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Influence of Steel Fibre Reinforcement on the Flexural Performance of Rubberized Concrete Beam

Karthikeyan R[1], Anuradha.B[1], Partheeban P[1], Hariharasudhan C[1], Suguna K[2,]
[1]Civil Engineering, Chennai Institute of Technology, India;
[2] Civil and Structural Engineering Annamalai University, India.

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ABSTRACT: The accumulation of discarded rubber on the land surface contributes to environmental pollution. To mitigate this issue, waste rubber can be incorporated into the concrete as a replacement for coarse aggregate. The addition of waste rubber in concrete results in insufficient strength due to the weak bond between the cement matrix and rubber shreds. To enhance this bond, a sand coating with resin is applied to the surface of the rubber shreds. This study investigates rubberized concrete beams with and without steel fibre reinforcement. Rubber shreds were added at 2.5%, 5%, and 7.5%, and steel fibres at 0.5%, 1%, and 1.5%. A total of twelve beams, each measuring 250 mm x 150 mm x 3000 mm, were prepared. Out of the twelve beams, three were cast without steel fibres, while the remaining nine included rubber and steel fibres. The beams were tested under four-point bending over a test span of 2800mm. The test results showed that RC beams with inclusion of steel fibres and sand coated rubber shreds exhibit improved flexural performance in terms of first crack load, deflection at first crack load, yield load, deflection at yield load, ultimate load, deflection at ultimate load, deflection ductility and energy ductility compared to those without fibres.

Keywords: Steel Fibre, Resin, Rubber shreds, Normal concrete, Ultimate load

1.INDRODUCTION

The use of waste materials in construction has generally been given low priority due to factors such as high processing costs, limited market acceptance, and logistical challenges Bashir et al. (2024). Among these materials, waste rubber represents a significant disposal problem, posing environmental and health concerns. Effective recycling methods are essential to manage this issue. Various techniques have been explored to recycle rubber waste, with particular emphasis on pyrolysis processes that convert discarded tires into valuable products such as oil, gas, and other petroleum-based materials Wang et.al. (2020). In recent days, waste tires can be used as a construction materials for making rubberized concrete in highways Grammelis .et.al (2021) and Formela. (2021). Crumb rubber is obtained from waste tire rubber and its used as an alternate of aggregates in concrete has improved the strength and longevity of concrete Addition of rubber waste in normal concrete as substitute of coarse aggregate and fine aggregate, it may enhance properties of rubberized concrete Li and Tier. (2024), Eisa .et.al (2020),Ahammed .et.al (2022) and Ghoniem and Nour.(2024). However, the substitution of traditional mineral aggregates with rubber particles can negatively impact the mechanical properties of concrete, due to the weak bond between the rubber and the cement paste matrix by and large Tayeh .(2013), Zhy. et.al (2012), Ling. (2011), Marzak. et.al (2025) and Ismail. (2016). To overcome this limitation, various surface treatment techniques have been developed to improve the interfacial bond strength. These include alkali etching Busic .et.al (2018), particle surface coatings Azline control are vital. Studies have also investigated the effect of modified rubber surfaces and hybrid fiber systems, such as corrugated or chemically treated fibers, on the interfacial bond and durability of the composite The addition of steel fibers into rubberized concrete has been extensively explored as a means of enhancing its mechanical performance Li and Li (2017) and Quareshi.et.al (2024). Steel fibers serve as distributed micro-reinforcement that bridge cracks, increase post-cracking load resistance, and improve energy absorption and ductility Hall and Najim (2014), Mohammed.et.al(2024), Noaman.et.al (2017), Abaza and Hussian(2016) and Fu.et.al (2019). When steel fibers are introduced, they help delay the onset of crack propagation and redistribute stresses more evenly throughout the matrix Ismail and Hassan (2017), Wang.et.al (2022), Zhang.et.al (2025) and Hussain et.al (2025). As a result, rubberized concrete beams

.et.al (2022), treatment with NaOH solutions Roy chand .et.al (2021) and chen et.al (2023), the use of coupling agents Bu. et.al (2022), and the application of thin cement paste layers, SBR latex, or organic sulphur coatings Lin. et.al (2023) and Gonzalez (1999). The incorporation of crumb rubber into concrete improves ductility, toughness, and energy absorption, as demonstrated in the studies by Ghoniem and Nour (2024). Cracks in rubberized concrete tend to initiate at the rubber-cement interface, where stress concentrations are highest Guo.et.al (2014), Gunevisi.et.al (2004) and Son.et.al (2016). In the absence of reinforcing fibers, once tensile stresses exceed the concrete's limited tensile capacity, rapid crack propagation can occur, leading to early stiffness loss and premature structural failure Pham.et.al (2024),Raffoul (2016) and Antel (2014). This issue becomes particularly critical in structural elements such as beams, where deformation capacity and crack

reinforced with steel fibers exhibit significantly higher flexural strength, yield load, and overall toughness compared to those without fiber reinforcement Ismail (2017), Mohammed.et.al (2024), Noaman.et.al (2017),Abdelaleem and Hassen. (2019) and Tanget.al (2025). Synergistic effects of steel fibers and rubber aggregates contribute to improved fracture toughness and durability Fu .et.al (2019) and He..et.al (2023).The presence of fibers has been reported to reduce shrinkage, enhance frost resistance, and improve resistance to high temperatures and chemical attacks Alsaif and Alharbi (2022) and Liang.et.al (2025). Lightweight recycled aggregate concrete in composite structures may exhibit lower bending resistance than normal concrete due to the reduced density and mechanical strength of the recycled aggregates Albidih and Alsaif (2024)

2. LITERATURE REVIEW

Wang. et al (2020) examined the impact of high rates of heating on material distribution and sulfur transformation in waste tire pyrolysis. This study has provided insights into chemical processes and yields of products. This work is, therefore, contributing towards a more comprehensive understanding of the mechanism involved in pyrolysis, thereby making the technology applicable to recycling waste rubber tires. Grammelis. et al (2021) gave a detail review on end-of-life tires (ELTs) and their management, focussing the reuse of textile fibers present in the tire composition. This work mentioned the growing interest in finding alternative uses for waste tires, as they present not only disposal issues but also potential for resource recovery. Eisa. et.al (2020) investigated the strength and durability characteristics of concrete that contained varying quantities of rubber tire aggregate in varying sizes. Comparing the concrete mixture to regular concrete, the former showed reduced compressive and breaking tensile strength. Under compressive and tensile pressures, these mixtures were able to absorb a significant amount of plastic energy and instead showed ductile, plastic failure rather than brittle failure. The effects of rubber aggregate on the decrease in concrete's compressive and tensile strengths have also been described by the author.

Madandoust . et.al (2012) used ANFIS to estimate the compressive strength of lightweight geopolymers. In the design of rubberised concrete, where artificial intelligence is becoming more prevalent, such models may also be pertinently applied. M. R. Hall and K. B. Najimi (2014) investigated the fracture behaviour of recycled aggregate concrete reinforced with steel fibres and crumb rubber. Their research indicates that the addition of rubber to concrete has increased its fracture toughness, making it a critical component in applications where structural material will be used. Y. Antil. (2014) optimised high-rubber content rubberised concrete. According to their experimental research, a larger rubber content can improve workability and toughness while decreasing compressive strength, which makes it appropriate for some applications where these qualities are important. The impact resistance and mechanical characteristics of self-consolidating rubberised concrete reinforced with steel fibres were investigated by M.Ismail. (2016) Various replacement levels of fine aggregate volume by CR (0–40%), binder content (550–600 kg/m^3), SF volume percentage (0, 0.35, 0.5, 0.75, and 1%), and SF size were the experimental variables. The authors assessed the modulus of elasticity, flexural strength, splitting tensile strength, compressive strength, and new characteristics. According to the authors, CS, STS, FS, and ME were impacted when the percentage of CR in the SCC combination increased, although impact resistance significantly improved. Additionally, they found that adding 0.35% SFs to SCRC mixtures improved the impact resistance, FS, and STS by an average of 2.68, 2.33, 19.5%, and 20%,

respectively. The impact of crumb rubber (CR) with or without steel fibres (SFs) on the shear behaviour and cracking of large-scale vibrated and self-consolidating concrete beams without shear reinforcement was examined M. Ismail 2017 Twelve beams were cast with varying SF volume fractions (0%, 0.35%, and 1%), CR replacement levels of fine aggregate volume (0%–35%), and SF lengths (35 and 60 mm). RuC mixes' mechanical and fresh characteristics were examined. The authors found that while increasing the CR content in self-consolidating concrete (SCC) from 0% to 25% improved the deformability characteristics of the tested beams, it had a negative effect on their fresh and mechanical properties, ultimate shear load, post-diagonal cracking resistance, and toughness.

3. EXPERIMENTALPROGRAM

3.1 Materials used

The concrete used had a compressive strength of 26 MPa. Its mix proportion included fine aggregate (715 kg/m^3), coarse aggregate in two sizes: 20 mm (702 kg/m^3) and 12.5 mm (468 kg/m^3), and ordinary Portland cement (380 kg/m^3) with a water-cement (w/c) ratio of 0.45.The transverse reinforcement consisted of deformed steel bars with a yield strength of 456 MPa. For partial replacement of coarse aggregate, rubber shreds prepared from conveyor belts were used. These rubber shreds were cut to a size of 20 mm and had a specific gravity of 1.24.To enhance bonding between the rubber shreds and the cement matrix, the rubber was pre-treated through a sand-coating process. The sand-coated rubber shreds are illustrated in Fig. 1. Karthikeyan .et.al (2024) and the detailed process for sand coating is shown in Fig. 2.Beam specimens were cast with varying levels of coarse aggregate replacement (2.5%, 5.0%, and 7.5%) using the pre-treated rubber shreds. Additionally, steel fibres were added at different volume fractions (0.5% and 1.0%) to assess their effect. The steel fibres had an aspect ratio of 80 and a tensile strength of 1225 MPa. (Fig.3). Fig. 4 presents the details of the specimen configurations and test matrix.

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Fig.1 Sand coated Rubber shreds

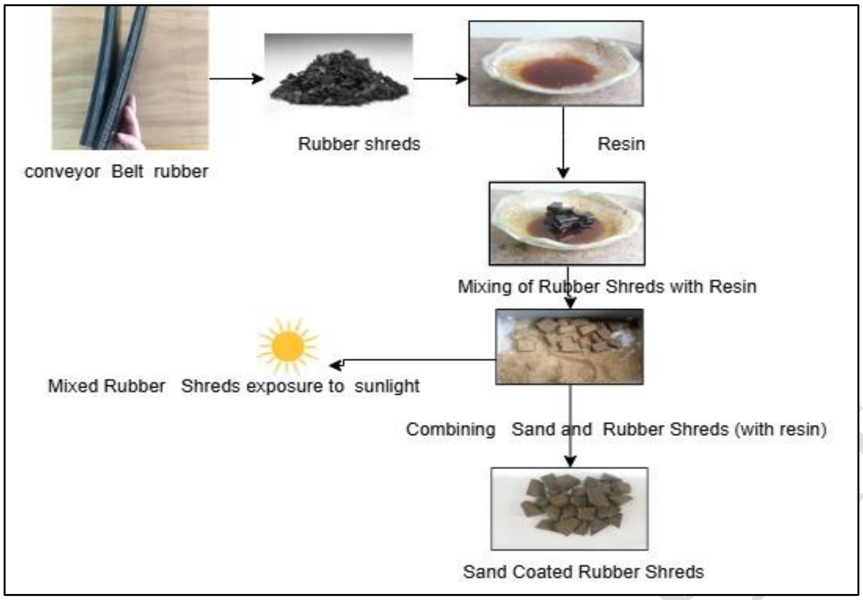

Fig.2 Process of Sand Coating of Rubber shreds

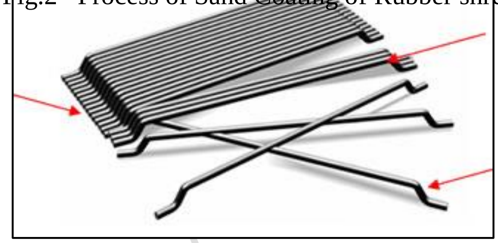

Fig.3 Steel Fibres

3.2 Test Specimen

Nomenclature of test specimens are presented in Fig.4

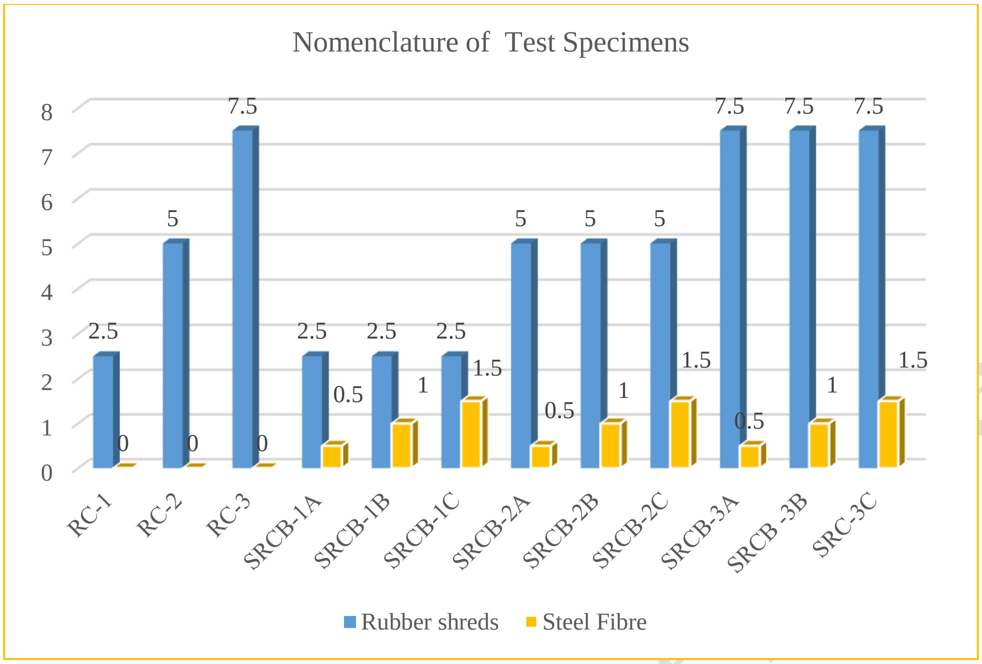

Fig.4 Details of Analysed Beam

3.3 Experimental Setup

Twelve reinforced concrete beams were subjected to four-point bending using a 500 kN capacity hydraulic loading frame. The beams were simply supported, with one roller support and one hinge support at opposite ends. To facilitate effective load transfer and prevent stress concentrations at supports, 100 mm bearing plates were used at both ends, leading to a clear test span of 2800 mm. The load was applied with a spreader beam that split the load into two point loads symmetrically along the span of the beam. This loading system produced a region of constant bending moment between the two applied loads with very little shear within this area a characteristic of four-point bending accuracy so that precise crack widths could be measured as cracks developed and progressed. Crack mapping was also made at routine intervals of load from the initial load at which crack formation was noticed to the failure point. Through this, crack sequence, spacing, and progressive development of crack widths were unambiguously identified. The loading was performed in displacement control to enable steady and progressive development of the cracks. During the test, both load-deflection and load-crack width traces were recorded to furnish the key information necessary for evaluation of the beam's tests. This setup was chosen in order to test directly the beam's flexural response to pure bending without shear interference. To capture deformation behaviour, mechanical dial gauges with a resolution of 0.01 mm were placed at mid-span (where the maximum deflection takes place) and directly below each load point in order to monitor local deformations under the acting loads. The gauges offered continuous displacement measurement during the test in order to allow high-precision monitoring of flexural deformation with rising load levels. Crack development was continuously monitored in the test via a crack detection microscope of ±0.02 mm

performance according to serviceability requirements (deflection capacity and crack restraint) and ultimate strength (peak load-carrying capacity and failure mode).Instrumentation and loading configurations are indicated in Figure 5, specifying the location of supports, the spreader beam, load points, and the location of gauges and crack monitoring devices. This detailed instrumentation allowed for the measurement of global response characteristics (total beam deflection and strength) and local response behavior (crack initiation, crack propagation, and localized deformations**).**

Fig.5 Test Set-up

4. RESULT AND DISCUSSION

4.1 Load - deflection Response of the Beam

Figures 6, 7 and 8 show the load-central deflection responses measured for all the tested beam specimens. In each instance, the load-deflection relationship initially followed a linear trend with a relatively steep slope, reflecting the elastic behavior of the uncracked concrete section. In this phase, the applied load was resisted mainly by the uncracked concrete with little contribution from the embedded reinforcement. The initial visible crack indicated a definitive change in behavior. Following the appearance of the first crack, the stiffness of the beams deteriorated progressively, as indicated by a gradual reduction in the gradient of the load-deflection curves. This reduction in stiffness corresponds to the reallocation of the internal forces, with an increasing proportion of tensile force relocated from the cracked concrete to the longitudinal reinforcement. The number and the crack width grew uniformly as the load was increased, particularly in the region of constant moment between the loads applied. At elevated levels of load, the longitudinal steel reinforcement started to yield, marking the onset of the post-yielding stage of the response. This phase was defined by a dramatic decrease in stiffness, as evident from a high degree of flattening of the load-deflection curves. From this point on, comparatively large deflections were noted even for small increases in applied load, reflecting the plastic deformation and limited ability to recover stiffness. The beams sustained further load up to their ultimate capacity, after which one or more modes of failure mechanisms such as gross flexural cracking, crushing of concrete in the compressive zone, or tensile reinforcement rupture controlled ultimate failure. The main test results such as first crack load, yield load, ultimate load, and respective deflections at these critical points are presented succinctly in Table 2 for all specimens

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Table 3 Results of Tested Beams

Identification of beams	First crack load(kN	Deflection at first crack load(mm)	Yield load(kN)	Deflection @yield load(mm)	Ultimate load(kN)	Deflection @ultimate load(mm)	Deflection Ductility	Energy Ductility(kN -mm)
RC-1	14.4	1.5	26.4	3.2	50.00	6.50	2.03	1.00
SRCB-1A	18.8	2.5	37.5	5.8	62.50	13.80	2.38	1.10
SRCB-1B	19.0	2.6	37.8	6.0	63.00	14.60	2.43	1.15
SRCB-1C	20.0	2.8	40.1	6.3	66.86	15.89	2.52	1.19
RC-2	16.5	1.8	30.3	4.1	53.00	7.20	1.76	0.92
SRCB-2A	20.6	2.9	41.1	6.9	68.50	18.60	2.70	1.26
SRCB-2B	20.7	3.0	41.5	7.1	69.10	21.20	2.99	1.40
SRCB-2C	21.0	3.1	42.1	7.3	70.23	22.52	3.08	1.45
RC3	17.1	2.0	31.4	4.5	55.00	7.80	1.73	0.90
SRCB-3A	20.7	3.0	41.3	7.2	68.86	20.80	2.89	1.35
SRCB-3B	21.8	3.3	43.5	7.7	72.50	24.90	3.23	1.49
SRCB-3C	22.2	3.5	44.5	7.9	74.12	26.12	3.31	1.52

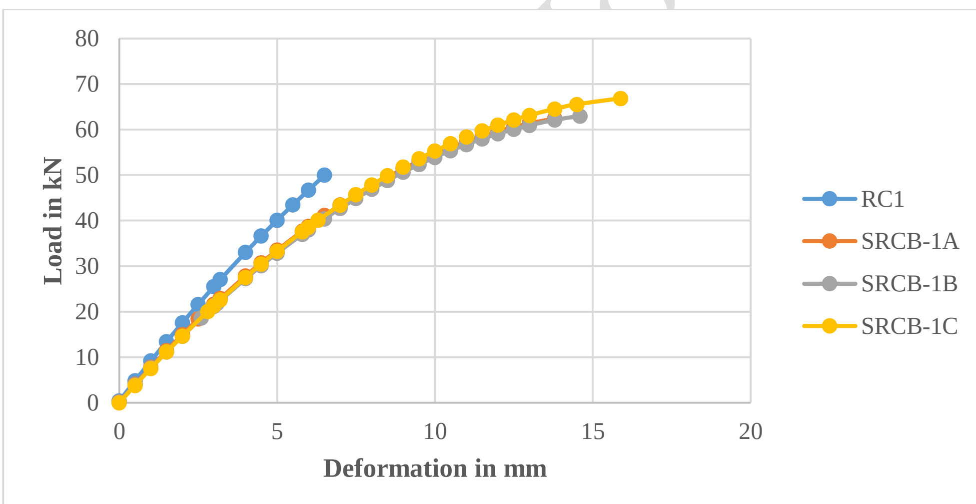

Fig. 6 Load-Deformation Curve for Rubberized Concrete Beams with 2.5% rubber shreds and varying steel fiber (SF) content (0%, 0.5%, 1%, and 1.5%).

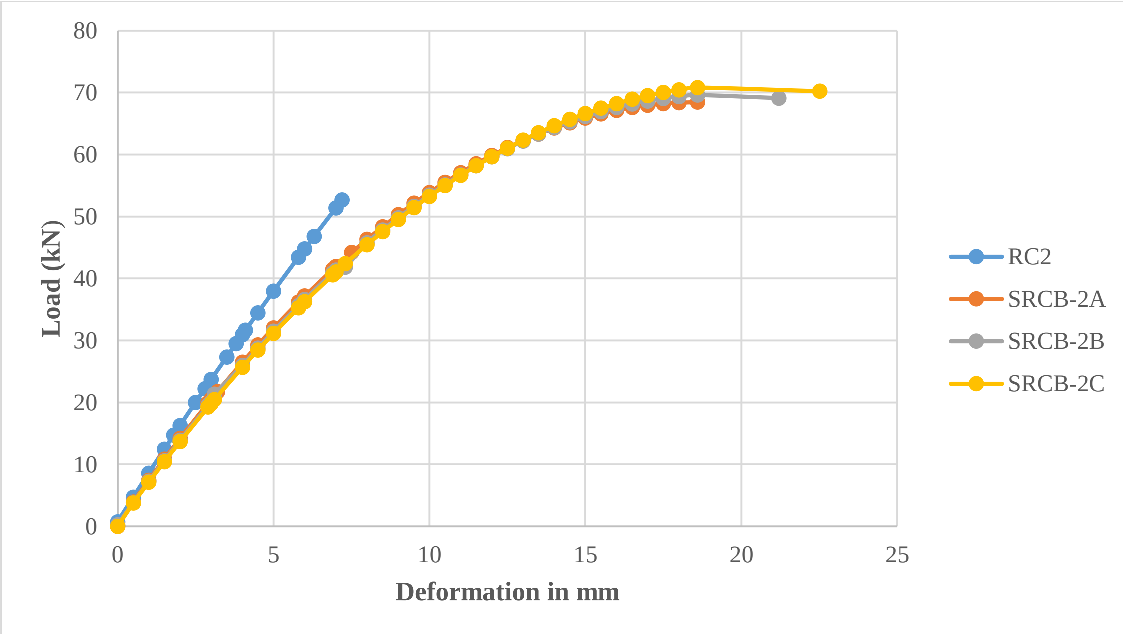

Fig. 7 Load-Deformation Curve for Rubberized Concrete Beams with 5% rubber shreds and varying steel fiber (SF) content (0%, 0.5%, 1%, and 1.5%).

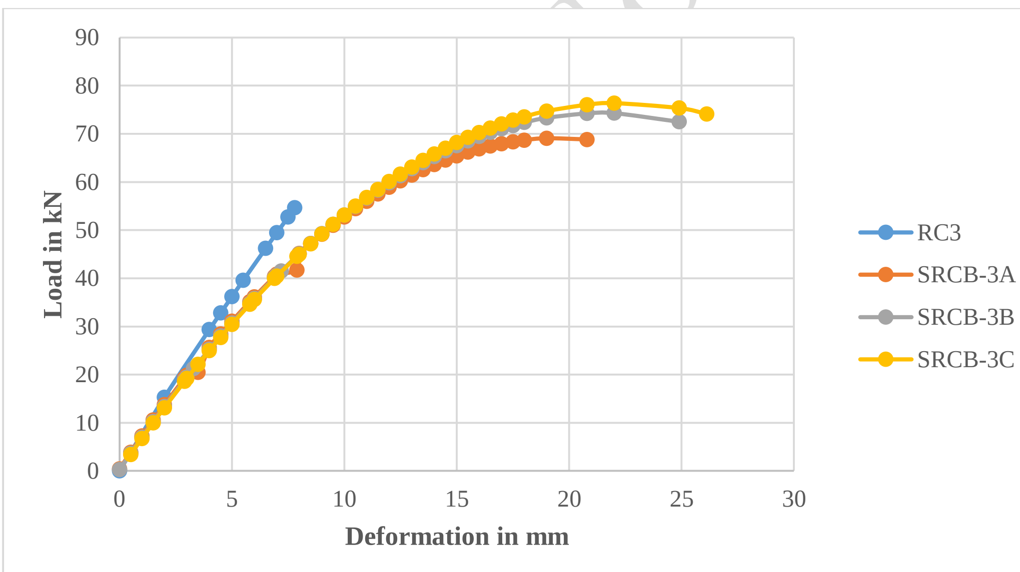

Fig. 8 Load-Deformation Curve for Rubberized Concrete Beams with 5% rubber shreds and varying steel fiber (SF) content (0%, 0.5%, 1%, and 1.5%).

4.2 Evaluation of First Crack Load, Yield Load and Ultimate Load for Rubberized Concrete Beams with and without Steel Fibres

The first crack loads for the tested rubberized concrete beams with and without steel fibres were found through visual examination during the loading process. The first crack loads for rubberized concrete beam with and without steel fibres are summarized in Table .1. The beam Specimens SRCB-1A, SRCB-1B and SRCB-1C exhibit an increase of 30.56%, 31.94% and 38.89% when compared to RC1.The Beam Specimens SRCB-2A, SRCB-2B and SRCB-2C showed an increase of 24.85%, 25.45%and 27.27%when compared to RC2. Beam Specimens SRCB-3A, SRCB-3B and SRCB-3C exhibit an increase of 21.05%, 27.49% and 29.825%

when compared to RC3.The increase in first crack load of rubberized concrete beams with steel fibres, compared to rubberized concrete without steel fibres is due to the crack bridging action of the fibres Hussein .et.al (2025). Steel fibres effectively hold micro cracks closed, redistribute stresses and delay propagation by reinforcing the concrete matrix Zhang.M .et.al (2025). This enhances the tensile strength of the beam and allows it to withstand higher load before the first visible crack forms. Additionally, the strong between the steel fibre and cement paste further resist the crack initiation, making the beam tougher and more resistant to early cracking Fu.et.al (2019). Together, these factors significantly improved the first crack load capacity, as evidenced in Fig. 9 that steel fibres have appreciable effect on the first crack loads.

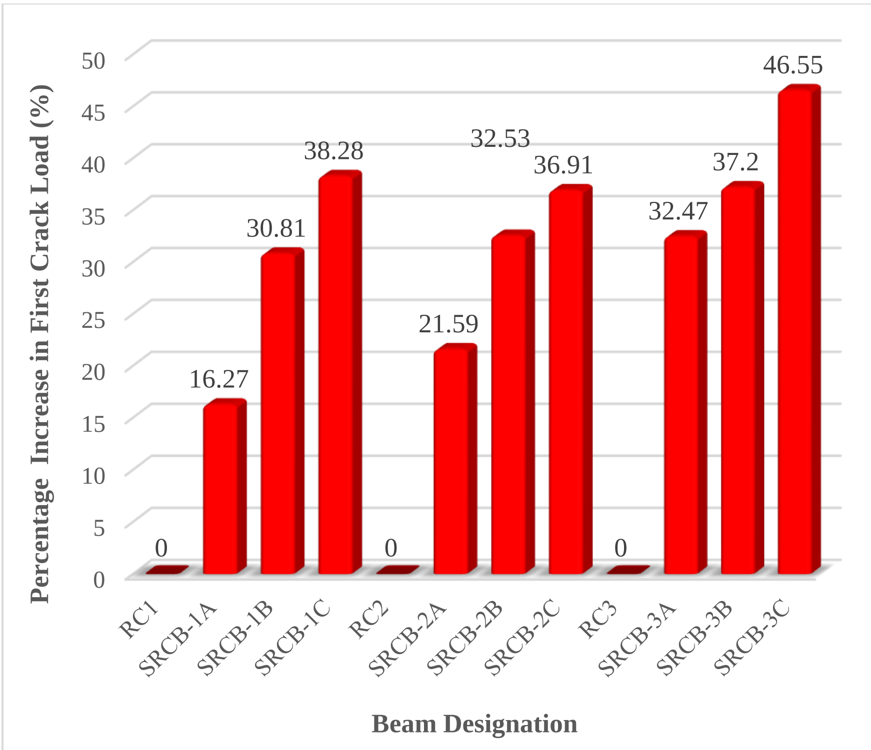

Fig 9. Variation in First Crack Load of Rubberized concrete Beams with and without Steel Fibre

The yield load of the rubberized concrete beams with and without steel fibre reinforcement is presented in Table .1.Yield load is a critical point in the load deflection curve, marking the transition from the elastic (linear) phase to the plastic (non-linear) phase. This is the stage where the beam undergoes permanent deformation under applied load. During the experimental investigation, yield loads were identified through visual inspection of the load –deflection curves, particularly focussing on the point where the response deviated from linear behaviour. The yield loads for rubberized concrete beam with and without steel fibres are summarized in Table .1. The beam Specimens SRCB-1A,SRCB-1B and SRCB-1C exhibit an increase of 42.05%,43.18% and 51.8% when compared to RC1.The Beam Specimens SRCB-2A,SRCB-2B and SRCB-2C showed an increase of 35.64%,36.96%and 38.94%when compared to RC2. Beam Specimens SRCB-3A,SRCB-3B and SRCB-3C exhibit an increase of 31.53%,38.54% and 41.72% when compared to RC3. The rise in yield load for rubberized concrete beams with steel fibres can be attributed to the reinforcing action of the fibres within the concrete matrix , Eisa .et.al (2020). In rubberized concrete without fibres, the rubber aggregates create weak interfaces within the matrix, where stress tends to concentrate under loading. This weakens the beam's ability to sustain higher loads before entering the plastic (non-linear) phase, resulting in lower yield loads He.et.al (2023). However, when steel fibres are introduced, they act as micro-reinforcement distributed throughout the concrete. These fibres effectively bridge cracks that form at the rubber-cement interface, hold the matrix together, and delay the formation and propagation of micro-cracks Tiwari P. K. and Singh V. K. (2025). Additionally, the fibres help to distribute applied stresses more evenly across the beam, reducing localized stress concentrations and allowing the beam to resist greater loads before plastic deformation begins. Steel fibres also contribute to enhanced tensile strength and improved bond strength within the concrete, both of which further increase the beam's resistance to yielding. This combined effect of crack bridging, stress redistribution, tensile strengthening, and enhanced ductility significantly raises the yield load of rubberized concrete beams with steel fibres compared to those without fibres Ghoniem.et.al (2024). Fig.10 that rubber coarse aggregates and steel fibres have noticeable influence on the yield loads of test beams

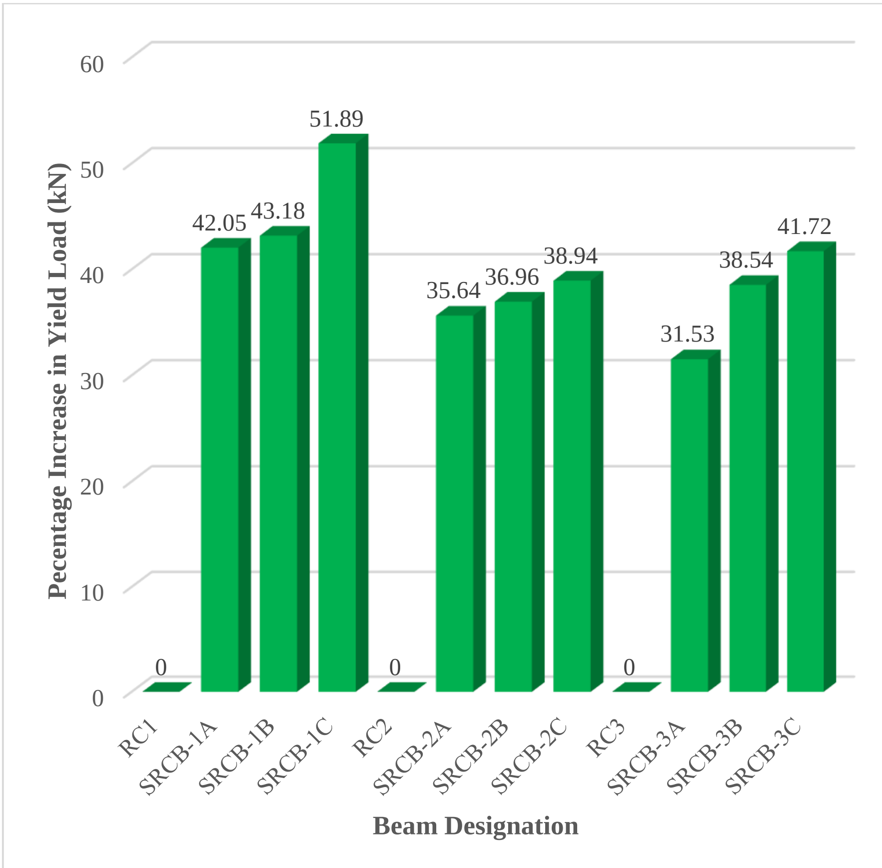

Fig 10. Variation in Yield Load of Rubberized concrete Beams with and without Steel Fibre

The ultimate load of the rubberized concrete beams with and without steel fibre reinforcement is presented in Table .1. The beam Specimens SRCB-1A,SRCB-1B and SRCB-1C exhibit an increase of 25%,26% and 33.72% when compared to RC1.The Beam Specimens SRCB-2A,SRCB-2B and SRCB-2C showed an increase of 29.25%,30.38%and 32.51%when compared to RC2. Beam Specimens SRCB-3A,SRCB-3B and SRCB-3C exhibit an increase of 25.2%,31.82 and 34.76% when compared to RC3. The increase in the ultimate load of rubberized concrete beams with steel fibres can be directly attributed to the fibres' ability to enhance tensile strength and crack resistance. As loads are applied, cracks formed in the concrete matrix. In the absence of fibres, these cracks propagate quickly, leading to premature failure Liang. et.al (2025). However, in fibre-reinforced beams, the steel fibres bridge the cracks, holding the concrete together and preventing sudden failure. This crack-bridging action increases the beam's ability to carry higher loads even after cracking, ultimately improving its performance under flexural stress Zhang. et.al (2025). Fig.11 that rubber coarse aggregates and steel fibres have noticeable influence on the ultimate loads of test beams

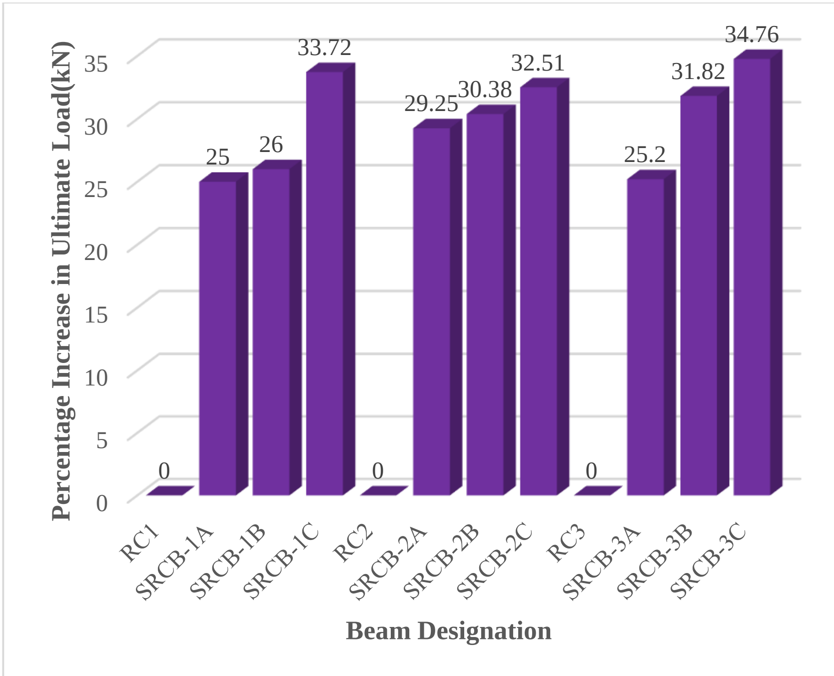

Fig 11. Variation in Ultimate Load of Rubberized concrete Beams with and without Steel Fibre

4.3 Evaluation of Deflection at First Crack Load, Yield Load and Ultimate Load for Rubberized Concrete Beams with and without Steel Fibres

The deflection behaviour of a beam **is** predominantly influenced by several key parameters, including the applied load**,** the effective span of the beam**,** the moment of inertia of its cross-sectional profile, and the modulus of elasticity of the concrete. In the case of rubberized concrete beams, the inclusion of steel fibres introduces additional stiffness to the composite material Hussein..et.al (2025**).** This enhanced stiffness plays a critical role in modifying the beam's deformation response at different stages of loading. The deflection at first crack loads for the tested rubberized concrete beams with and without steel fibres were found through visual examination during the loading process. The deflection at first crack loads for rubberized concrete beam with and without steel fibres are summarized in Table .1. The beam Specimens SRCB-1A,SRCB-1B and SRCB-1C exhibit an increase of 66.67%,73.33% and 86.67% when compared to RC1.The Beam Specimens SRCB-2A,SRCB-2B and SRCB-2C showed an increase of 61.11%,66.67%and 72.22% when compared to RC2. Beam Specimens SRCB-3A,SRCB-3B and SRCB-3C exhibit an increase of 50%,65% and 75% when compared to RC3. The deflection at first crack load in rubberized concrete beams containing steel fibres consistently increases when compared to rubberized concrete beams without steel fibres due to the enhanced crack resistance and improved tensile behaviour imparted by the fibres Ahmed et.al (2022). In rubberized concrete without fibres, the concrete matrix and rubber aggregates alone resist tensile stresses which causes the cracks initiate relatively early once the tensile strength of the concrete is exceeded. However, when steel fibres are incorporated, they act as micro-reinforcement distributed throughout the concrete matrix. These fibres bridge micro-cracks and delay their propagation by transferring tensile forces across potential crack planes, allowing the beam to withstand greater deformation before the first visible crack forms Wang.et.al (2022). Additionally, the presence of steel fibres redistributes internal stresses more evenly, reducing localized stress concentrations at rubber-concrete interfaces, which are typically weak points. This combined action of crack bridging, stress redistribution, and improved tensile strength allows the beam to bend and deflect more before cracking occurs Zhang. (2025). Moreover, the rubber aggregates themselves contribute to flexibility, further enhancing the beam's ability to accommodate deformation. Therefore, the synergistic effect of steel fibres and rubber aggregates results in significantly higher deflection at first crack load compared to beams without steel fibres. Fig.12 that rubber coarse aggregates and steel fibres have appreciable effect on the deflection in first crack load.

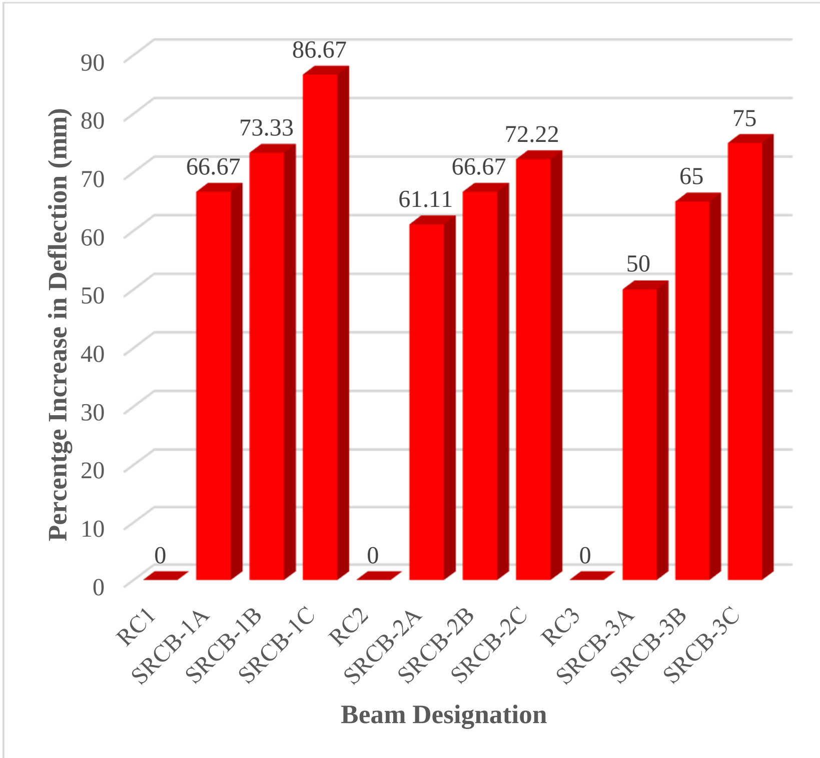

Fig 12. Variation in Deflection at First Crack Load of Rubberized concrete Beams with and without Steel Fibre

The deflection at yield loads for rubberized concrete beam with and without steel fibres are summarized in Table .1. The beam Specimens SRCB-1A, SRCB-1B and SRCB-1C exhibit an increase of 81.25%, 87.5% and 96.87% when compared to RC1.The Beam Specimens SRCB-2A, SRCB-2B and SRCB-2C showed an increase of 68.89%, 73.17% and 78.05% when compared to RC2. Beam Specimens SRCB-3A, SRCB-3B and SRCB-3C exhibit an increase of 60%, 71.11% and 75.56% when compared to RC3. The deflection at yield load in rubberized concrete beams with steel fibres increases significantly compared to rubberized concrete beams without fibres due to the combined effect of improved tensile capacity, enhanced crack control, and increased ductility introduced by the steel fibres Ahmed et.al (2022). In rubberized concrete without fibres, once yielding initiates in the steel reinforcement, the concrete experiences rapid crack widening, leading to a faster loss of stiffness and limited deformation capacity Albidah and Alsaif. (2024). However, in fibre-reinforced rubberized concrete, the steel fibres act as crack arresters, bridging cracks and transferring tensile stresses across them Hussein .et.al (2025). This bridging action slows down crack propagation and allows the beam to continue deforming while still resisting load, thus increasing the deflection at yield Gonzalez. et.al (1999). The fibres contribute additional tensile resistance which causes the beam can carry more tensile strain before the steel reinforcement reaches its yield point. Additionally, the presence of rubber aggregates enhances flexibility, making the beam less brittle and more capable of accommodating larger deformations. The combined effect of crack bridging, stress redistribution, and improved flexibility ensures that the transition from elastic to plastic behaviour is smoother, thereby increasing the deflection at yield load. This behaviour highlights the synergistic interaction between the rubber aggregates and steel fibres, which significantly improves the beam's overall deformation capacity compared to rubberized concrete without fibres. Fig.13 that rubber coarse aggregates and steel fibres have appreciable effect on the deflection in yield load

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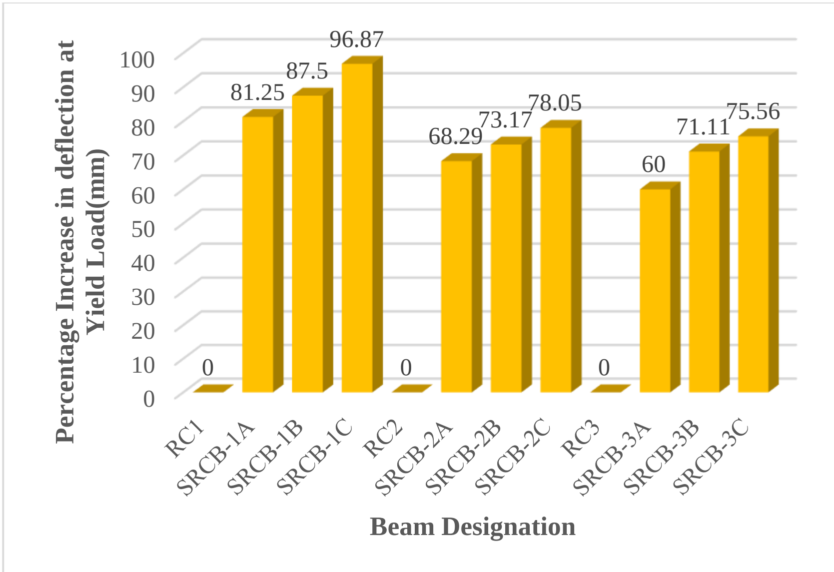

Fig 13. Variation in Deflection at Yield Load of Rubberized concrete Beams with and without Steel Fibre

The deflection at ultimate load of the rubberized concrete beams with and without steel fibre reinforcement is presented in Table .1. The ultimate loads for rubberized concrete beam with and without steel fibres are summarized in Table .1. The beam Specimens SRCB-1A,SRCB-1B and SRCB-1C exhibit an increase of 112.31%,124.62% and 144.46% when compared to RC1.The Beam Specimens SRCB-2A,SRCB-2B and SRCB-2C showed an increase of 158.3%,194.46% and 212.53%when compared to RC2. Beam Specimens SRCB-3A,SRCB-3B and SRCB-3C exhibit an increase of 166.67%,219.93% and 234.78% when compared to RC3. The deflection at ultimate load in rubberized concrete beams with steel fibres consistently shows a marked increase compared to rubberized concrete beams without fibres due to the enhanced post-cracking behaviour, improved energy absorption, and increased ductility provided by the steel fibres, Modarres and Ghalehnovi,(2024). In rubberized concrete without fibres, once the beam reaches its ultimate load, the cracks rapidly widen, and the concrete experiences localized crushing and brittle failure, limiting its capacity to undergo further deformation Ismail and Hassan. (2017). In contrast, the presence of steel fibres transforms the failure mode into a more ductile process. These fibres act as tensile bridges across cracks, holding the cracked sections together and allowing the beam to sustain additional deformation even after reaching peak load Noaman. et.al (2017). This results in the beam having a much higher residual load-carrying capacity, enabling it to resist further deflection before complete failure. Furthermore, the rubber aggregates themselves enhance flexibility and energy absorption, reducing the severity of stress concentrations and allowing the beam to tolerate larger strains. The combined effect of crack bridging by fibres, stress redistribution, and flexibility introduced by rubber aggregates ensures that the beam remains intact and continues to deform under sustained loading, leading to significantly higher deflection at ultimate load when compared to rubberized concrete without fibres Zhang. et.al (2025). This ductile post-peak behaviour is particularly beneficial in ensuring warning before failure, making fibre-reinforced rubberized concrete a superior choice for structures requiring enhanced toughness and resilience. Fig.14 that rubber coarse aggregates and steel fibres have appreciable effect on the deflection in ultimate load.

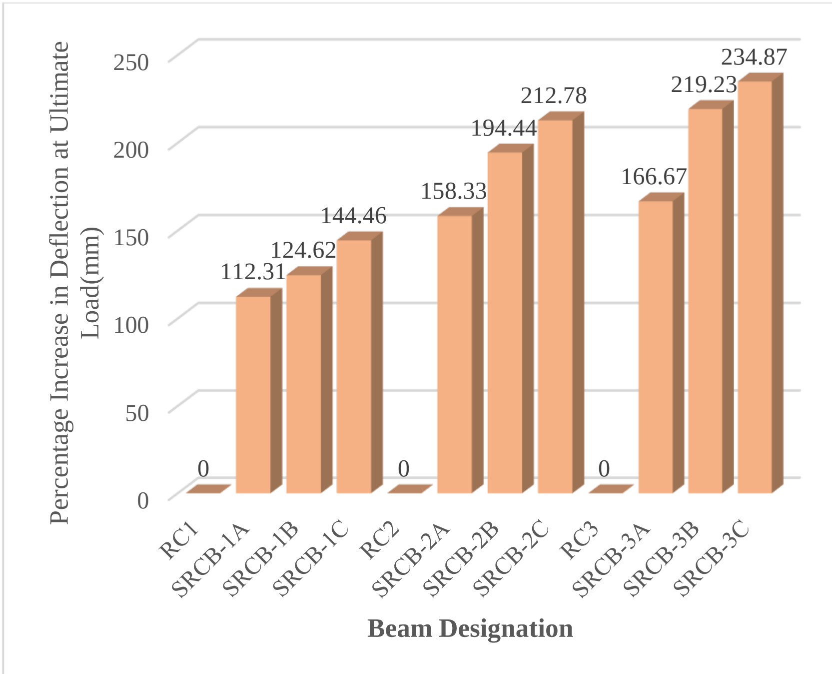

Fig 14. Variation in Deflection at Ultimate Load of Rubberized concrete Beams with and without Steel Fibre

4.4 Evaluation of Failure Modes and Crack Patterns for Rubberized Concrete Beams with and without Steel Fibre

Fig. 14 shows the observed crack patterns in all tested beams at the ultimate load stage. In the first phase of loading, fine vertical cracks were noted in the moment zone. As the applied load increased, the initial flexural cracks extended further, along with the development of additional flexural cracks over the span. As the loading continued, the flexural cracks away from the mid-span progressed diagonally towards the loading points gradually. Table 2 provides a summary of major cracking parameters for all beams tested, including maximum crack width, total cracks, average crack spacing, and failure modes observed. The observations presented in Table 2 and Fig. 15&16 demonstrate that rubberized concrete beams with steel fibre experienced higher crack numbers and wider crack widths than the rubberized concrete beam without steel fibre. The reason behind such behavior lies in the increased capacity of energy absorption offered by the rubber aggregates and the micro-reinforcement. This increased capacity allowed the beams to deflect larger amounts before failing, eventually resulting in wider cracks.

Table 2 Crack Formation and Failure Mode of rubberized concrete Beam with and Without Steel Fibre

SI.No	Beam Designation	Maximum Width of Crack (mm)	Maximum No. of Cracks(mm)	Average Spacing of Cracks (mm)	Mode of Failure
1	RC1	0.60	16	145	Flexure
2	SRCB-1A	0.80	17	138	Flexure
3	SRCB-1B	1.20	19	127	Flexure
4	SRCB-1C	1.70	21	117	Flexure
5	RC2	0.90	18	155	Flexure
6	SRCB-2A	1.40	20	120	Flexure
7	SRCB-2B	1.80	22	110	Flexure
8	SRCB-2C	1.92	23	100	Flexure
9	RC3	1.20	20	170	Flexure
10	SRCB-3A	2.00	22	97	Flexure
11	SRCB-3B	2.60	23	85	Flexure
12	SRCB-3C	3.20	20	78	Flexure

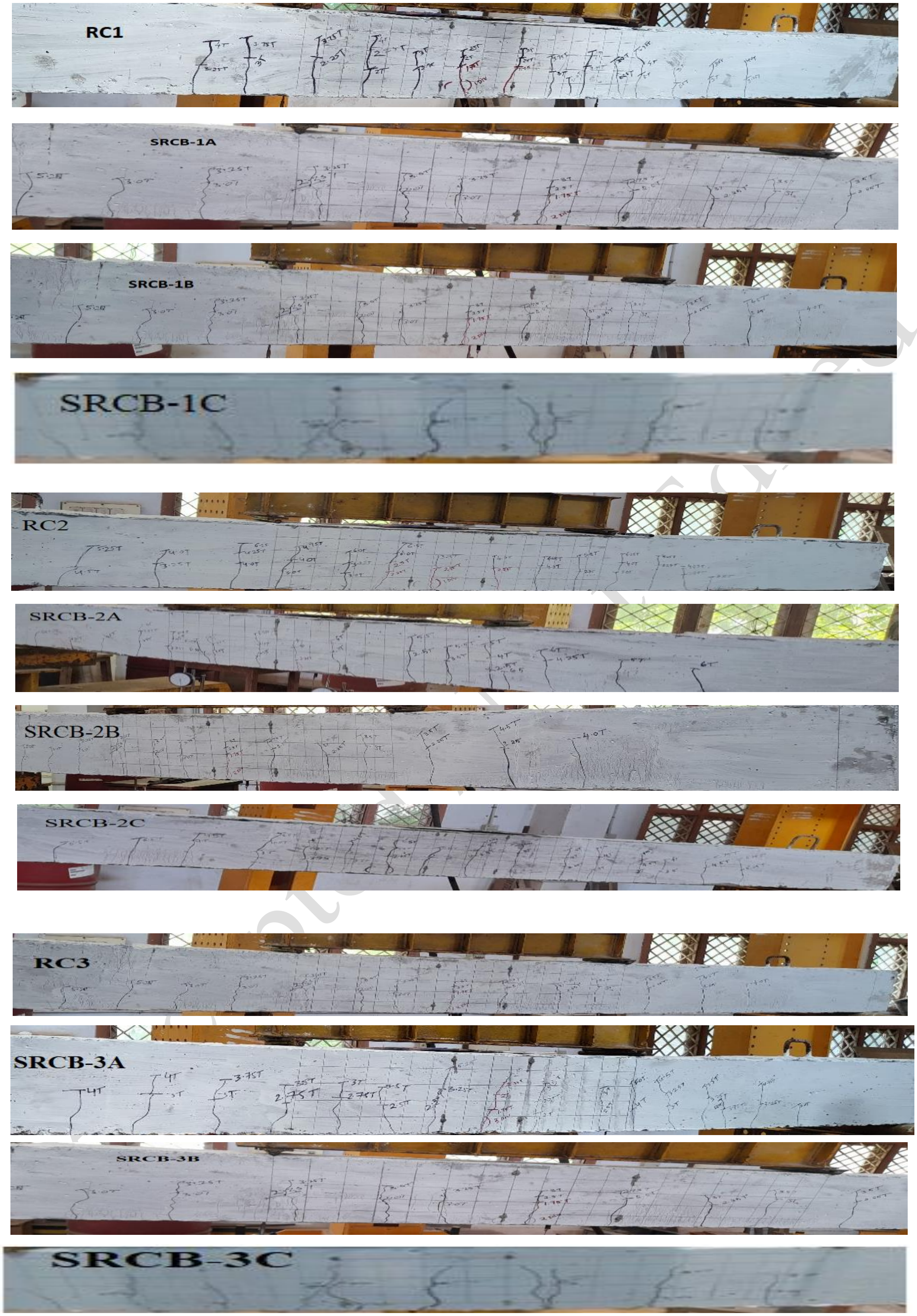

Fig .15 Crack Development in Tested Beams

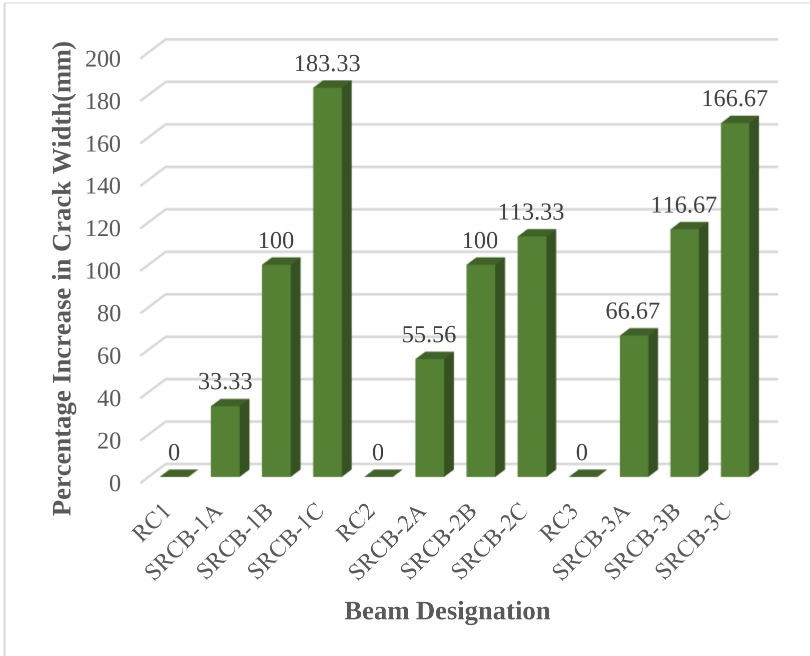

Fig 16. Variation in Maximum Crack Width of Rubberized concrete Beams with and without Steel Fibre

4.5 Evaluation of Deflection Ductility and Energy Ductility for Rubberized Concrete Beams with and without *S*teel Fibre

The ductility index ratio of all tested beams is presented in Table 3. The formulas used for ductility evaluation are mentioned below. As a general rule, higher ductility index of a structural member indicates its ability to undergo large deformation prior to failure and thus provides ample warning to the occurrence of failure. The rubberized concrete beams with steel fibre showed a maximum increase of about 91.33% in deflection ductility and 68% of energy ductility when compared to the rubberized concrete beam without steel fibre Alsaif .et.al (2022).

Fig.17 and.18 show the percentage increase in deflection ductility and energy ductility. The higher energy absorption capacity of rubber aggregates and micro-reinforcement would have enabled the tested beams to exhibit higher ductility. This increase may also be due to the improvement in fibre - matrix interfacial bond Yildizel .et.al (2023).

Deflection Ductility = Ultimate Deflection /Yield Deflection

Energy Ductility = Total Energy Absorbed up to Failure / Energy Absorbed up to Yielding

Table 3 Ductility Indices of Tested Beams

Identification of beams	Deflection Ductility	Energy Ductility
RC-1	2.03	1.00
SRCB-1A	2.38	1.10
SRCB-1B	2.43	1.15
SRCB-1C	2.52	1.19
RC-2	1.76	0.92
SRCB-2A	2.70	1.26
SRCB-2B	2.99	1.40
SRCB-2C	3.08	1.45
RC3	1.73	0.90
SRCB-3A	2.89	1.35
SRCB-3B	3.23	1.49
SRCB-3C	3.31	1.52

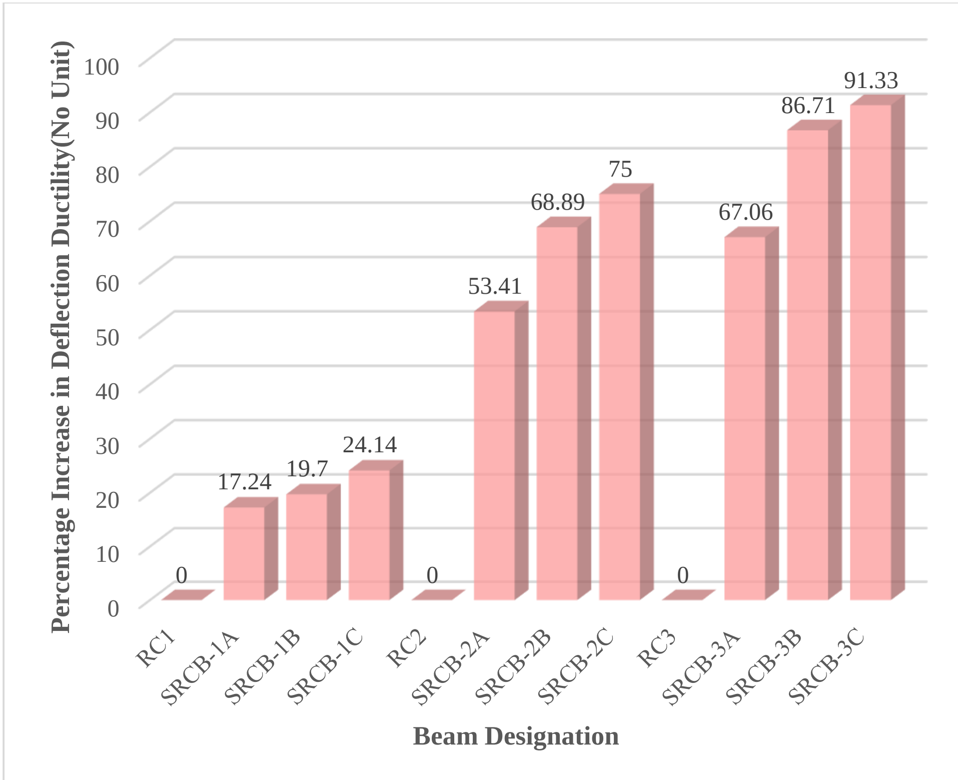

Fig 17. Variation in Deflection Ductility of Rubberized concrete Beams with and without Steel Fibre

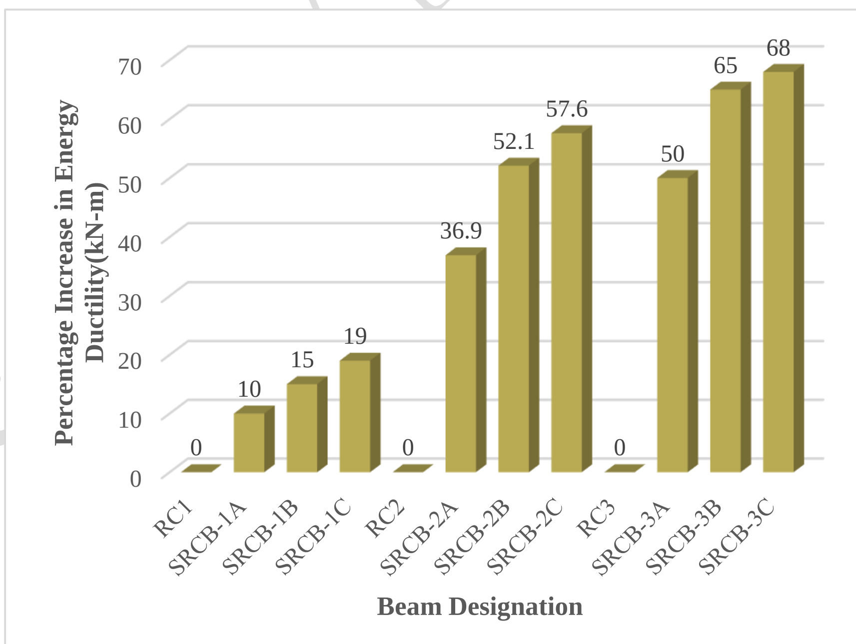

Fig 18. Variation in Energy Ductility of Rubberized concrete Beams with and without Steel Fibre

4.6 Energy Capacity

The energy capacity for all tested beams is presented in Table 4. As a general rule, higher ductility in a structural member would result in higher energy capacity. The energy capacity was obtained as the area under the load - deflection relationship curve. The rubberized concrete beams with micro-reinforcement showed a maximum increase of about 191.27% in energy capacity when compared to the rubberized concrete beam without steel fibre. The energy capacity (Fig.19) increased with increase in rubber content and steel fibre volume fraction. The higher energy absorption capacity of rubber aggregates and micro-reinforcement would have enabled the tested beams to exhibit higher ductility resulting in higher energy capacity

Table 4 Energy Capacity for Tested Beams

SI.No	Beam Designation	Energy Capacity (kN-mm)
1.	RC-1	160.74
2.	SRCB-1A	304.25
3.	SRCB-1B	330.24
4.	SRCB-1C	358.41
5.	RC-2	205.58
6.	SRCB-2A	426.63
7.	SRCB-2B	517.52
8.	SRCB-2C	567.73
9.	RC3	226.88
10.	SRCB-3A	473.97
11.	SRCB-3B	616.70
12.	SRCB-3C	660.77

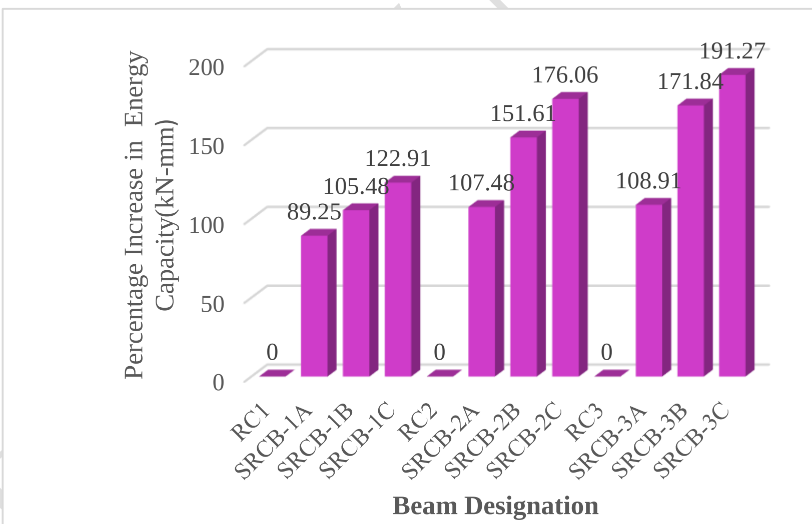

Fig 19. Variation in Energy Capacity of Rubberized concrete Beams with and without Steel Fibre

5. CONCLUSION

This study investigated the flexural behavior of sand-coated rubberized concrete beams with and without steel fibres, aiming to enhance both sustainability and structural performance. The experimental results showed that the inclusion of steel fibres significantly improved key flexural parameters such as first crack load, yield load, ultimate load, deflection at first crack load, deflection at yield load, deflection at ultimate load, deflection ductility, and energy ductility. The greatest improvements were observed in beams containing 2.5% rubber with 1.5% steel fibres when compared to beams with 2.5% sand-coated rubber alone. Similar enhancements were noted for beams with 5% rubber with 1.5% steel fibres compared to those with 5% sand-coated rubber alone, and for beams with 7.5% rubber and 1.5% steel fibres compared to their counterparts without fibres. These findings highlight the practical viability of combining treated rubber waste and steel fibres in concrete to produce beams with superior flexural strength, ductilty and energy absorption capacity, offering an environmentally responsible method for rubber waste utilization. The results support the adoption of this composite system in structural applications, especially where improved flexural performance is essential. Future research should focus on developing and evaluating advanced surface treatment methods for rubber shreds to enhance their bonding characteristics with the cement matrix. It should also aim to improve the flexural strength and overall performance of rubberized concrete beams. Moreover, extending the investigation to include the use of different mineral admixtures such as silica fume, zeolite, and metakaolin could offer further improvements in strength, durability, and workability. These efforts would help expand the practical applications of rubberized concrete as a sustainable and high-performance construction material in modern structural engineering

Conflict of Interest- Authors has no Conflict of Interest

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