the ultimate load at 48.69% compared to Co0. The incorporation of steel fibers into concrete mix significantly improved the blast resistance performance of the columns. The displacement of Co3 columns with only RSF increased by an average of 29.86%, and the associated load increased by 48.06% compared to Co0, as indicated in Fig. 9a and 9d (Table3). The columns containing CR (15%) and RSF (0.6%) (Co5) demonstrated higher displacement, at around 44.67%, compared to Co0 due to increased ductility to 1.33 compared to all the rest of the specimens, as depicted in Fig. 9a–9f.

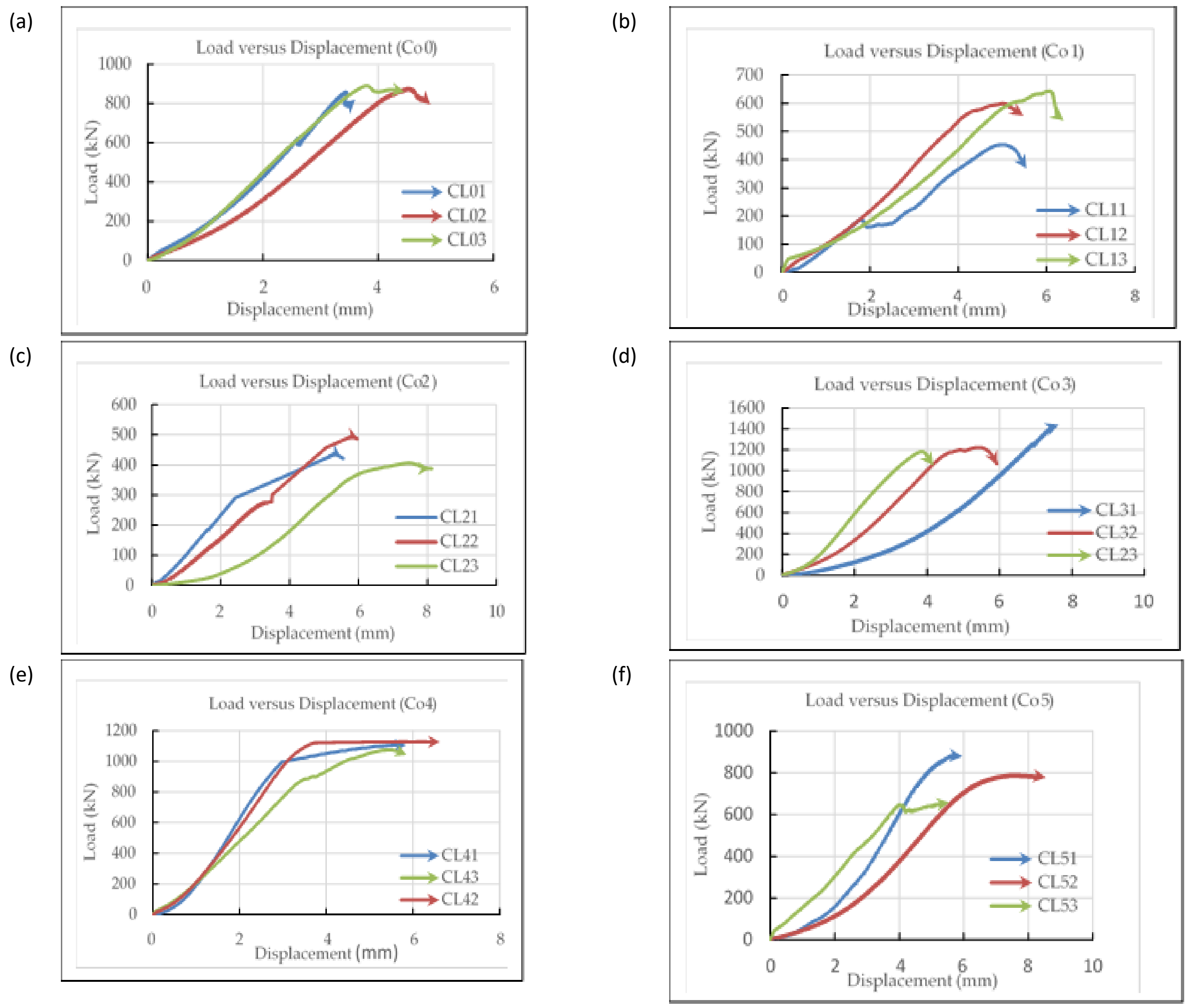

Figure 10 Load-displacement behaviours of the investigated structural columns. (a) Columns Co0, (b) Columns Co1, (c) Columns Co2, (d) Columns Co3, (e) Columns Co4, and (f) Columns Co5.

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Discussion

Concrete Properties

The density of rubberized concrete declined with any percentage of crumb rubber due to the density of sand being significantly high (2.65), at approximately twice that of Cr (1.22), thereby contributing to this observed difference. Conversely, the fully fibrous concrete had a slightly higher value due to the higher density of this material, which plays a major role in improving and delaying the cracking behavior. Generally, the decrease in density is ascribed to the incorporation of rubberized components in the concrete composition, which have a lower density than conventional concrete constituents (Ismail et al., 2017). In compressive and tensile properties, it has been reported that those reductions in properties are primarily due to replacing hard materials (sand) with softer and lighter-weight Cr (Wang et al., 2017). Ismail et al. (2017) suggest that another contributing factor is the bonding between rubber and concrete ingredients, particularly weak cement, leading to deformation and initial cracks around rubber particles and resulting in reduced compressive and tensile strength.

Characteristics of the columns

This increase in total energy suggests that the ideal percentage in Co5 enhances their overall performance compared to the rest of the specimens due to incorporated RSF for controlling the cracking progress with the Cr distributed in whole specimens to absorb the load. In secant stiffness (K), the addition of rubberized concrete in the columns led to a decrease in stiffness. According to Ahmed (2017), the decrease in stiffness led to increased deformability and improved the energy absorption capacity of the specimen under high loads, resulting in enhanced ductility. In the ultimate load, the highest value was found in fibrous concrete, as the fiber helped to delay cackles and decreased the number of cracks, while in rubberized concrete, the ultimate load decreased and the number of cracks increased.

Cracking behavior

Increasing the parentage of rubber replacement led to increased diagonal numbers with the cracks converging, as shown in Co2. This phenomenon is attributed to the relatively lower modulus of elasticity of rubber aggregate compared to traditional fine aggregate materials, leading to increased column cracking until failure (Alwi Assaggaf et al., 2022; Gesoğlu et al., 2011). Prior research has indicated that the incorporation of Cr into conventional concrete results in an increased number of diagonals, as well as a reduction in the spacing width between these diagonals, irrespective of whether the concrete is rubberized or contains a combination of rubber and fibers (Ismail et al., 2009).

Load-displacement behaviors

In general, columns with RSF exhibited increased stiffness and ductility from initial loading to failure due to their ability to delay deformation. In summary, the addition of recycled steel fiber in concrete columns resulted in improved failure modes and increased load capacity compared to conventional concrete. The results suggest that the RSF and Cr materials exhibited the capacity to absorb load and delay crack propagation during the experiment (Ismail et al., 2009; Rossli et al., 2012). The increase in displacement indicates the enhanced ductility and crack resistance provided by the combination of Cr and RSF in the concrete mix.

Conclusion

Eighteen columns with varying ratios of Cr and different lengths of RSF (at a fixed ratio) were evaluated for their mechanical properties and performance under compression. Key findings include replacing sand aggregate with Cr decreased properties such as density, compressive strength, split tensile strength, and toughness. However, RSF concrete without Cr showed higher compressive (16.84%) and tensile (7.20%) strengths compared to control specimens, attributed to fiber length and strong bonding; columns with RSF exhibited better toughness, ultimate load, deflection, and total energy absorption compared to rubberized concrete, especially for Co1 and Co2.

The combination of rubber's load absorption and steel fiber's tensile strength improved load capacity, ductility, and toughness in fibrous rubberized concrete, leading to increased fracture resistance and higher load capacity than rubberized concrete alone. Fibrous concrete columns showed improved crack patterns, with fewer cracks as RSF length increased, indicating the fiber's role in crack control. While higher Cr percentages led to more cracking, steel fiber in the Co4 and Co5 columns helped limit cracks and maintain structural integrity by distributing stress evenly, thereby improving the columns' failure modes.

Nomenclature

P_{cr}	First crack load
Δ_{cr}	Cracking displacement
P_u	Ultimate load
P_{yield}	Yield load
Δ_{yield}	Yield displacement
Δ_u	Ultimate displacement
E_{total}	Total energy
K	Secant stiffness
μ	Ductility index

The limitations of the study

The crumb rubber (Cr) has limitations in the replacement of sand aggregates, leading to the loss of compressive and tensile strength, with more cracks as Cr increased. However, the use of steel fiber helped to maintain structural strength and controlled cracking at certain percentages of Cr.

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Compliance with ethics guidelines

The authors declare they have no conflict of interest or financial conflicts to disclose.

This article contains no studies with human or animal subjects performed by the authors.

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