

Improving the Performance of Concrete Beams with Crumb Rubber and Steel Fibers: An Experimental Study

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ABSTRACT

This study explores the flexural behavior of concrete beams incorporating crumb rubber derived from waste tires and Steel Fibers (SF), aiming to evaluate their viability as sustainable construction materials. Addressing both the environmental concerns and mechanical performance, the current research examines the potential of these additives to enhance the structural efficiency of reinforced concrete beams. Six reinforced concrete beams were cast using varying proportions of crumb rubber (5% and 10%) as a partial replacement for fine aggregate and SF as tensile reinforcement. Two reinforcement ratios were used to examine the interaction effects. Standard specimens were also tested to evaluate compressive, tensile, and flexural strength. The flexural performance was assessed through four-point bending tests, with the load-deflection behavior, crack patterns, and strain distributions recorded. The results showed that crumb rubber reduced both the initial crack and ultimate load capacities due to its low stiffness and weak interfacial bond with the cement paste. However, the inclusion of SF significantly improved the crack resistance, ductility, and load-bearing capacity, achieving at least a 24% increase in the ultimate load over the rubber-only counterparts. The beams with higher reinforcement ratios demonstrated superior structural performance, while the failure modes remained predominantly flexural. The findings suggest that a combination of 10% crumb rubber and 1% SF offers an effective balance between the mechanical performance and environmental sustainability.

Keywords-concrete; crumb rubber; steel fiber; beam

I. INTRODUCTION

The increasing demand for sustainable construction materials has driven significant research into the partial replacement of conventional concrete constituents with recycled materials. One promising approach involves the incorporation of crumb rubber, a recycled material obtained from waste tires, into concrete mixtures. Crumb rubber offers an environmentally friendly solution for managing tire waste while enhancing certain mechanical properties of concrete,

particularly its ductility and energy absorption capacity [1-3]. However, it has been demonstrated that the inclusion of crumb rubber typically results in a reduction of the compressive, tensile, and flexural strengths, primarily due to the poor bonding between the rubber particles and the cement matrix and the lower stiffness of rubber compared to the mineral aggregates [3-5]. To address the strength limitations associated with the crumb rubber concrete, researchers have investigated the addition of SF. The latter are well-known for their ability to bridge the cracks, enhance the post-cracking behavior, and

improve the tensile strength, ductility, and toughness of concrete [6-9]. When introduced into the concrete mixtures, SF act as a secondary reinforcement mechanism, effectively controlling the crack propagation and increasing the energy absorption capacity of the structural elements. The synergistic use of crumb rubber and SF has been shown to mitigate the adverse effects of rubber on the mechanical strength while preserving the enhanced ductility and toughness that rubberized concrete offers [1, 10, 11].

Adding crumb rubber to concrete reduces the strength but improves the ductility, while SF can offset these losses. Authors in [6] found that replacing fine aggregate with rubber significantly reduced the compressive, tensile, and flexural strengths, though the ductility and energy absorption increased. Authors in [3] reported 28–42% strength drops in plain concrete with 5–20% rubber, whereas SF mixes exhibited only 1–34% losses (5% SF mix showed negligible reduction). Flexural tests demonstrated that rubber reduced the ultimate flexural load (e.g., 5%, 10%, 15% rubber gave 25%, 49%, 55% flexural strength drop [2]), while the SF addition significantly improved the post-peak behavior. Authors in [1] tested rubberized SFRC beams and found enhanced flexural toughness and deflection capacity in the steel fiber/rubber mixes. Authors in [2], likewise, observed that pure rubberized beams had a much higher ductility and deflection compared to plain beams, and that hybrid (layered rubber and normal) beams further boosted the ultimate load, stiffness, and toughness. It has been established that SFRC with up to 10–15% crumb rubber shows improved toughness, and that the layering or hybrid schemes can further recover the strength [1, 2, 12].

Subsequent experiments confirmed these trends. For instance, authors in [4] observed a synergistic effect: adding SF mitigated the negative impacts of rubber. They reported that hybrid mixes (e.g., 10% crumb rubber and SF) achieved up to 49% higher compressive, 39% higher tensile, and 76% higher flexural strength over plain control concrete. The results exhibited that the flexural rupture modulus also changes with the addition of hybrid mixes. For the mixes with 1.0–1.5% SF, roughly double the flexural strength of plain concrete was achieved, whereas 1–2% crumb rubber alone reduced it remarkably. Embedded SF bridged cracks and regained the lost strength caused by rubber, yielding much higher toughness [1, 4, 13].

It has been shown that adding up to about 5–10% crumb rubber can improve the concrete ductility and energy absorption (at the expense of 30–50% strength loss), but combining crumb rubber with 0.5–1.0% SF can largely offset the strength loss while preserving toughness [10, 11, 14]. Authors in [10] found that 0.5% hooked SF increased the compressive strength by 33% compared to the rubber mix, and proposed an optimal 5–10% rubber replacement for sustainable SFRC design. In flexural performance, SF-reinforced rubberized beams develop similar ultimate loads to plain RC and exhibit much improved crack control [9-11]. Designers should take into account the reduced workability (slump losses) [1, 8] and reduced elastic modulus in rubberized mixes [14], and use adequate reinforcement and fiber content to ensure

ductile failure. Overall, crumb rubber alone makes concrete weaker but improves the ductility. SF alone substantially increases the tensile, shear, and flexural capacity, while the combined effect of rubber and fibers is synergistic: fiber reinforcement compensates for rubber's weaknesses, yielding a more ductile, yet, still strong concrete [2, 7, 10, 14]. These findings inform the design of eco-friendly concrete beams with recycled rubber and SF additives.

This study experimentally investigates the complex interactions arising from the incorporation of varying percentages of rubber combined with SF, focusing on their effects on the structural performance of reinforced concrete beams under static loading conditions. The key parameters examined include the load-deflection behavior, crack patterns, and strain distribution. Through this experimental approach, the study aims to provide valuable insights for optimizing the design of sustainable concrete structures that effectively balance the strength, ductility, and environmental benefits.

II. MATERIALS AND METHODS

A. Standard Concrete Mix

The control concrete mix was prepared with a mix ratio of 1:1.16:1.66 by volume, and a water-cement ratio of 0.39. Ordinary Portland Cement (OPC) was used as the primary binder. The aggregates utilized consisted of natural river sand as fine aggregate and crushed stone with a nominal maximum size of 20 mm as coarse aggregate. The mixing water complied with ASTM C1602 specifications [15]. The mix was designed to achieve a structural-grade concrete with a target compressive strength of 23MPa.

B. Modified Mixes with Crumb Rubber, SF, and Superplasticizer

Several modified concrete mixes were prepared by incorporating crumb rubber and SF in varying proportions. Crumb rubber, used in powder form with particle sizes ranging from 0.3 to 0.6 mm, was incorporated as a partial volume replacement for the fine aggregate at replacement levels of 5% and 10%. Prior to mixing, the crumb rubber was subjected to basic cleaning but received no chemical or surface treatment. SF in a curly profile, with a diameter of 0.2 mm and a length ranging from 12 mm to 14 mm, was added to enhance the mechanical properties of the concrete. The SFs were incorporated at weight percentages of 0.5% and 1% relative to the cement content, depending on the mix type. Figures 1(a) and 1(b) display a sample of the crumb rubber and the SF, respectively.

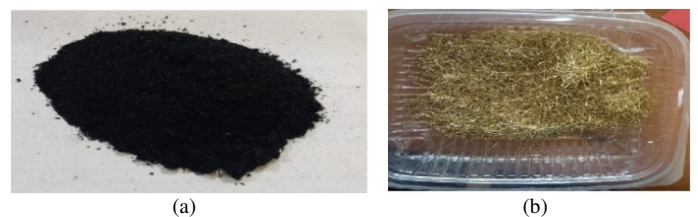


Fig. 1. Samples of: (a) crumb rubber; (b) SF.

To maintain workability, a polycarboxylate-based superplasticizer (Sika Viscocrete-5) was added to all mixes at a dosage of 1362 mL per 550 kg of cement. This dosage was kept constant across all mix types to ensure the consistency in the fresh concrete properties. Each mix was thoroughly homogenized using a mechanical mixer before casting.

C. Dimensions of the Beams and Reinforcement Details

A total of six reinforced concrete beams were prepared and tested, each with a rectangular cross-section measuring 150 mm in width and 150 mm in depth, and a total length of 1500 mm. The clear span between the supports was maintained at 1300 mm for all specimens.

Two reinforcement configurations were employed in the tension zone, corresponding to reinforcement ratios of 1.68% (As_1) and 2.43% (As_2). For the As_1 configuration, the tension zone was reinforced with two 10 mm diameter steel bars, while for the As_2 configuration, it was reinforced with two 12 mm diameter bars. In all beams, two 10 mm bars were used in the compression zone. Shear reinforcement was provided using 7 mm stirrups spaced at 220 mm center-to-center throughout the beam length. All reinforcement conformed to the relevant ASTM specifications. Details for the reinforcement types are listed in Table I. Additionally, Figures 2(a) and 2(b) illustrate the reinforcement details for the As_1 and As_2 , respectively.

TABLE I. BEAM REINFORCEMENT DETAILS

Parameter	As_1 : 2Ø10 mm	As_2 : 2Ø12 mm
Tensile reinforcement diameter	10 mm	12 mm
No. of bars	4	4
Area per bar	78.54 mm ²	113.04 mm ²
Total steel area	383.08 mm ²	452.39 mm ²
Beam width (b)	150 mm	150 mm
Beam depth (h)	150 mm	150 mm
Clear cover	20 mm	20 mm
Effective depth (d)	125 mm	124 mm
Reinforcement ratio (ρ)	1.68%	2.43%

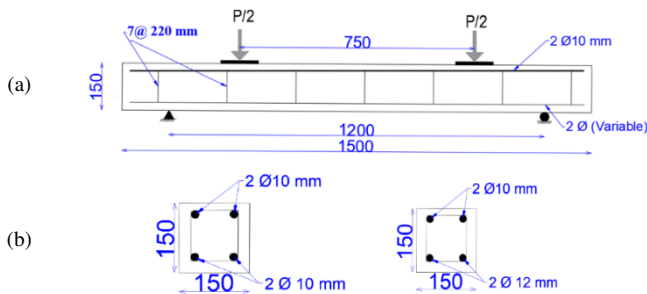


Fig. 2. Reinforcement details for: (a) As_1 , (b) As_2 (all dimensions in mm).

The beams were labeled according to their material composition and reinforcement configuration. For example, beam 10R-1SF- As_1 refers to a specimen with 10% crumb rubber content, 1% SF addition, with the first longitudinal reinforcement ratio ($As_1 = 383.08 \text{ mm}^2$, i.e., $\rho = 1.68\%$).

D. Casting Process

The concrete was mixed using a mechanical drum mixer to ensure the uniform distribution of the materials. For each mix,

in addition to the main beam, standard test specimens, including cylinders (150 mm \times 300 mm) and prisms (100 mm \times 100 mm \times 400 mm), were also cast to evaluate the compressive, tensile, and flexural strength.

All beam specimens were cast in wooden molds. Mechanical vibration was applied using a needle vibrator to eliminate the entrapped air and ensure the full compaction of the fresh concrete. After casting, the specimens were covered with plastic sheets to prevent moisture loss and were demolded after 24 h.

Subsequently, the beams and specimens were cured by immersion in water tanks for 28 days under standard laboratory conditions, in accordance with the ACI 318-19 [16] curing recommendations.

III. TESTING PROCEDURES

A. Flexural Strength Test Setup

The flexural performance of the beams was evaluated using an Avery hydraulic universal testing machine under load control. A four-point bending setup was employed, with the beams simply supported on roller supports spaced 1.3 m apart. The load was applied at the midspan of the beams through a hydraulic actuator. The loading rate was 200kN/min, ensuring a gradual increase in the load to allow for accurate observation of the crack initiation and propagation. Deflection measurements were captured using a mechanical dial gauge positioned directly beneath the beam at midspan. The dial gauge provided real-time monitoring of the vertical displacements throughout the loading process.

B. Compressive and Tensile Strength Tests

Standard cylindrical specimens (150 mm diameter \times 300 mm height) and prismatic specimens (100 mm \times 100 mm \times 400 mm) were cast alongside the beams for compressive, split tensile, and flexural strength evaluations. All tests were conducted after 28 days of curing.

The compressive strength tests were performed following ASTM C39 [17], using a 2000 kN capacity hydraulic universal testing machine. Similarly, the split tensile strength tests were carried out according to ASTM C496 [18] using the same machine. The results from these tests provided supplementary data to assess the influence of crumb rubber and SF on the basic mechanical properties. The same machine with a suitable configuration was used to test the concrete prisms for flexural strength. The results of the compressive, flexural, and splitting tensile strength tests are presented in Table II. It is evident that the inclusion of crumb rubber alone led to a reduction in the mechanical properties, with compressive strength decreasing by approximately 22.4% and flexural strength by about 23.6% compared to the control mix. However, the addition of SF effectively mitigated these adverse effects. Notably, the mix containing 10% crumb rubber and 1% SF exhibited a compressive strength approximately 48% higher than the corresponding rubber-only mix. This enhancement was even more pronounced in terms of the flexural performance, highlighting the significant toughening effect provided by the SF.

TABLE II. COMPRESSIVE, FLEXURAL, AND SPLITTING TENSILE STRENGTHS OF CONTROL SPECIMENS

Beam ID	Compressive strength (MPa)	Flexural strength (MPa)	Splitting tensile strength (MPa)
0R-0SF-As ₁	23.80	1.61	2.73
5R-0.5SF-As ₁	21.69	1.63	2.61
10R-1SF-As ₁	27.35	1.58	2.93
5R-0SF-As ₁	19.15	1.21	2.45
10R-0SF-As ₁	18.47	1.23	2.41

C. Data Acquisition and Strain Measurement

The concrete strains during flexural loading were monitored using two electrical resistance strain gauges attached to the side face of each beam at the midspan. One strain gauge was installed near the top fibers (in the compression zone) and the other near the bottom fibers (in the tension zone).

The strain data were recorded using a data logger, which continuously captured the strain variations corresponding to the applied load. This arrangement enabled a detailed analysis of the strain distribution across the beam depth and facilitated the comparison between different mix compositions. The full test setup is depicted in Figure 3.

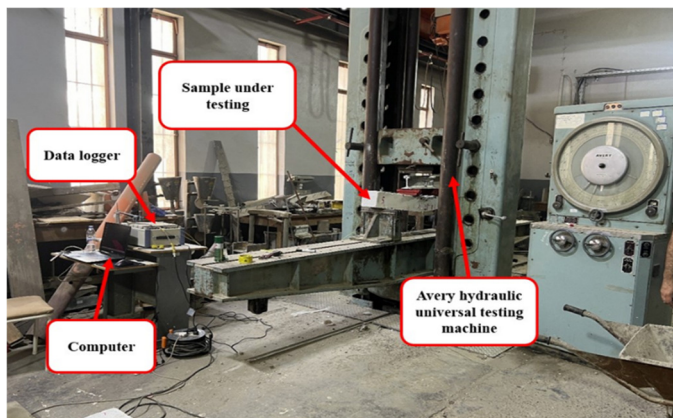


Fig. 3. Experimental setup for measuring strain distribution.

IV. RESULTS AND DISCUSSION

A. Load Capacity and Load-Deflection Relationship

The experimental results detailing the first crack occurrence, failure load, and midspan deflections for each tested beam are summarized in Table III. As seen in Table III, the beam designated as 10R-1SF-As₁, which replaces 10% of the fine aggregates with crumb rubber and includes 1% SF, experienced a 20% increase in the initial crack load compared to the reference beam. In contrast, all other beams exhibited an average reduction of approximately 51% in the initial crack load.

Generally, replacing 5% and 10% of fine aggregate with crumb rubber resulted in reductions in both the initial crack and ultimate loads. This decrease can be attributed to the lower stiffness of the rubber and the weaker bond between the rubber and the surrounding paste, particularly evident in beams 5R-0SF-As₁ and 10R-0SF-As₁.

This conclusion is supported by several studies, which attribute the reduction in the load capacity to the improper dispersion and high deformability of the crumb rubber, contrasting with the inherent brittleness of the surrounding cementitious matrix [19-23]. However, the addition of SF to the concrete mix effectively compensated for this reduction, leading to a notable improvement in the flexural performance—though still lower than that of the control beam. Specifically, incorporating 0.5% SF increased the ultimate load by approximately 69% compared to the rubber-only mix. Further increasing the SF content to 1% resulted in an additional 24% enhancement in the ultimate load capacity over beams containing crumb rubber without fibers.

Figure 4 illustrates the load-deflection responses of the beams. As discussed above, the inclusion of crumb rubber reduces the flexural strength and modulus of elasticity of the concrete beam. However, beam 10R-0SF-As₁, when compared to the load-deflection curve of the control beam, exhibited a similar behavior, higher stiffness, and lower deformation, achieving about 73% of the control beam's load capacity; though, it failed at a lower load. Therefore, it can be inferred that a concrete mixture with 10% crumb rubber replacement is an optimal content for maintaining performance.

Moreover, when 1% SF is added to the same crumb rubber quantities, in Beam 10R-1SF-As₁, a significant improvement in the cracking resistance was observed compared to the control beams. The randomly distributed SF in the matrix delayed the crack initiation and hindered further widening of the cracks. Additionally, the combined effect of SF and crumb rubber increased the flexural rigidity, reducing the maximum deflection to approximately 46% of that observed in the control beam. Figure 4 also highlights that using a larger diameter of steel reinforcement, as seen in Beam 5R-0.5SF-As₂, can significantly enhance its load capacity. Specifically, employing two rods, each 12 mm in diameter, in the tension zone increases the load capacity by 139% compared to the control beam.

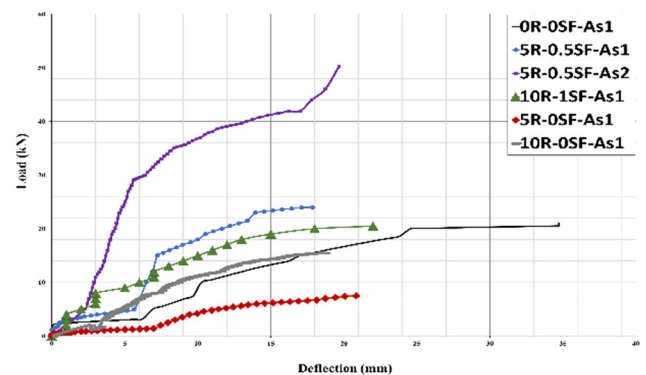


Fig. 4. Experimental load-mid-span deflection responses.

TABLE III. BEAM FLEXURAL TEST RESULTS

Beam ID	Initial crack load (kN)	Initial crack deflection (mm)	Failure load (kN)	Max. deflection (mm)	Toughness (kN.mm)
0R-0SF-As ₁	5.0	6.91	21.0	34.72	460.93
5R-0.5SF-As ₁	1.9	0.46	24.0	17.85	253.89
5R-0.5SF-As ₂	3.0	6.00	50.2	19.66	610.28
10R-1SF-As ₁	6.0	3.00	20.5	22.00	314.0
5R-0SF-As ₁	2.0	7.45	7.50	20.85	82.71
10R-0SF-As ₁	3.0	3.47	15.5	18.59	173.20

The load–deflection curves were utilized to evaluate the toughness indices, as outlined in Table III. A consistent trend observed in the results indicates that the inclusion of SF in rubberized concrete significantly enhances the overall toughness by at least 30%, compared to the rubberized beams without SF. This enhancement is consistent with previous studies [1, 7, 24, 25], which attribute the improvement to the SF’s ability to bridge the macro-cracks, thereby increasing both the load-bearing capacity and deformation resistance.

B. Failure Pattern

All tested beams exhibited a flexural failure mode, initially marked by the formation of small flexural cracks at the midspan. As the load increased, these cracks propagated from the bottom of the beam towards the loading points until failure.

The effect of SF was particularly pronounced in the beam with 5% rubber replacement, 5R-0.5SF-As₁. The presence of SF resulted in stitching and reduced the number of cracks at failure. In beam 10R-1SF-As₁, increasing the rubber replacement content to 10% led to larger crack widths and a higher number of cracks at the failure stage compared to the control beam. This behavior can be attributed to the loss of bonding between the rubber and matrix, rendering the fibers unable to prevent the cracks from forming due to tensile bending at the bottom surface of the beam. These observations are consistent with [7, 26-28], where the inclusion of SF mitigated the adverse effects of the rubber incorporation and provided a confining effect on the binder matrix. The typical crack patterns observed in the tested specimens are presented in Figure 5.

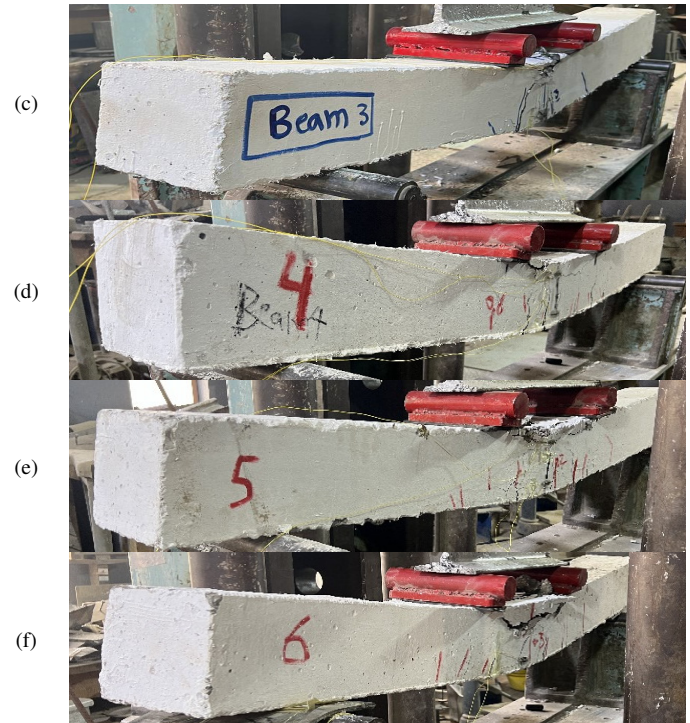


Fig. 5. Crack patterns in tested beams at failure: (a) 0R-0SF-As₁, (b) 5R-1SF-As₁, (c) 5R-1SF-As₂, (d) 10R-1SF-As₁, (e) 5R-0SF-As₁, and (f) 10R-0SF-As₁.

C. Concrete Strains

The load-concrete strain behaviors of the test are presented with/through curves in Figure 6. The reference beam, 0R-0SF-As₁, has a higher tensile strain when compared with the rubberized concrete beams, 5R-0SF-As₁ and 10R-0SF-As₁, which means that the rubber particles reduce the efficiency of the stress transfer between the cement paste and aggregates.

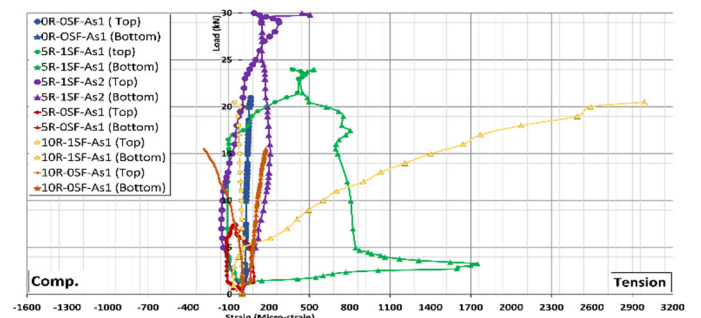


Fig. 6. The load-concrete strain behavior of all tested beams.

More uniform strain can be obtained by adding SF to the concrete mix, which allows the beams to undergo a greater deformation before failure. This is a desirable behavior for many applications, including the seismic resistance.

V. CONCLUSIONS

The present investigation aimed to evaluate the flexural behavior of reinforced concrete beams incorporating crumb rubber and Steel Fibers (SF). Six beams were tested under four-point bending. The main variables were the inclusion of SF and crumb rubber (0%, 5%, and 10%) as partial fine aggregate replacement, in addition to the variations in the tensile reinforcement area. The following conclusions can be drawn:

- The flexural strength of rubberized concrete beams generally decreased with an increasing rubber content compared to the control beam. Specifically, the flexural strength was reduced by 64% and 26% for the concrete mixes containing 5% and 10% crumb rubber, respectively. This decline is primarily attributed to the weak interfacial bond between the rubber particles and the surrounding cementitious matrix, which compromises the overall integrity of the composite.
- The inclusion of SF significantly enhanced the flexural performance of rubberized concrete beams. The addition of 1% SF resulted in a 69% increase in the ultimate load capacity compared to the beams containing only crumb rubber. SF contributed to improved crack resistance, delayed crack propagation, and reduced midspan deflections, ultimately leading to enhanced ductility.
- Increasing the tensile reinforcement area from 157 mm² to 226 mm² led to a substantial improvement in the load-carrying capacity, ranging from 14.2% to 139%, for rubberized concrete with SF compared to the control beam.
- All tested beams exhibited flexural failure modes characterized by crack initiation and propagation. The beams containing SF demonstrated narrower cracks and a more evenly distributed cracking pattern, whereas those without fibers developed wider, more localized cracks.
- The toughness of rubberized concrete improved significantly with the inclusion of 0.5% SF, showing a 67% increase compared to the beam with 5% crumb rubber alone. However, the rate of toughness improvement diminished at higher fiber contents, reaching approximately 44% at 1% fiber dosage.
- A crumb rubber content of 10% appears to be more favorable than 5%, offering a better balance between the mechanical performance and environmental benefits. Although a reduction in the flexural strength was observed, the 10% rubberized mix exhibited enhanced strain capacity, making it a viable option for sustainable construction practices. Further research is encouraged to optimize the mix design and maximize both the structural efficiency and ecological impact.

The experimental work conducted in this study confirms many findings reported in the literature, including the

improvement of concrete's crack resistance through the inclusion of SF, and highlights the critical role of SF in compensating for the strength reductions caused by crumb rubber. These results demonstrate that the combined use of SF and crumb rubber effectively enhances the durability and overall safety of concrete. Future studies should explore the optimization of the fiber types, contents, and rubber particle sizes to further improve the mechanical performance of crumb rubber concrete. Also, investigations incorporating numerical simulation results would complement the experimental findings and provide deeper insights into the stress-strain behavior and failure mechanisms.

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