Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 11, No. 08, August, 2025

Effect of Waste Tire Rubber Particles on the Properties of Rubberized Concrete

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Received 23 March 2025; Revised 15 July 2025; Accepted 21 July 2025; Published 01 August 2025

Abstract

Millions of waste tires accumulate annually worldwide, posing environmental and public health challenges. Recycling these tires in concrete production presents a sustainable and practical solution. The present study was intended to investigate the effects of waste tire particles of varying sizes and shapes; specifically granular, short fiber, and mixed fine crumb rubber, along with coarse shredded rubber; on the characteristics of rubberized concrete. Fine rubber particles replaced sand, while shredded rubber replaced stone aggregates at 5%, 10%, and 15% substitution levels by weight. Results revealed that increasing rubber content reduced density, compressive strength, modulus of elasticity, and tensile strength. However, workability, Poisson's ratio, ductility, and toughness improved significantly in comparison with conventional concrete. This study compares the effects of particle size and shape of rubber used in rubberized concrete. Notably, the newly introduced short fiber-type rubber particles exhibited superior mechanical properties compared to the granular and shredded rubber forms, revealing their potential for structural applications.

Keywords: Waste Tire Rubber; Rubberized Concrete; Crumb Rubber; Fiber Rubber; Partial Aggregate Replacement.

1. Introduction

The global proliferation of discarded tires is intensifying due to increasing vehicular use, with an estimated one billion tires discarded annually [1], and it is anticipated to rise to five billion by 2030 [2]. The improper disposal of these tires constitutes a major environmental hazard [3, 4]. Recycling waste tires into rubber particles for use in concrete, known as Rubberized Concrete (RuC), offers a promising avenue for waste management, material sustainability, and environmental preservation [5-7]. Additionally, this approach reduces the demand for natural fine and coarse aggregates, thereby conserving non-renewable resources [8].

Prior studies reported that increasing the quantity of rubber in concrete reduced compressive, tensile, and flexural strength [9-12]. Miller & Tehrani [10] explored the influence of different replacement ratios, ranging from 0% to 100% in 20% increments, on both cylindrical and beam samples. The mechanical properties of the samples reduced with increasing rubber content. Sofi [11] prepared M60 grade concrete, substituting sand with Crumb Rubber (CR) up to 20% in increments of 2.5%. It was found that as the CR percentages increased, both compressive and flexural strength gradually decreased. Kadhim & Al-Mutairee [13] used CR and shredded rubber, substituting 5% to 20% fine as well as coarse aggregate. The results indicated that replacing sand and gravel using tire rubber resulted in a decrease in compression, rupture, and tensile properties. Youssf et al. [14] used three different categories of particle size, between

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http://dx.doi.org/10.28991/CEJ-2025-011-08-021

0.15 mm and 3 mm, and found that the slump values were lower for relatively fine rubber particles and higher for comparatively coarse rubber particles. Parung et al. [15] investigated the use of shredded tire chips (between 4.75 mm and 19 mm in size) as a substitute for stone chips by 10%, 20%, and 30%. They discovered that using 10% tire chips reduced the average compression and tension properties by 18% and 26%, respectively. Mo et al. [16] observed that the lowest and highest flexural strength losses for introducing CR were around 27.3% and 29.4%, respectively, for the particle size variations of 0.6-1.18 mm and 0.3-1.18 mm. Abbas et al. [17] used three different waste tire rubber particle sizes: 1 mm, 3–5 mm, and 7–10 mm and found that the impact resistance improved with increased size and rubber dosage across all tested combinations.

RuC has better toughness and impact resistance [17–19], heat and sound insulation [20, 21], and energy dissipation capacity and ductility [5, 22–24] compared to Normal Concrete (NC). Bisht & Ramana [25] noticed that the water absorption capacity and abrasion resistance improved in RuC when using 4%, 4.5%, 5%, and 5.5% CR substituting fine aggregate. According to Xiong et al. [26], the abrasion resistance of RuC was significantly enhanced by larger rubber particles compared to the smaller ones. Sugapriya & Ramkrishnan [27] found that the damping ratio increased, while the frequency values decreased in all sets as the rubber fraction increased. Due to the high resilience of RuC under abrasive conditions, it can be utilized in regions susceptible to acid attack [28]. Li et al. [29] noted that the incorporation of tire particles gradually decreased the sorptivity height in the absorption test.

The amount of increase or decrease in strength properties is contingent upon the proper content, size, and shape of rubber particles, including the design mix ratio [24]. Therefore, previous research findings suggested using rubber content up to 15% to achieve adequate concrete strength [30–32]. Although some studies have examined the impact of rubber content, replacement ratio, and particle size, they mainly focused on coarse or fine aggregate replacement and used long and thick rubber fibers on the mechanical characteristics of concrete. Limited attention has been given to the combined effect of CR particle size and shape on key mechanical properties. In particular, there is a lack of comparative studies to evaluate the effects of fine and coarse aggregate substitution using rubber particles of different sizes and shapes. To address this gap, this study presented a comparative analysis of varying sizes and shapes of rubber particles from scrap tires, substituting sand and stone by 5%, 10%, and 15%. This study investigates the individual effects of four distinct rubber particle types, including an underexplored short rubber fiber, on both fresh and hardened concrete. The research explored the uniaxial stress–strain behavior, failure modes, and mechanical characteristics of RuC, including Poisson's ratio, ductility, and toughness, especially in the context of minimizing strength loss. Finally, the findings were compared with those of conventional concrete to better understand the effect of rubber content and its size and shape on concrete performance and to find out the optimal combination for improved properties.

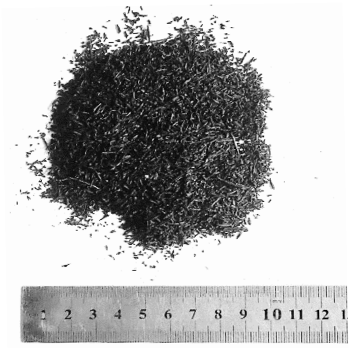
2. Materials and Experimental Procedure

2.1. Materials

A blended hydraulic cement, classified as CEM II/B-M, containing 65–79% clinker, 21–35% fly ash, limestone, and slag, and 0–5% gypsum, was used in this study. The physical characteristics of cement were assessed following the American Society for Testing and Materials (ASTM) standards and are given in Table 1. Natural sand with a particle size not exceeding 4.75 mm and a fineness modulus of 2.85 was used as the fine aggregate. Crushed stone chips were used as coarse aggregate with a particle size not exceeding 19 mm and a fineness modulus value of 7.32. Crumb Rubber (CR) and shredded rubber derived from waste tires were used as partial substitutes for sand and stone, respectively. The CR particles were categorized into three types, such as Small Crumb Rubber (SCR) ranging from #8 to #30 mesh; Fiber Crumb Rubber (FCR) ranging from #4 to #8 mesh; and Mixed Crumb Rubber (MCR) ranging from #4 to #16 mesh, which was obtained by mixing SCR and FCR. These CR particles were used to replace 5%, 10%, and 15% of the sand by weight. The SCR particles were granular in form, and the FCR particles were short fibers whose lengths varied from 7 mm to 15 mm. However, the FCR particles successfully passed through the #4 mesh sieve because of their elongated shape and small lateral dimension that resembles fibers. The MCR particles were a mixture of both SCR and FCR. The size of the Coarse Shredded Rubber (CSR) varied between 9.5 and 19 mm and it was used to replace stone chips up to 15% by weight. The photographs of the various types of tire particles used in the present study are presented in Figure 1.

Table 1. Properties of cement

Physical Properties	Test Results
Normal consistency	31%
Specific gravity	3.15 g/cc
Initial setting time	30 min
Final setting time	195 min
28-day compressive strength	37.3 MPa



(a) Small crumb rubber
(from #8 to #30 mesh)

(b) Fiber crumb rubber
(from #4 to #8 mesh)

(c) Mixed crumb rubber
(from #4 to #30 mesh)

(d) Coarse shredded rubber
(from 9.5 mm to 19 mm)

Figure 1. Waste tire rubber particles used in this study

Particle size distribution graphs of the aggregates are presented in Figure 2. Lower and upper limits of particle size distribution for fine aggregate (FA) and coarse aggregate (CA) as per ASTM C33 [33] are also presented in Figure 2. The grain size distribution of sand and stone chips falls within the lower and upper limits, whereas all rubber particles remain out of the range, as observed in Figure 2. However, the compositions of FA after replacing sand with CR particles (5%, 10%, and 15% of sand) were found to be within the lower and upper limits. A similar pattern was also seen for the coarse aggregate after partial replacement of stone chips using CSR of different percentages. Standard parameters of the aggregates, including different types of CR and coarse shredded rubber, were determined in the laboratory following ASTM standards and presented in Table 2.

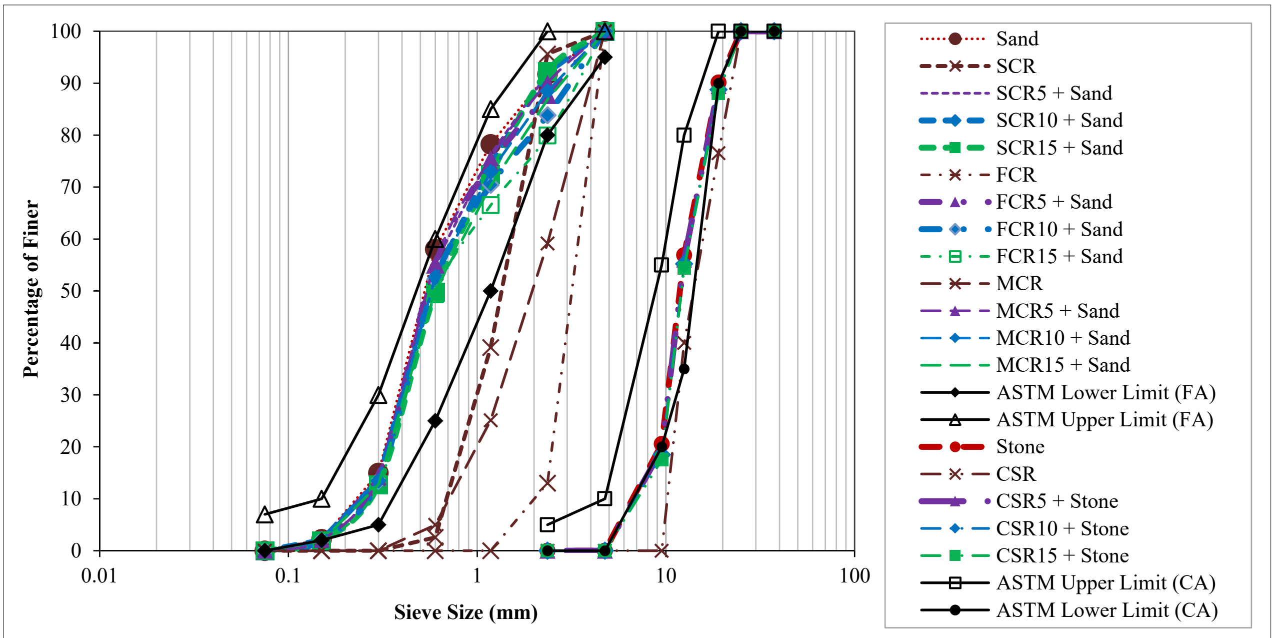


Figure 2. Particle size distribution curve of the aggregates

Table 2. Physical properties of aggregates

Physical properties	SCR	FCR	MCR	Sand	CSR	Stone Chips
Nominal maximum size (mm)	0.6	2.36	2.36	4.75	19	19
Fineness modulus	3.63	4.91	4.11	2.85	7.83	7.32
Unit weight (kg/m^3)	465	494	480	1571	700	1737
Aggregate crushing value (%)	-	-	-	-	-	55.75
Water absorption capacity (%)	0.95	0.97	0.96	6.27	1.1	0.4
Specific gravity (SSD)	1.05	1.13	1.09	2.5	1.55	2.82
Specific gravity (OD)	1.04	1.12	1.08	2.35	1.53	2.79

2.2. Concrete Mixtures and Sample Preparation

Concrete mix proportions were determined using the ACI 211 method [34] and the amounts are presented in Table 3. A total of thirteen batches were considered, including one control batch (i.e., NC) and twelve RuC batches, wherein each batch FA or CA was replaced by different types of CR and CSR, respectively. Sand was partially replaced with SCR, FCR, and MCR by 5%, 10%, and 15% in batches 2 to 10, while the quantity of stone remained the same as in the NC. In batches 11 to 13, the stone chips were partially replaced with CSR by 5 to 15%, with the sand content kept identical to NC. Sample ID was chosen based on the type of substituted rubber aggregate and its percentage, such as SCR5, which indicates the concrete mix where 5% of FA was replaced by SCR. A constant amount of cement (425 kg/m^3) was used in all mixes. Water-cement ratio was also 0.47 for all batches.

Table 3. Quantity of materials for each batch of mixing

Batch No.	Sample Id.	Cement (kg/m^3)	Sand (kg/m^3)	Stone (kg/m^3)	Rubber particles replacing sand (kg/m^3)	Rubber particles replacing stone (kg/m^3)	Water (kg/m^3)
1	NC	425	600.2	1129.2	0	-	200
2	SCR5	425	570.2	1129.2	30	-	200
3	SCR10	425	540.2	1129.2	60	-	200
4	SCR15	425	510.2	1129.2	90	-	200
5	FCR5	425	570.2	1129.2	30	-	200
6	FCR10	425	540.2	1129.2	60	-	200
7	FCR15	425	510.2	1129.2	90	-	200
8	MCR5	425	570.2	1129.2	30	-	200
9	MCR10	425	540.2	1129.2	60	-	200
10	MCR15	425	510.2	1129.2	90	-	200
11	CSR5	425	600.2	1072.7	-	56.5	200
12	CSR10	425	600.2	1016.3	-	112.9	200
13	CSR15	425	600.2	959.8	-	169.4	200

A total of 91 concrete cylinders (as seen in Figure 3) were cast, with 7 samples prepared for each of the 13 mix batches. Among these, 39 cylinders were tested to evaluate compressive strength and modulus of elasticity, another 39 for splitting tensile strength, and the remaining 13 for determining Poisson's ratio. The cylindrical samples were 100 mm in diameter and 200 mm in height. Initially, the rubber particles were soaked in water mixed with washing detergent for eight hours to remove dirt from the surface and to fill the voids with water. Then, the particles were left to rest in a basket to drain the water, soaked again in clean water to remove residual detergent, and exposed to air to reach a surface-dry condition. All the materials were mixed by hand for about six minutes due to the small quantity required for each batch. The first three minutes were spent mixing sand, stone, cement, and rubber particles. The water was then progressively introduced and continuously blended for about three minutes to get a homogeneous consistency, and the slump test was done right away. The steel molds were used for casting concrete cylinders and discarded from the samples when 24 hours had passed after casting. The prepared samples were submerged in water to ensure complete hydration of cement for a 28-day curing period, after which different testing and analyzing results were conducted. A graphical flowchart of the working methods is presented in Figure 4.

Figure 3. Prepared concrete cylinders

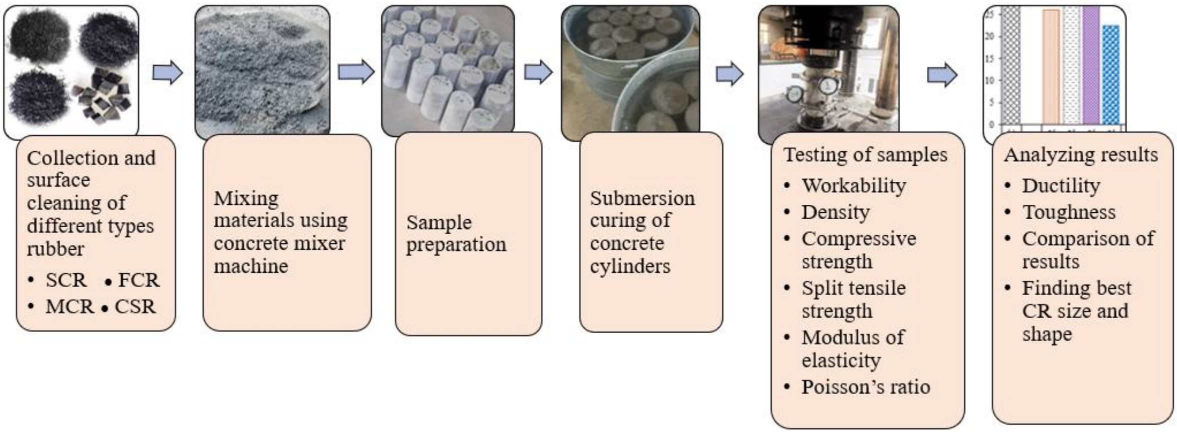


Figure 4. Graphical flowchart of working methodology

2.3. Test Procedure

All experimental procedures were conducted according to ASTM standards. Workability was assessed using the slump test as per ASTM C143-15 [35], as shown in Figure 5-a, to investigate the size and shape effect of rubber particles on the concrete workability. The compression and elasticity modulus tests were done following ASTM C39-21 [36], and the splitting test was done in accordance with ASTM C496-17 [37]. The test setup of compressive and split tensile strength is demonstrated in Figures 5-b and 5-c, respectively. The ASTM C492M-14 [38] guideline was followed to determine the Poisson's ratio of concrete, as shown in Figure 5-d.

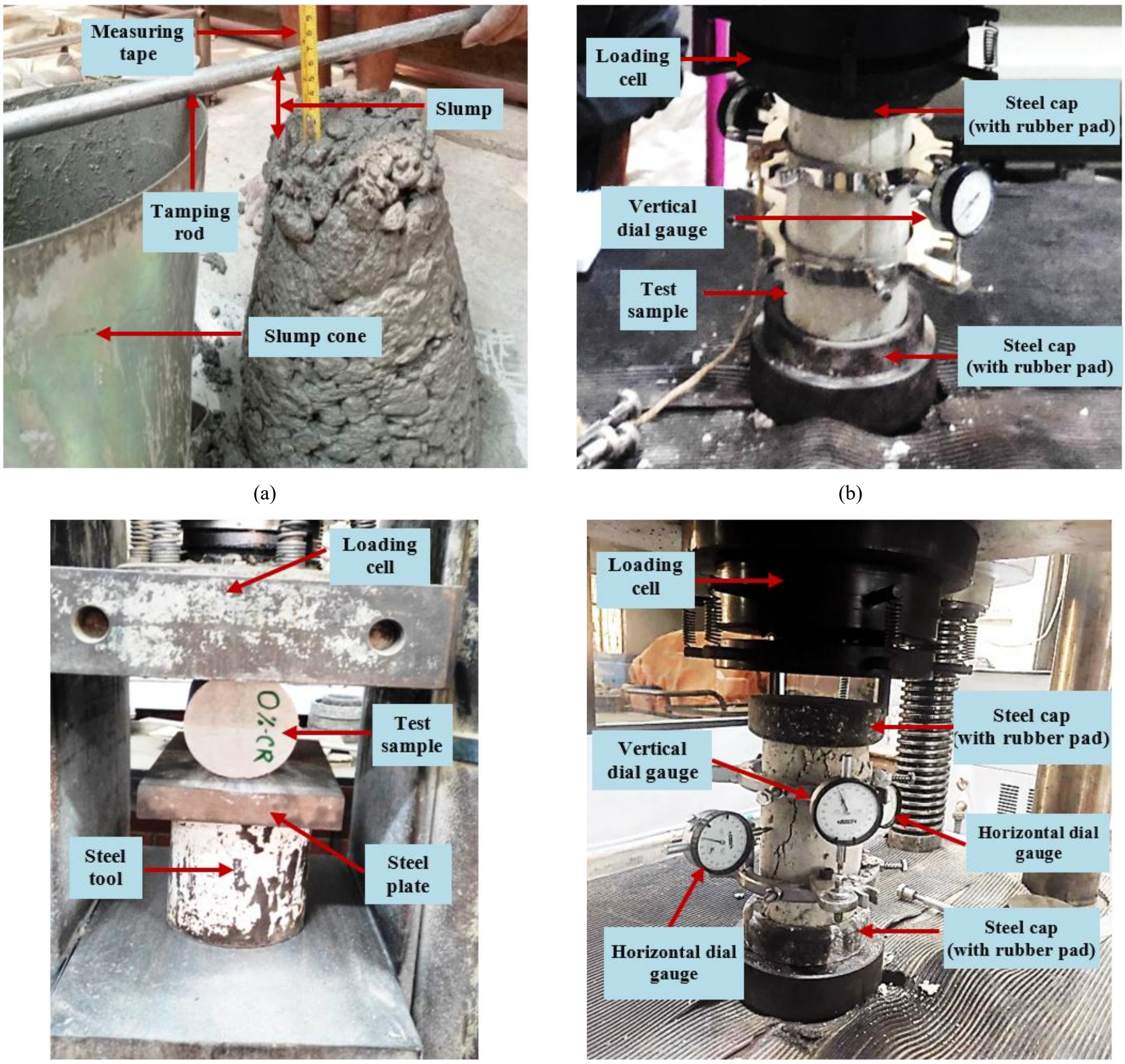
3. Experimental Results and Discussions

3.1. Workability

The workability was evaluated through the slump test method, and the findings are tabulated in Table 4, from which it is observed that the workability increases with increasing the percentages of tire particles in the concrete mix compared to NC. This might be attributed to the limited ability of rubber particles to absorb water [39], the cleaning of rubber surfaces with detergent, and the filling of voids with water during cleaning, which may increase mobility within the mix. Cleaning with detergent removed contaminants (such as oils, dust, and other residues) from the surface of the rubber particles, which might reduce the inter-particle friction between the CR particles, making them easier to mix and flow. Mohammadi et al. [40] also observed that the water soaking method before mixing the tire particles with concrete ingredients has a positive influence on improving the workability of RuC. In addition, previous studies also revealed that the rising content of tire particles contributes to the improvement of the slump value in the concrete mix [41-44].

It was seen from Table 4 that the slump value decreased by approximately 18% for 5% SCR but then increased by 4% and 16% with 10% and 15% SCR, respectively, compared to NC. The short fiber FCR exhibited a higher slump value compared to the other fine CR replacements, such as SCR and MCR, at all replacement levels. An identical behavior was also observed in earlier studies, where the addition of CR fiber to concrete significantly improved the material's workability [45, 46]. However, the slump value increased by 26% to 67% with the replacement of CA by 5%

to 15% CSR, respectively, in the concrete mix, which was the highest percentage improvement among all forms of rubber particles used in the present study. This evidence suggests that the coarse particles of waste tire rubber exhibit higher workability compared to the fine particles, and the larger size of the fine CRs contributes to greater workability than the smaller size. Su et al. [47] stated that concrete consisting of the substitution of sand with larger-sized rubber demonstrated greater workability compared to concrete containing smaller-sized rubber particles. This enhancement in workability results from the reduced surface area and hydrophobicity of coarse tire particles, make them more suitable for workability than fine particles. Coarse particles cause less friction inside the mix and spread out more evenly, providing a more consistent flow compared to fine particles.



(a) (b) (c) (d)

Figure 5. Experimental test setup (a) slump, (b) compressive strength and modulus of elasticity, (c) splitting tensile strength, and (d) Poisson's ratio

Table 4. Slump of concrete mixes with different types of rubber particles

Rubber Particles	Slump (mm)			
	0%	5%	10%	15%
NC	73	-	-	-
SCR	-	60	76	85
FCR	-	85	97	108
MCR	-	80	88	97
CSR	-	92	106	122

3.2. Density

The change in concrete density as a result of incorporating rubber particles is presented in Figure 6. The test finding revealed that the concrete density reduced with increasing rubber content compared to the NC mix, which showed a bulk density of 2321 kg/m³. The bulk density decreased by 2% to 11% for SCR, 3.5% to 14% for FCR, 3% to 12.5% for MCR, and 7.5% to 22% for CSR by replacing 5% to 15% of sand and stone chips, respectively. Compared to the other rubber particles, CSR showed a more noticeable effect on reducing the density of concrete. This suggests that the density dropped as the percentage of rubber particles rose, with the larger particles reducing it more than the smaller ones. The decrease in concrete density may result from the lower density and specific gravity of the trash tire in comparison with natural fine and coarse aggregates [48–50]. This phenomenon is compatible with the previous study. Islam et al. [51] also observed that the smaller-sized (8 mm to 15 mm) rubber particles resulted in greater density compared to the larger-sized (15 mm to 25 mm) rubber. In this study, the specific gravity of CR was between 1.05 and 1.13, which was considerably lower than that of sand (i.e., 2.5), highlighting a significant difference in density. Dumne [52] found that substituting 15% of coarse aggregates with rubber significantly reduced the density by 14.3%. Jayathilakage et al. [53] stated that a 100% replacement of CA with 15 mm shredded rubber may reduce the density by 20% compared to NC. Santos-Ortega et al. [54] reported a 4% to 12% reduction in density for using 10% to 20% CR substituting sand. Chaturvedy et al. [55] used 5% to 15% CR as a substitute for sand and observed a 1.4% to 4.3% decrease in concrete density. It was revealed that the density of the RuC is generally influenced by the rubber particle size [56]. Therefore, the density obtained in this study appears to be consistent with prior research.

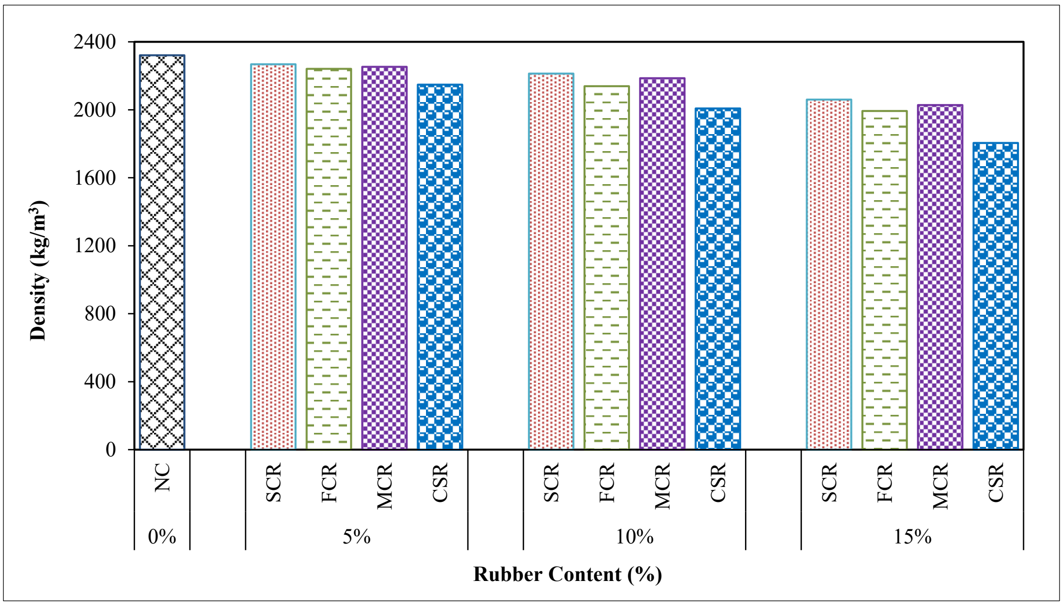


Figure 6. Density of RuC for different rubber contents

3.3. Compressive Strength

Concrete specimens containing various sizes and proportions of rubber particles were tested after 28 days to determine compressive strength. The test results are presented in Figures 7 and 8. The results indicate that NC had 31.52 MPa compressive strength, which progressively decreased as the rubber particle quantity increased from 5% to 15%. FCR showed reductions in compressive strength of 11.42%, 14.55%, and 21.37% for 5%, 10%, and 15% replacement, respectively. The reduction was more prominent for SCR and MCR. In case of 15% replacement of FA by SCR and MCR, the concrete strength reduced by 34% and 28%, respectively. Replacing CA with SCR reduced the concrete strength by approximately 28% to 41% for 5% to 15% replacement, respectively. Previous studies also reported a notable decrease in compressive strength of RuC due to the addition of tire rubber [57-60]. A substantial decrease of up to 85% in compressive strength has also been reported in previous studies [57, 58]. Singaravel et al. [61] found that a rubber replacement level within 10% by volume caused a subtle decrease in compressive strength, whereas a 15% replacement significantly lowered strength by 30–50% compared to high-performance concrete. Hiremath et al. [62] investigated the impact of CR at 2.5–10% content and observed a reduction of up to 65% of compressive strength. This might be attributed to the presence of salt, poor hydraulic connectivity, low water absorption, and the smooth texture of rubber particles [63–65]. These factors hinder the adhesion between binder and rubber particles, which leads to an unstable bond between the ingredients of the concrete mix. Because of this, applied force is not distributed uniformly, which leads to early concrete rupture as fractures develop and spread swiftly, surrounding the rubber particles throughout the loading stage. Furthermore, the use of discarded tire particles caused the development of voids, which reduced the compressive strength of concrete.

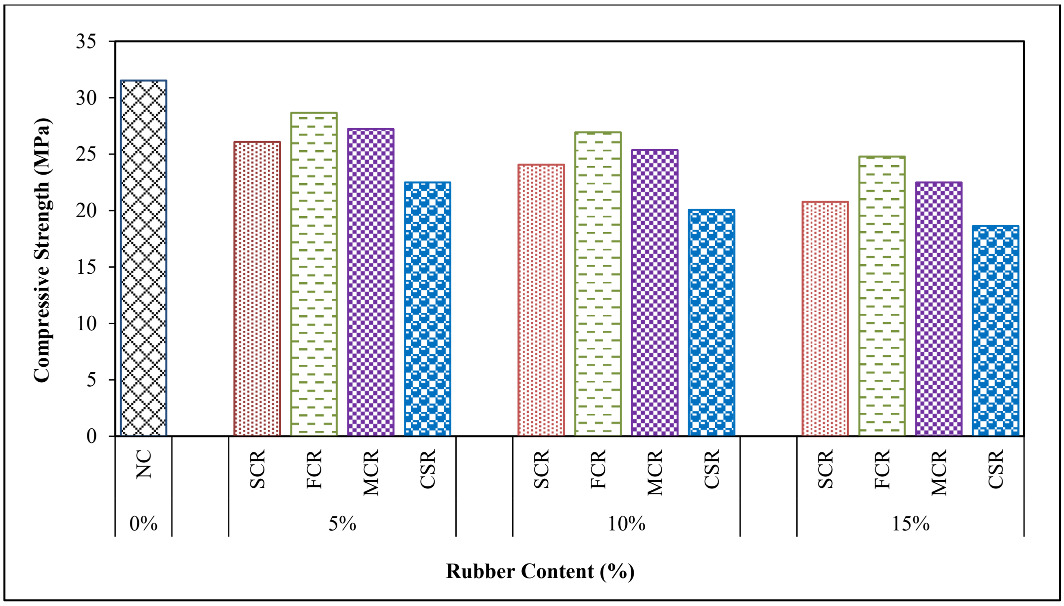


Figure 7. Compressive strength of RuC for different types of rubber particles

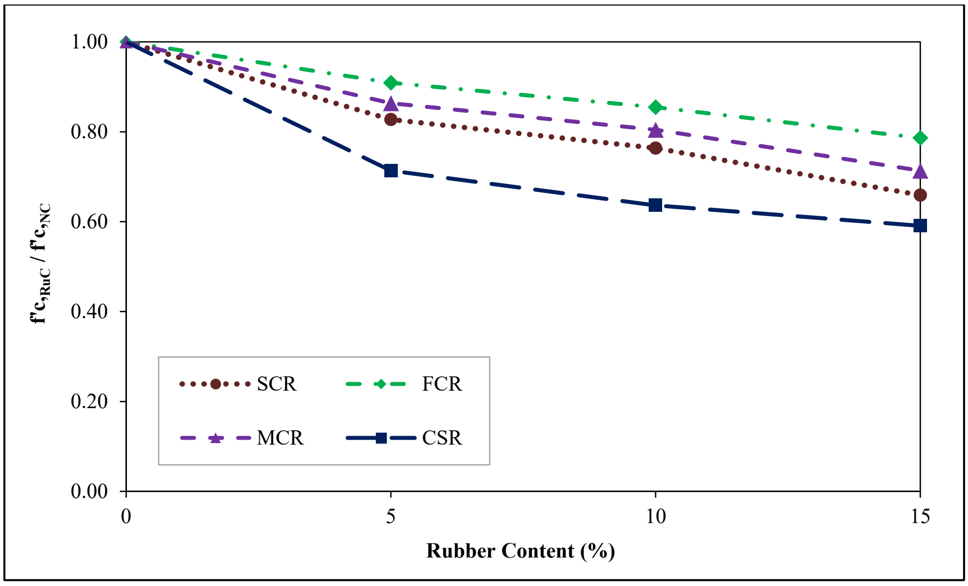


Figure 8. Compressive strength ratio of RuC and NC

The test findings indicated that the substitution of sand by CR had a relatively low impact on the compressive strength, while replacing stone chips with CSR produced the lowest compressive strength values. This behavior occurs due to the additional surface area of larger tire particles that leads to rapid degradation of adhesion and, consequently, a greater loss of strength compared to smaller particle sizes. Liu et al. [66] and Siddika et al. [67] observed that the strength of RuC dropped as the size of tire particles rose. Among the different types of tire particles, FCR showed less reduction of the compressive strength values across all other types of rubber. The reduction in strength of RuC with FCR is related to the fact that these FCR particles were relatively larger in length, looked like short fibers, and had less surface area. Their fineness modulus was also higher than sand and other rubber particles such as SCR and MCR. Previous studies also reported that the finer-sized rubber particles exhibit greater compressive strength compared to the larger rubber particles [42, 43]. Youssf et al. [14] also asserted that the concrete strength may be enhanced by raising the fineness modulus of aggregates. In addition, Li et al. [68] found that concrete made with waste tire fiber strips exhibits better strength compared to concrete made with small CR particles.

3.4. Splitting Tensile Strength

In Table 5, the splitting strengths of concrete substituting sand and stone chips with 5% to 15% of different-sized rubber particles are presented. This value for NC was 3.11 MPa, and it decreased as the tire rubber percentages increased from 5% to 15% for SCR, MCR, and CSR, with the exception of 10% FCR. The reduction in the tensile strength varied depending on the type of rubber particles used. The splitting tensile strength reduced 12% to 38% for SCR, 4% to 12%

for FCR, 7% to 35% for MCR, and 34% to 42% for CSR, corresponding to rubber replacement levels from 5% to 15%. Like the compressive strength, the effect of introducing tire particles on the tensile strength is less for FCR. These results also indicated that replacing coarse aggregate with CSR exhibited a more adverse impact on tensile strength than fine aggregate replacements. The smooth texture of the rubber particles accelerates crack formation under loading, thereby reducing the overall stiffness of the concrete. Previous research also supports this trend, suggesting that increasing the amount of rubber utilized to substitute natural aggregate makes a substantial reduction in the splitting strength of RuC [69–72]. According to Khalil et al. [73], tensile strength decreased by 29% as the rubber content used increased from 0% to 40%. Similarly, Eisa et al. [74] stated that this strength was reduced by 25% to 42% when CR percentages increased from 5% to 20%. A significant decline of about 50% was also observed in splitting tensile strength from previous studies [57, 58]. A reduction in split tensile strength is attributed to factors similar to those impacting compressive strength [75].

Table 5. Correlation between compressive and splitting tensile strength

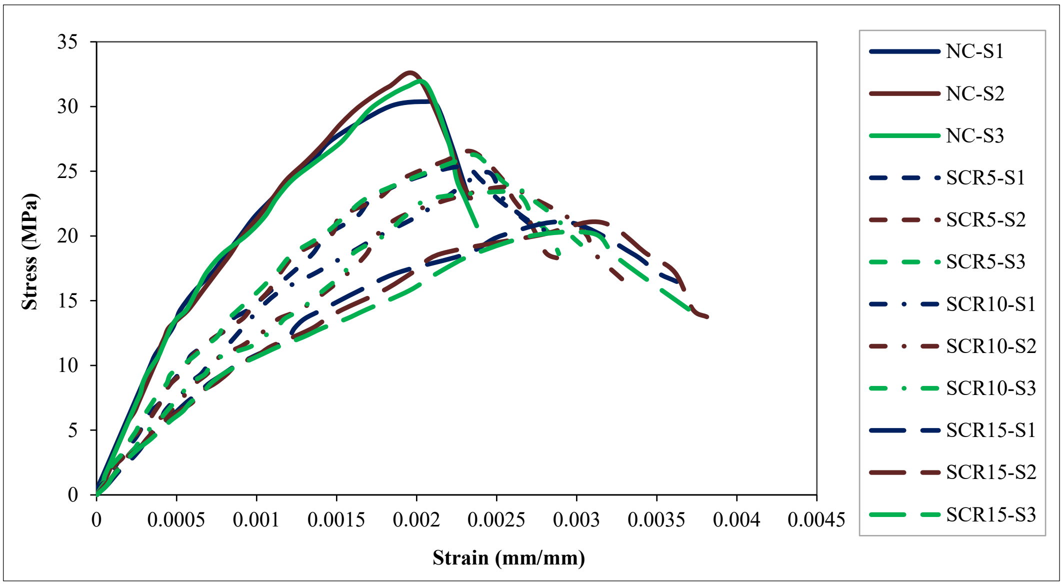
Sample Id.	Rubber content	Splitting Tensile Strength (MPa)	Compressive Strength (MPa)	% of f_{st}/f'_c	$f_{st}/\sqrt{f'_c}$
NC	0%	3.11	31.52	9.85	0.55
SCR	5%	2.73	26.08	10.48	0.54
	10%	2.32	24.07	9.63	0.47
	15%	1.93	20.77	9.31	0.42
FCR	5%	2.97	28.66	10.35	0.55
	10%	3.07	26.94	11.39	0.59
	15%	2.75	24.79	11.11	0.55
MCR	5%	2.88	27.22	10.57	0.55
	10%	2.39	25.36	9.43	0.47
	15%	2.01	22.49	8.95	0.42
CSR	5%	2.06	22.49	9.14	0.43
	10%	1.91	20.06	9.55	0.43
	15%	1.79	18.62	9.61	0.41

Among the various forms of fine CR, FCR exhibited the highest tensile strength. Gupta et al. [76] also found that the tensile strength reduction is contingent upon the size and variety of tire rubber particles. This performance variation can be explained by the influence of particle size and shape. The short fiber shape of FCR particles can bridge microcracks, delay crack propagation, and potentially improve energy absorption, providing additional tensile strength with up to moderate levels. In contrast to others, with the increase of the percentage of FCR from 5% to 10%, the tensile strength increased around 5%.

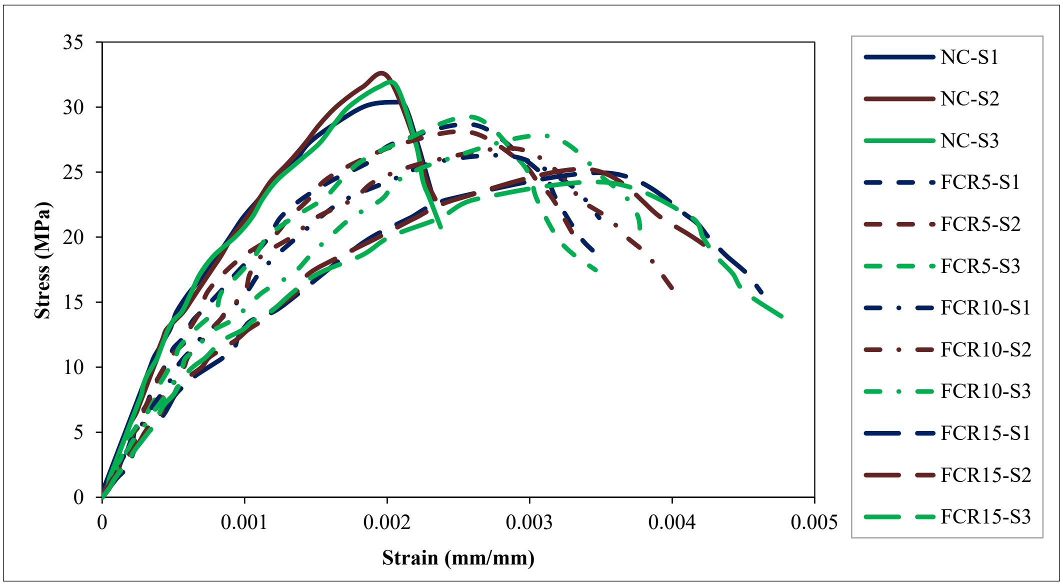
In literature, it is stated that the tensile strength of concrete is generally proportional to the compressive strength or the square root of the compressive strength of concrete [77–81].Usually the tensile strength of concrete varies between 7–15% of its compressive strength [77–79]. From Table 5, it is observed that the tensile strength of RuC pertained within the range. In addition, the splitting strength divided by the square root of the compressive strength ($f_{st}/\sqrt{f'_c}$) values are provided in Table 5. Normally, this value for concrete lies between 0.50 and 0.66 [80, 81]. Though this value for NC is within this range, for RuC these ratios vary significantly with different types of rubber particles. The $f_{st}/\sqrt{f'_c}$ ratios of RuC with FRC fall within the range (0.55-0.59) for all percentages of replacement. The $f_{st}/\sqrt{f'_c}$ ratios of RuC with SCR, MCR and CSR were found lower than 0.5 for 10% and 15% replacement.

3.5. Stress-Strain Relationship

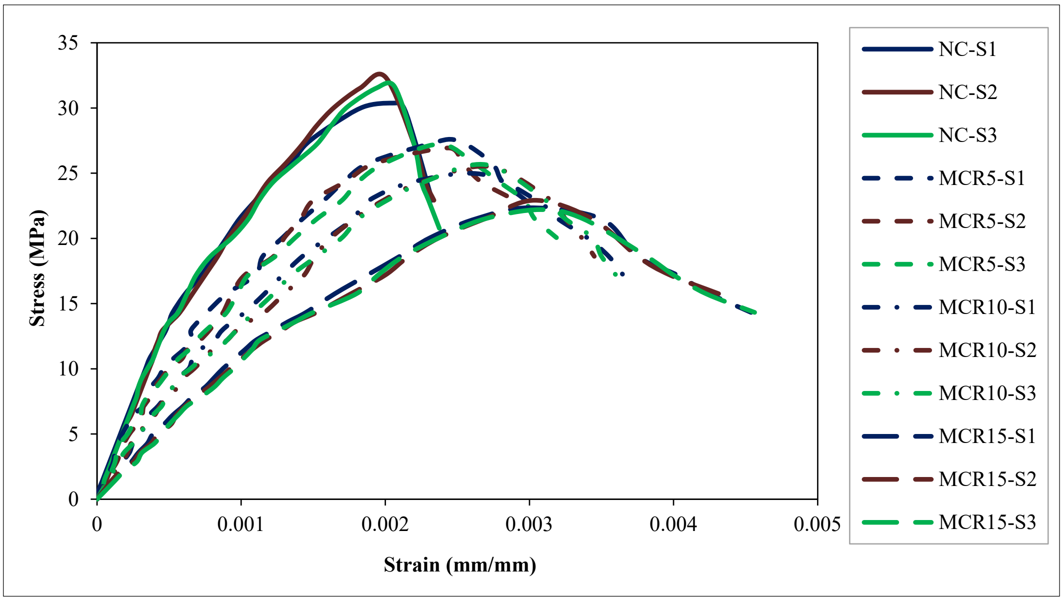
In this investigation, three specimens were used to test each concrete mix to observe the stress-strain behavior of NC and RuC. The stress-strain relation of RuC for 5%, 10%, and 15% replacement of FA and CA with different sizes of rubber particles is presented in Figures 9-a to 9-d. The three samples show nearly identical relationships with each other. The stress-strain graphs are categorized into the pre-peak and the post-peak regions. The initial part of the curves is linear in the pre-peak region. Thereafter, the stress-strain relationship becomes nonlinear, and this nonlinearity increases with increasing strain. This behavior is consistent with both reference NC mixes and RuC mixes. The slope of the ascending part in the pre-peak region for RuC decreases with an increase in CR content. The descending part in the post-peak region shows a milder slope compared to the NC, and consequently, the curvature radius increased at the peak of the curves. A similar pattern was also observed in prior research [82–84], where studies pointed out that incorporating CR increased the curvature radius at the peak of the stress-strain curve. In addition, the overall shape of the curve became noticeably shorter and wider compared to that of traditional concrete.



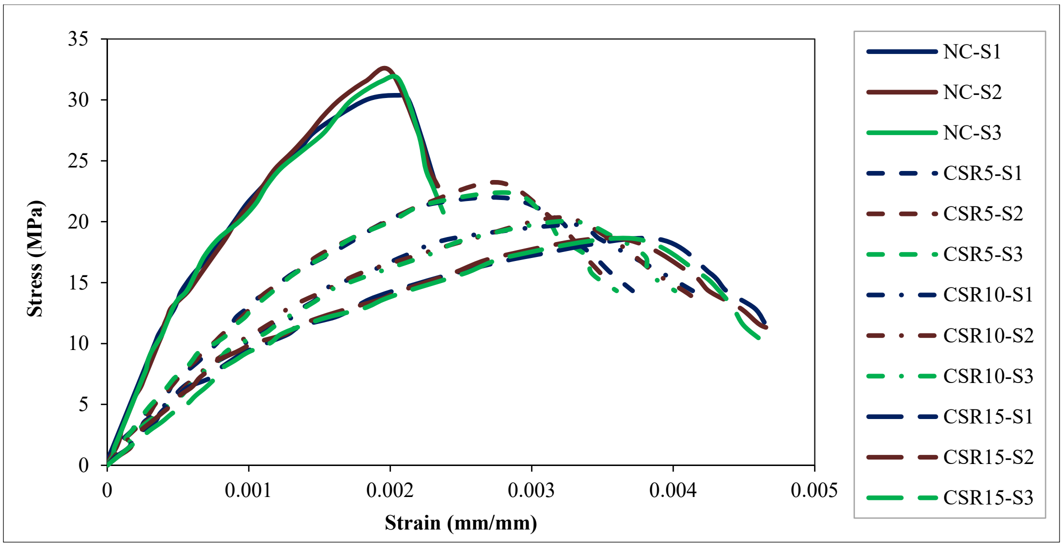
(a) SCR



(b) FCR



(c) MCR

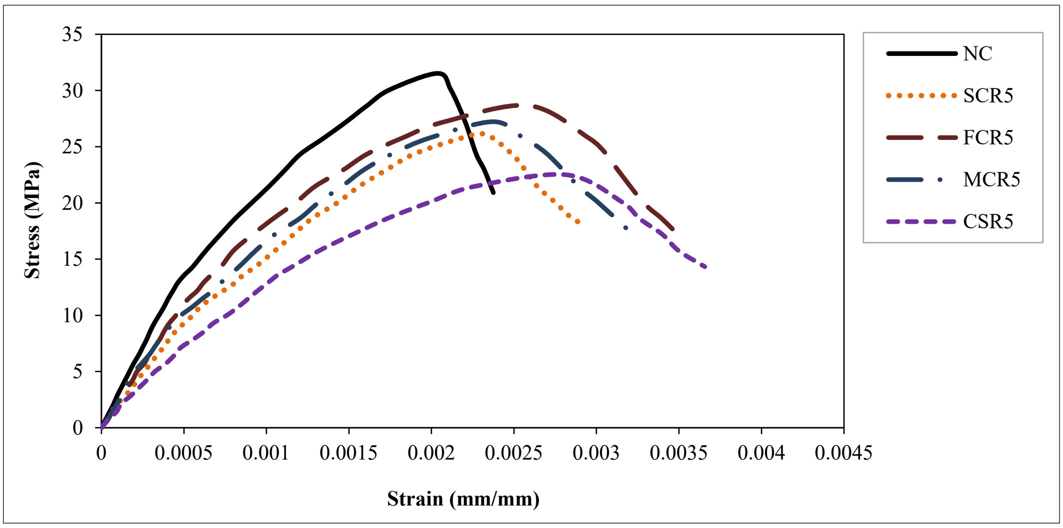


(d) CSR

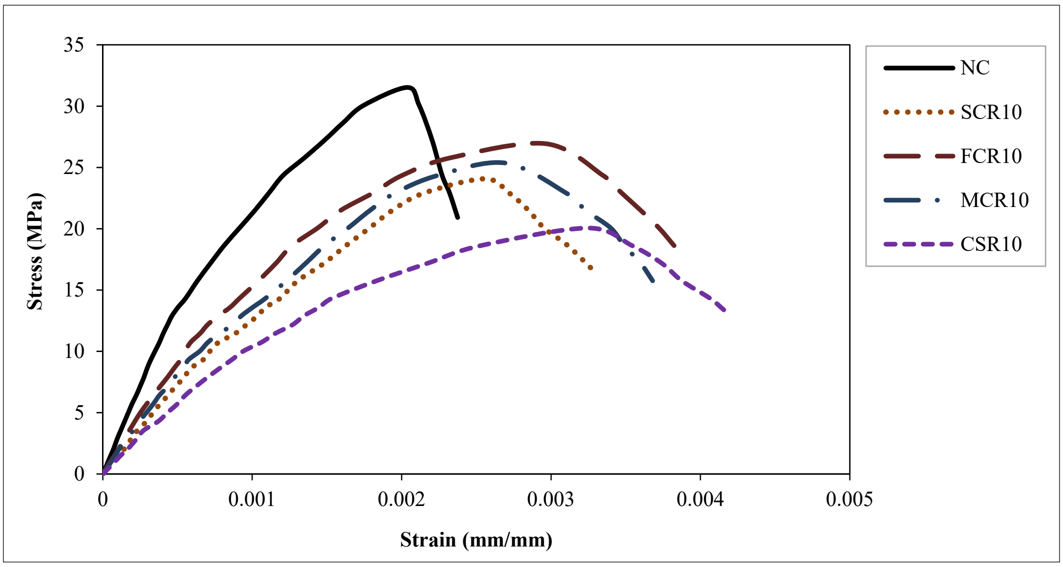
Figure 9. Stress-strain curves of RuC for different types of waste tire rubber

As seen in Figure 9, though the peak compressive stress decreases, the strain at ultimate stress rises as the rubber percentage increases from 5% to 15%. The strain values associated with the ultimate stress for 5% of all rubber particles and 10% of SCR and MCR particles are between 0.002 and 0.003. For 10% of FCR and CSR, the maximum strain falls within 0.0025 to 0.0032. Furthermore, these strain values are over 0.003 when 15% of rubber particles are included. These results indicate that the strain at ultimate stress increases when the size and percentages of rubber particles increase. Previous studies also observed increased strain capacity of RuC due to increasing rubber content compared to the regular concrete. According to Khaloo et al. [85], the strain at peak stress increased from 0.0071 to 0.062 as the percentage of rubber increased from 12.5 to 50, with particle sizes ranging between 2 and 15 mm. Noaman et al. [86] also reported that the strain at peak stress rose from 0.0089 to 0.012 with the use of 5% to 15% CR having particle sizes between 1.18 and 2.36 mm.

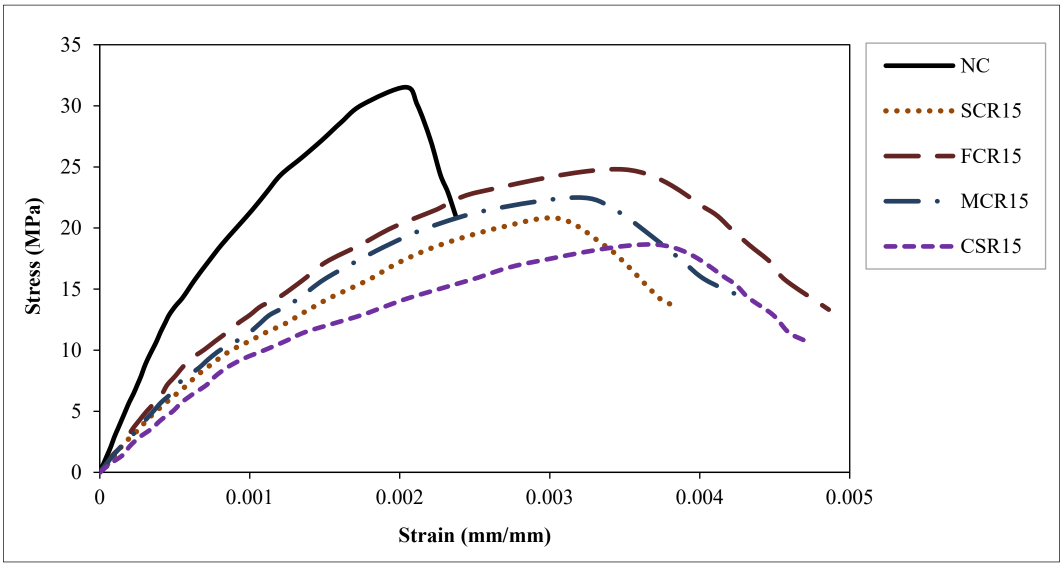
The comparison of stress-strain behaviors of the tested concrete specimens for each group with 5%, 10%, and 15% replacement of FA or CA with different types of waste rubber particles, such as SCR, FCR, MCR, and CSR, is shown in Figures 10-a to 10-c. Here, average stress-strain graphs of each group of concrete mix were plotted. The strain at ultimate stress for NC was 0.0022. This strain value increases by approximately 1.1 to 1.3 times, when SCR was used as a replacement for FA. For RuC using FCR, the strain at ultimate stress increased by 1.2 to 1.6 times, and this variation was 1.1 to 1.5 times for RuC with MCR. However, CSR showed a greater variation in strain at ultimate stress, ranging from 1.3 to 1.7 times. It is clear that replacing stone chips with coarse rubber particles showed lower strength but higher strain compared to fine rubber particles; replacing sand and FCR showed greater strain at peak stress compared to SCR and MCR. Therefore, different-sized particles exhibit different strain values, and it is evident that the size of the used CR greatly affects the strength and strain of concrete [87, 88]. A previous study by Alizadeh et al. [89] also revealed that RuC exhibits more ultimate strain than NC.



(a) Using 5% waste tire rubber



(b) Using 10% waste tire rubber



(c) Using 15% waste tire rubber

Figure 10. Comparison of compressive stress-strain curves for NC and RuC

Considering all of the above findings, it is clear that rubber particle size and shape have a significant impact on concrete behavior. FCR showed greater stress and strain compared to other types of rubber particles. This is due to the fiber shape of FCR that produced a bridging in the crack lines until total failure. Although the ultimate stress decreased with increasing the amount of rubber, the strain at ultimate stress increased, as demonstrated in the stress-strain graphs. A similar pattern was consistently observed in earlier research [74, 87-89].

3.6. Modulus of Elasticity

The elasticity moduli of NC and RuCs are presented in Table 6. It was observed that the elasticity modulus of RuC was lower than NC and this effect became more prominent with the increase of rubber percentage. Furthermore, the decrease of the elastic modulus was relatively low for FCR, which results in the highest modulus of elasticity among all types of particles that replaced sand. The modulus of elasticity of RuC decreased from 36% to 58% for SCR concrete, 21% to 44% for FCR concrete, 23% to 53% for MCR concrete, and 50% to 63% for CSR concrete when compared to NC, where the rubber content varied from 5% to 15%. Previous studies also observed a reduction in the modulus of elasticity for RuC compared to NC for increasing tire rubber percentage [86, 90–92]. Noaman et al. [86] found that the substitution of sand by 5%, 10%, and 15% of tire particles lowered the modulus of elasticity values in RuC by 9.4%, 13.9%, and 18.5%, respectively. In comparison to concrete without any rubber, Walid et al. [87] observed that the elastic modulus of both ground and crushed RuC decreased as the rubber content increased. They found that when the rubber percentage of the concrete ranged from 15 to 45%, the modulus of elasticity declined by 14.8 to 29.9% for ground RuC and 27.4 to 49.4% for crushed RuC, compared to NC. Liu et al. [92] found that by increasing the amount of sand replaced with rubber from 0% to 20%, the elasticity modulus reduced by 22.11%. According to Ul Aleem et al. [93], the initial elastic modulus of RuC decreased by 13.75% to 45%, with CR percentages of 5 to 20%, respectively. Rubber has a much lower elasticity modulus than traditional aggregates, which might be the cause of this drop in the modulus of elasticity, resulting in a less stiff concrete [22, 65, 87]. The weak adhesion between rubber chips and the cement matrix may also be a cause of the reduction of the elastic modulus of RuC. Furthermore, the factors that lead to a reduction in elastic modulus bear similarities to the factors that contribute to the decrease in compressive strength of RuC, as previously discussed.

As per ACI 318-19 [94], the following Equations 1 and 2 can be applied to determine the modulus of elasticity when the weight of concrete (w_c) values lie between 1440 kg/m^3 and 2560 kg/m^3. The unit weights of concrete with 5% to 15% different rubber particles varied from 1805 kg/m^3 to 2268 kg/m^3, which were within this range. Therefore, the Equations 1 and 2 were applied to estimate the modulus of elasticity value of RuC and presented in Table 6. According to the test findings, the modulus of elasticity of NC well matched the predictions of the equations. However, for RuC both the equations significantly over estimated the modulus of elasticity. The ratio of test results and predicted values by equations decreased with increasing rubber percentage. Therefore, these equations are not suitable to estimate the modulus of elasticity of RuC.

$$E_c = w_c^{1.5} \times 0.043 \times \sqrt{f_c'} \tag{1}$$

$$E_c = 4700\sqrt{f_c'} \tag{2}$$

Table 6. Comparison of the modulus of elasticity of experimental results with the standard equation

Sample Id.	Rubber content	$Ec_{,expt.}$ (MPa)	$Ec_{,eq1}$ (MPa)	$Ec_{,eq2}$ (MPa)	$\frac{Ec_{,expt.}}{Ec_{,eq1}}$	$\frac{Ec_{,expt.}}{Ec_{,eq2}}$
NC	0%	27,705	26,996	26,388	1.03	1.05
SCR	5%	17,663	23,717	24,001	0.74	0.74
	10%	13,857	21,962	23,059	0.63	0.60
	15%	11,446	18,324	21,422	0.62	0.53
FCR	5%	21,748	24,420	25,160	0.89	0.86
	10%	17,639	22,078	24,393	0.80	0.72
	15%	15,524	19,048	23,400	0.81	0.66
MCR	5%	21,065	23,993	24,523	0.88	0.86
	10%	15,395	22,132	23,669	0.70	0.65
	15%	12,876	18,625	22,291	0.69	0.58
CSR	5%	13,831	20,303	22,291	0.68	0.62
	10%	11,036	17,328	21,049	0.64	0.52
	15%	10,159	14,231	20,283	0.71	0.50

3.7. Poisson's Ratio

The Poisson's ratio for various types of RuC is presented in Figure 11, from which it is clear that RuC has a greater Poisson's ratio than NC. The Poisson's ratio of conventional concrete usually lies between 0.1 and 0.2 [95, 96], and it was found to be 0.18 in this study. However, it was seen that the values of Poisson's ratio were more than 0.2 for all varieties of RuC. The Poisson's ratio values of 0.22, 0.23, and 0.25 were found for concrete when 5%, 10%, and 15% of sand were replaced by FCR, respectively. These values were higher than the Poisson's ratio found for RuC, where SCR and MCR were used as replacements. The CSR mixes that replaced stone chips exhibited a higher Poisson's ratio than the other mixes. Thus, it may be said that the Poisson's ratio increased as the quantity and size of rubber particles increased. Chayaboot et al. [97] found Poisson's ratios within a range between 0.19 and 0.22 for 25% to 100% of sand replacement with CR. The cause of increasing this value is attributable to the high Poisson's ratio of tire rubber and its propensity to distort under load. The typical Poisson's ratio value is approximately 0.48-0.50 for rubber [98], which is nearly double that of NC. The rubber particles in the concrete cylinder deform greatly when loaded. Moreover, the RuC has a lower modulus of elasticity than NC, leading to significant deformation under load and hence increased the Poisson's ratio.

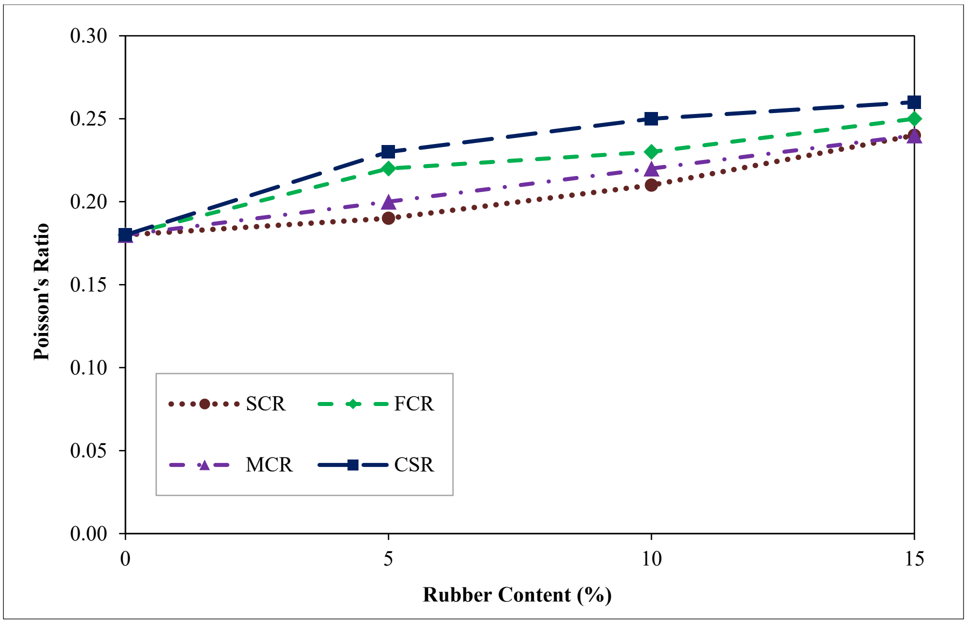


Figure 11. Poisson's ratio of RuC for different rubber contents

3.8. Failure Behavior

The failure mode of RuC is an important indicator of the adhesion of cement molecules with the rubber particles, which significantly influences the selection of the particle size. The cracking patterns and failure behavior of NC and RuC are depicted in Figures 12-a to 12-e. The addition of rubber to the concrete mix caused a significant quantity of visible cracks on the tested sample surface. For CR replacing fine aggregate of concrete, the cracks seem larger, as shown in Figures 12-b to 12-d. This evidence represents a satisfactory bond between the ingredients of concrete and CR particles. On the other hand, for CSR particles replacing coarse aggregates, the cracks in concrete cylinders increased in number; such an increase may reveal a relatively weak bond between concrete and rubber, as presented in Figure 12-e. These phenomena may happen because of the weak interface between the cement matrix and rubber particles, which may limit compressive deformations while enabling stress to accumulate more quickly than in regular concrete. This allows for more uniform and gradual development of microfractures at interfaces [88, 99]. Similar patterns were also observed by Strukar et al. [90]. Nematzadeh et al. [100] reported that the number and width of cracks increased without total rupture as the amount of rubber increased. Onuaguluchi & Banthia [101] stated that the rubber fiber has the ability to limit crack formation and propagation by bridging cracks. During the test, Moolchandani et al. [102] observed that conventional concrete failed in a brittle manner, while RuC resisted brittle fracture. In comparison to concrete without rubber, axial compressive loading significantly deforms the rubber particles within the cement paste, creating transverse stresses and microcracks that cause fractures to propagate earlier [103].

(a) (b) (c) (d) (e)

Figure 12. Failure mode of (a) NC, (b) SCR, (c) FCR, (d) MCR, and (e) CSR

3.9. Ductility

Ductility of the concrete was determined by the process suggested by Bouzid et al. [104] and presented in Figure 13. They evaluated the ductility of the concrete by the displacement ductility factor, which is known as the ratio of failure displacements (Δ_f) and yield displacements (Δ_y). The displacement on the ascending segment of the graph at 80% of the peak load is known as the yield displacement, and the displacement on the descending portion of the graph at 80% of the peak load is known as the failure displacement, as indicated in Figure 13. The ductility factor was computed using Equation 3.

$$\text{Ductility factor} = \Delta_f / \Delta_y \quad (3)$$

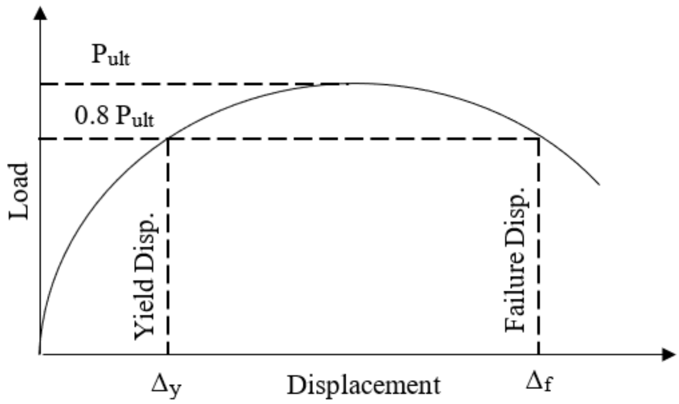


Figure 13. Evaluation of ductility by Haytham and Rabia [104]

It is seen from Figure 14 that the ductility of RuC improved compared to NC. Concrete with FCR had greater ductility compared to NC, SCR, and MCR. The ductility of the concrete was improved by 1.2 times to 1.9 times for SCR, 1.21 times to 1.26 times for MCR, and 1.25 times to 1.35 times for CSR due to 5% to 15% replacement of sand by rubber particles. Whereas FCR improved the ductility by 1.29 times at 5% replacement and 1.40 times at 15% replacement compared to the regular concrete. Therefore, the mixing of rubber particles into the concrete elements may enhance ductility, and the coarse particles would give more ductility than the fine particles. The causes for the improvement of ductility are behind the fact that rubber particles absorb more energy through their elastic properties, bridging and delaying the propagation of cracks, and dissipating energy to reduce brittleness. Its softer nature reduces stress concentrations, thereby preventing sudden fractures. In addition, the longer fibers of FCR make a stronger, more continuous internal network, distributing stress more evenly and resisting rapid crack growth better than smaller particles. Ductility and strain capacity of RuC were also found to be increased according to the previous research due to the addition of rubber instead of sand [88, 90, 105, 106]. Li et al. [88] stated that the addition of rubber had a positive effect on the post-ultimate ductility capacity of concrete.

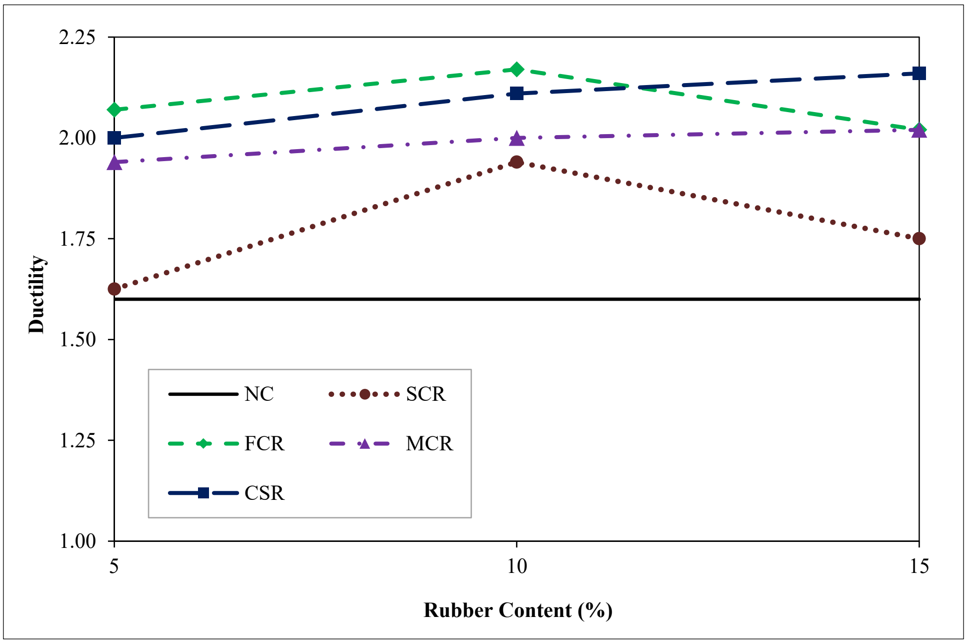


Figure 14. Ductility of concrete for different rubber contents

3.10. Toughness

Toughness is the capacity of a substance to absorb energy and undergo plastic deformation prior to breaking, which is an essential parameter for evaluating the dynamic properties of any material. In this investigation, the toughness of concrete was measured according to Husem & Pul [107] by determining the area within the stress-strain graph found from the compression test. The toughness of the tested samples is shown in Figure 15, where RuC showed higher toughness compared to the NC. The results of RuC indicate that the toughness increased by 6.5% to the maximum of 46% because of the 5% to 15% addition of rubber content, respectively. RuC with SCR exhibited the lowest increase in toughness, from 6.5% to 13.3%, whereas FCR showed the greatest increase, from 20.9% to 46% for 5% to 15% of rubber particles, respectively. Overall, fine aggregate replacements by FCR and MCR exhibited better toughness compared to the coarse aggregate replacements by CSR. FCR and MCR showed greater toughness in concrete due to their elongated shape, which allows them to bridge cracks while absorbing more energy and delaying crack propagation effectively. These longer fibers improve energy dissipation under load and further increase toughness through internal distribution in concrete mixes, which distributes stress more uniformly than smaller CR particles. Previous studies demonstrated that incorporating rubber particles from used tires into concrete substantially enhances its toughness [86]. According to Akbari et al. [108], increasing the proportion of CR instead of fine aggregates between 0 and 20% total fracture energy increased by 63%.

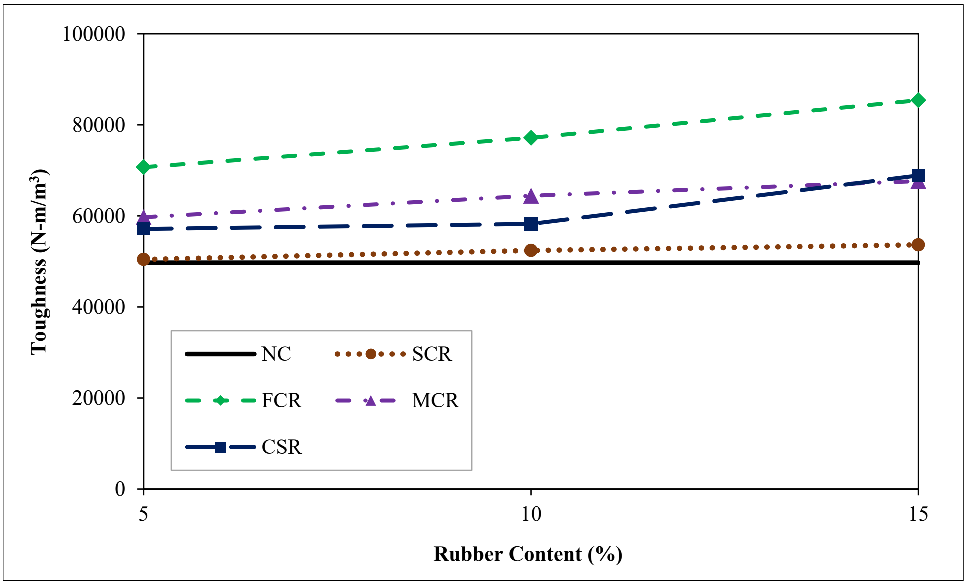


Figure 15. Toughness of concrete for different rubber contents

4. Conclusions

In this study, the properties of RuC were evaluated through experiments. In RuC, fine aggregate (i.e., natural sand) was substituted by different types of CR particles, and coarse aggregate (i.e., stone chips) was substituted by shredded rubber. Three types of rubber particles extracted from waste tires were used as a partial substitute for FA. Among them, SCR was the finest and passed through the #16 sieve and was retained on the #30 sieve. The particle lengths of fiber-like CR (i.e., FCR) ranged from 7 mm to 15 mm; however, they passed through #4 and were retained on #8 sieves due to their small lateral dimension. MCR was a mixture of SCR and FCR. The size of shredded rubber varied from 9.5 mm to 19 mm. From a standard concrete mix, FA or CA were partially replaced by each type of tire rubber particle up to 15% by weight. The effects of particle size and shape of waste tire rubber on concrete properties are summarized as follows:

- The workability increased with the increasing of FA and CA substitution percentages by different types of rubber particles. Comparing the concrete where FA was replaced by different types of CR, FCR showed more workability compared to SCR and MCR. Slump value was maximum when CA was replaced by shredded rubber. The bulk density of concrete also decreased with increasing the percentages of replacement from 5% to 15% of FA and CA. It was decreased by a maximum of 11%, 14%, 12.5%, and 22% for SCR, FCR, MCR, and CSR, respectively, when 15% of sand and stone were substituted.
- The compressive strength, splitting tensile strength, and modulus of elasticity of concrete steadily decreased as the percentages of rubber particles increased. However, these properties of concrete were higher for small rubber particles than those of coarse ones. Concrete with FCR consistently showed the highest strength among all other RuC using SCR, MCR, and CSR used in this study for 5%, 10%, and 15% replacements. In addition, the test sample with 10% of FCR exhibited the highest splitting tensile strength compared to other samples. Poisson's ratios of RuC were found to be higher than that of NC.

- The experimental stress-strain graphs of RuC demonstrate that increasing the rubber content results in a reduction in ultimate stress and a corresponding increase in strain at ultimate stress compared to the NC. The fracture pattern supports that RuC is less brittle than NC because the fractures are more closely spaced and form a mesh without separating the larger pieces.
- The RuC exhibited a notable improvement in the ductility and toughness compared to the NC. Notably, FCR mixes outperformed all other types of rubber particles in both ductility and toughness. The ductility and toughness of RuC were enhanced by 29% to 57% compared to NC when 5% to 15% of sand was substituted for FCR.

It can be concluded that replacing CA with CSR has the most detrimental effect on strength. Comparing different sizes and shapes of CR as a replacement for FA, FCR provides better properties than other sizes and is preferable for use in concrete.

5. Declarations

5.1. Author Contributions

Conceptualization, A.H., S.A., and R.A.; methodology, A.H., S.A., and R.A.; software, A.H.; validation, A.H. and S.A.; formal analysis, A.H.; investigation, A.H. and R.A.; resources, A.H.; data curation, A.H.; writing—original draft preparation, A.H.; writing—review and editing, A.H., S.A., and R.A.; visualization, S.A. and R.A.; supervision, S.A. and R.A.; project administration, S.A. and R.A.; funding acquisition, A.H., S.A., and R.A. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding and Acknowledgements

The authors would like to convey their appreciation to the Department of Civil Engineering at the Bangladesh University of Engineering and Technology for providing financial support from the research fund to cover the expenditures of the experimental study. The authors recognize the supporting personnel of the Concrete Lab of this university for their assistance during testing. Additionally, the authors gratefully acknowledge the support of Daffodil International University in partially covering the article publication charge for this article.

5.4. Conflicts of Interest

The authors declare no conflict of interest.

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