Research Article

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Shear capacity of reinforced concrete beams with recycled steel fibers

https://doi.org/10.1515/eng-2022-0457
received March 31, 2023; accepted May 03, 2023

Abstract: This study investigates the effect of using recycled steel fibers (RSFs) extracted from cut tires with dimensions of 0.8 and 40 mm in diameter and length, respectively. Different percentages of fibers were used, which are 0.5, 1, 1.5, and 2%. Ten beams with dimensions of 150 mm × 240 mm and a length of 1,700 mm were tested, two of which are control beams without stirrups and using stirrups at a distance higher than the upper limit (*d*/2), which is a distance of 250 mm. In the case of using steel fibers without a stirrup, it is noticed that shear resistance increases gradually, but the type of failure remains shear. When using a minimum stirrup with steel fibers, the shear resistance increased significantly by 11.1, 23.7, 33.3, and 41.4%, respectively, compared to the reference beam without steel fibers so that the increased shear capacity in the presence of the minimum stirrups and optimal ratio of steel fibers of 2% reaches 122%, compared to the reference beam without stirrup and steel fibers, as well as converting the type of failure from shear failure to pure bending failure. When using a stirrup, this effect will be greater. The presence of RSF reduces deflection at cracking load, while increasing deflection at the ultimate load. Therefore, the stiffness and ductility ratio increased with the presence of steel fibers by 41.5 and 50.3%, respectively. Also, steel fibers delayed the appearance of beam cracks and reduced their widths.

Keywords: recycled steel fibers, stirrups, cracking load, optimal ratio, shear capacity

Nomenclature

A_v	area of shear reinforcing bars, mm^2
b_w	width of the beam, mm
d	effect depth, mm
d/a	effect depth/shear span
D_f	diameter of fibers, mm
FRC	fiber reinforced concrete
e	e = 1.0 when (a/d) ≥ 2.5, e = (2.5 × d/a) when (a/d) ≤ 2.5
F	fiber factor
Ft	represents a value of the residual tensile stress provided by fibers' three-point prism bending test in the laboratory, Mpa
f_{yv}	yield stress of shear reinforcing bars, MPa
f'_c	compressive strength of concrete, MPa
f_t	tensile strength of concrete, MPa
f_r	flexural strength of concrete, MPa
Kt	stiffness of the beam
L_f	length of fibers, mm
M_{cr}	cracking moment
NC	normal concrete
P_u	ultimate load
P_{cr}	cracking load
RSF	recycled steel fibers
S	space of shear reinforcing bars, mm
V_u	ultimate shear strength
V_c	ultimate shear strength of concrete
V_s	ultimate shear strength of stirrups
V_f	ultimate shear strength of fibers
Δ_u	deflection of the beam at ultimate load
Δ_{cr}	deflection of the beam at cracking load
ψ	ductility ratio of the beam
ρ_w	ratio of longitudinal bars
μ_f	fiber shape factor, μ_f = 1.0 for fibers with deformed ends and μ_f = 0.67 for round fiber
ρ_f	percentage of steel fibers,

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1 Introduction

Steel fiber reinforcement in concrete was studied in the early 1950s and 1960s. In August 1971, the first steel fiber-reinforced concrete pavement in the United States was installed at a truck weighing station near Ashland, Ohio. In 1972, two bridge deck overlays were completed in Pennsylvania [1]. Because of its brittle nature, plain concrete has low tensile strength and limited ductility, resulting in low energy absorption and resistance to crack control. This has highlighted the need to improve the ingrained weak concrete properties for improved usage and serviceability. Steel fibers in concrete help to control cracking and change the behavior of the cracked material by bridging with fibers across the cracks [2,3]. Damaged tires are generally delivered to landfill sites for disposal. Due to the increased landfill waste, steel fiber extracted from tires is of growing interest in the construction industry. Using recycled construction materials to preserve natural resources and the environment is sustainable. The environmental damage caused by the accumulation of damaged tires has increased, resulting in a related problem that must be solved. It is used in civil engineering to recycle and extract steel fibers and scrap rubber tires; concrete requires some form of tensile reinforcement to compensate for its brittle behavior and improve tensile strength and stress capacity for use in structural applications. Over 400 tire factories have recently produced a billion tires per year. As a result, there is the potential for millions of tires to be recycled [4], as shown in Figure 1.

The steel fiber reinforced concrete (FRC) is more rigid than regular concrete. To optimize the performance of single fiber, fibers must be distributed uniformly; fiber clustering must be avoided. The impact of fibers on workability is primarily because the fibers have a longer shape than the aggregates, resulting in a larger surface area per volume. Stiff fibers push apart relatively large particles compared to the fiber length, increasing granular friction. The distribution of fibers is determined by the size of the fibers in relation to the aggregates. Fibers should be no shorter than the maximum aggregate size to be effective in the hardened state. The fiber length is typically 2–4 times that of the maximum aggregate size [5,6]. The main characteristic is that steel fibers are randomly distributed in the matrix concrete. Steel fibers in concrete make it more homogeneous and isotropic, transforming it from a brittle to a ductile material. The amount of fibers added to a concrete mix is expressed as a percentage of the total composite concrete [7]. Many previous studies looked at the contribution of industrial fibers to shear resistance and the properties of hardened concrete, including the mechanical behavior of steel FRC beams' shear strength, were investigated. Six beams were tested until shear pressure caused them to break. Prisms were also tested to determine how much fiber contributed to the concrete's shear strength. Steel fibers were 35 mm long, straight with hooks at the ends. The proportion of 1.0 and 2.0% of volumetric fractions were used. The ultimate shear strength of concrete increases by 87% with 1% fiber content and by 99% with 2% fiber content. The outcomes showed a significant contribution, using steel fibers to strengthen concrete beams' shear strength and to narrow cracks, which can minimize the structure's reinforced concrete stirrup count. Empirical equations were also used to evaluate beam capacity, and it was discovered that some of these equations did not accurately forecast, while others gave a high level of variability. The concrete beams of steel fiber reinforcement provide the maximum shear strength [8]. The shear

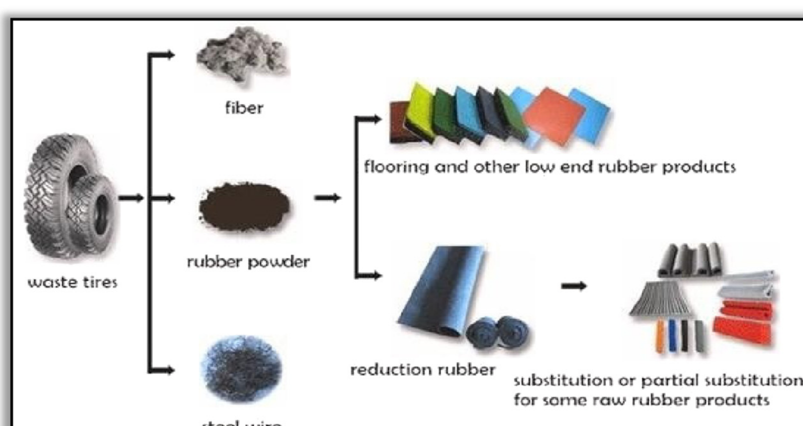

Figure 1: Waste tires for recycling [4].

strength of the steel fibers reinforced concrete beams was examined. The determined parameters were fiber type, fiber volume proportions, and the presence of stirrups in reinforced concrete beams. According to test results, fibers increased shear strength, stiffness, and ductility values and regulated concrete cracking behavior. Steel fibers were used in place of glass fibers to improve the overall shear behavior of concrete. The initial shear cracking load values increased by 12.5 and 31.25%, respectively, in the presence of 0.2 and 0.6% steel fibers. However, the ultimate load values increased by 11.43 and 28.57%, respectively. The presence of stirrups in the shear zone reduces the risk of a rapid and brittle kind of shear failure. Furthermore, fibers and stirrups increased the ductility value because they improved the concrete's tensile strength [9]. Also, eight beams of steel fiber reinforced normal strength concrete, with dimensions of 200 mm wide, 250 mm deep, and 1,500 mm long, were tested bent under two concentrated loads with and without stirrups. Straight, hooked, and corrugated steel fibers were the three types that were considered to be potential replacements for traditional transverse reinforcement. The main testing criteria, in this case, were the value of fibers present, their aspect ratio, and whether stirrups existed. Three aspect ratios (50, 55, and 60) and four fiber value proportions (0, 0.5, 1.0, and 1.5%) were used. Shear strength is increased by 35% with the addition of straight steel fibers of 0.5 and by 44.5% with the addition of steel fibers of 1.5%, surpassing the upgrading seen with transverse reinforcement when higher amounts of fibers are used. Additionally, using 3 cm hooked, 5 cm hooked, and corrugated fibers, the shear strength increased by 50.7, 46, and 43%, respectively, when effective steel fibers were added at 1% value content [10]. The investigation proposes an experimental program that includes the casting and testing of 20 beam specimens to examine the structural behavior of steel fiber reinforced concrete wide beams. Effective shear spans are compared to the depth at a ratio of 2.5 and 3.5, respectively. Additionally, two nominal strength levels of "Normal strength concrete" (30 MPa) and "High strength concrete" (60 MPa) are presented. End-hooked and staggered steel fibers are used, with volume fractions of 0.5 and 1.5%, respectively. The results show that steel fibers significantly enhance the mechanical characteristics and structural behavior. The shear failure mode was changed to "Flexural" by adding steel fibers. In addition, the use of "End-hooked" has increased the ultimate load in "Normal strength" from 19.75 to 65.98%, and the use of "Staggered" has increased the ultimate load from 10.52 to 43.81%, while in the "High strength concrete" a range increased from 13.5 to 43.57% for "End-hooked" fibers and 7.25 to 29.29% for "Staggered" fibers [11]. The previous studies on recycled steel fibers (RSFs) from tires determined the properties such as compressive, splitting, and flexural strengths. Test results showed that the fibers recovered from scrap tires affected the mechanical behavior of concrete, similar to commercial fibers. Depending on the geometrical properties of the fibers and fiber content, the test result indicates the fracture modulus of the concrete. When the amount of RSF is 40 kg/m^3, and the diameter is 0.6 mm, the flexural strength is increased to the greatest extent (67.8%), higher than that of plain concrete [12]. When volume fractions of RSF are mixed into the concrete and when the corresponding fiber contents were (35,70) kg/m^3, they used the diameters (0.8, 1.0, 1.2) mm, and the concrete tensile strengths increased by 27.8, 21.8, and 16.9% and 35, 31, and 24.5%, respectively [13]. The fiber length has a positive influence on compressive, flexural and split-tensile strengths, which increased by more than 10, 50, and 30%, respectively [14]. Results show that using RSF positively affects all the mix designs, especially ductility, and post fracture energy absorption increases with the fiber content. depending on the water-to-cement ratio (0.6, 0.5, and 0.4), and the optimum percentage of RSF [15]. In previous studies, much of the focus has been on the shear performance of beams with high-cost industrial steel fibers. No such attention has been paid concerning RSF from tires. This study fills the knowledge gap and would enrich the literature and expand research into more sustainable engineering and efficient use of recycling. This study incorporated steel fiber from tires into concrete in various dosages to determine an ideal combination after careful consideration. Steel fiber reinforced concrete and control specimens were used in the experiments, and it was determined how strong the compressive, splitting tensile, and flexure forces were. Different ASTM and BS standards were followed in the test's execution.

2 Study objective

The environmental damage caused by the accumulation of damaged tires has increased. It is used in civil engineering to recycle and extract steel fibers. Steel fiber, in particular, is added to concrete to improve its mechanical properties. When the reinforced concrete beam fails in shear, it represents a significant shortcoming due to the possibility of a sudden and brittle failure mechanism, which means that building occupants do not have enough prior notice before fracture.

3 Methodology and materials

The experimental work in this study consists of ten supported beams. All beams have a rectangular cross-section with dimensions of 150 mm width, 240 mm height, and 1,700 mm length. All beams tested in this study were reinforced with two 10 mm diameter plain bars in the compression zone to hold and fix the shear reinforcement in place and two 16 mm diameter plain bars in the tension zone. Web reinforcement stirrups of 6 mm diameter deformed bars at 250 mm and without stirrups are used in the beams, as shown in Figure 2.

3.1 Cement

The cement used in this study is Portland cement (AL-JISR) type (42.5R-SR), from Karbala, Iraq. This type of cement was used because, in the experimental mixtures, it gave the best results. It is tested out in accordance with Iraqi Standard Specification [16].

3.2 Coarse and fine natural aggregate

This study employs rounded gravel with a maximum size of 14 mm from the region of Anbar, Iraq and fine aggregate from the region of Najaf, Iraq. This aggregate's physical properties and coarse and fine aggregate's grading conform to Iraqi Standard Specification [17].

3.3 RSF

During this research work, RSF extracted manually by cutting rubber from damaged tires were used, which had a diameter of 0.8 mm. The extracted RSF were cut into straight pieces of 40 mm in length, by a cutting machine as shown in Figure 3. In the present work, RSFs of 0, 1.0, 1.5, and 2% of the total weight of concrete were added. The wire extracted from the tires was examined using a specific mechanism, i.e., by making a hook at both ends of the wire, and examined by means of a tensile test device located in the laboratory, as shown in Figure 4. The properties of RSF are listed in Table 1.

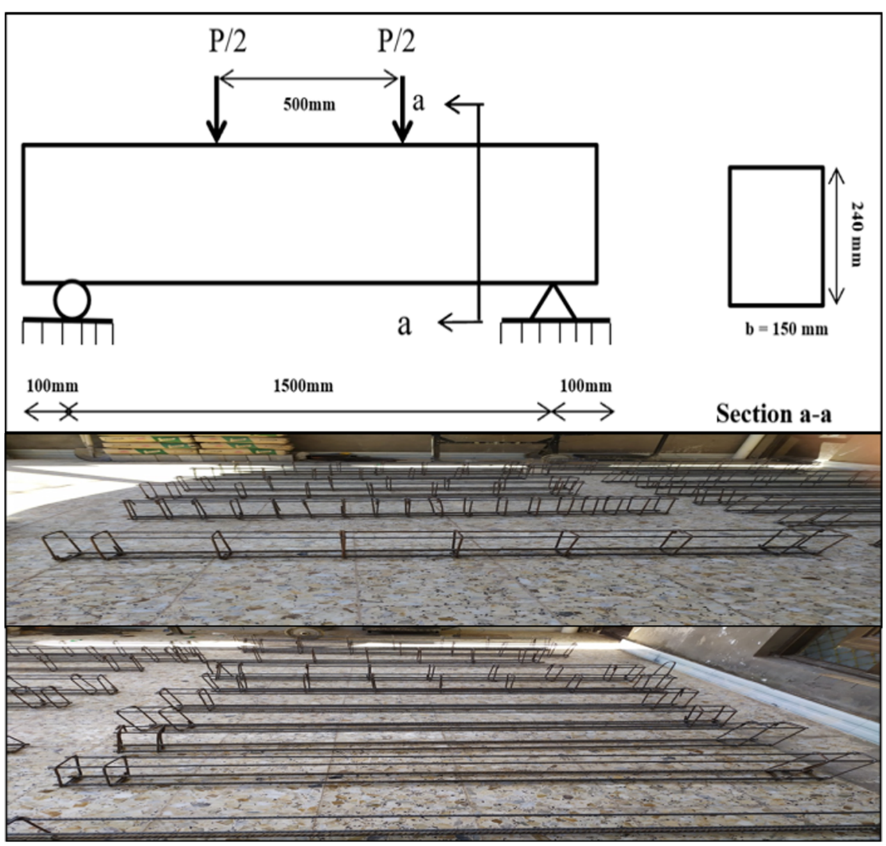

Figure 2: The details of beams and reinforcement.

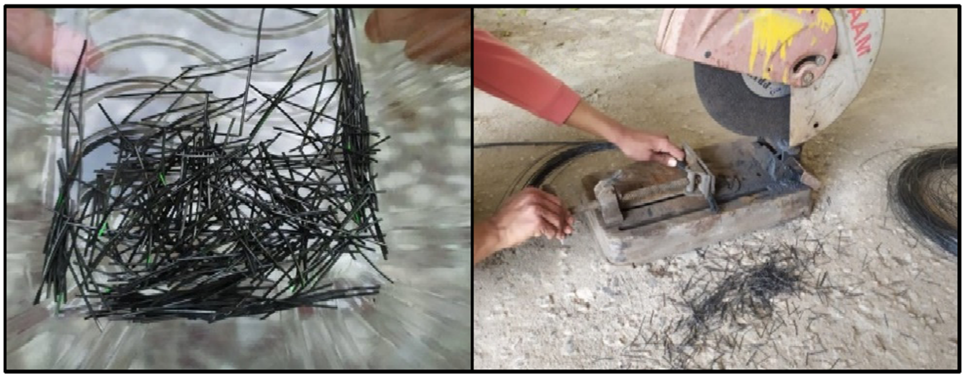

Figure 3: RSF from tires.

Figure 4: Test of RSF.

Table 1: RSF properties

Properties	Specifications
Relative density	7,860 kg/m^3
Ultimate strength	1,300 MPa
Average length	40 mm
Nominal diameter	0.8 mm
Aspect ratio (L_f/D_f)	50

Table 2: Details of mix design

Mix	Cement (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	Water (L/m^3)	W/C
NC	450	570	1,150	250	0.55
Dosage of RSF					
Weight	0%	0.5%	1%	1.5%	2%
RSF (kg/m^3)	0	12.5	25	37.5	50
Volume	0	0.16%	0.32%	0.48%	0.64%

3.4 Steel reinforcement bars

Three sample bars of nominal diameter of 6, 10, and 16 mm with a length of 500 mm each are tested in the laboratory to determine the reinforcing properties. The results conformed to the ASTM A615/A615M-15 [18].

3.5 Mix design

The variables include steel fiber (RSF%) addition at a proportion of the total weight of concrete, as shown in Table 2. Three cube specimens of 150 mm × 150 mm, three cylinders of 150 mm × 300 mm, and three prisms of 100 mm × 100 mm × 500 mm were tested, to obtain the mechanical properties of hardened concrete. Many experimental mixtures have been made to reach the best mixture in terms of workability.

4 Results and discussion

4.1 Compressive, tensile, and flexural strengths

The compressive, tensile, and flexural strength tests are the most common mechanical properties of all hardened

Table 3: Result of specimen test

Mix	N F0	N F0.5	N F1	N F1.5	N F2
f'_c	28.24	29.38	29.64	30.27	31.4
f_t	2.85	3.31	3.72	3.85	3.96
fr	4.78	5.66	5.89	6.92	7.1

concrete tests because it describes the features of concrete that are connected to its strength and the inherent importance of the strength of concrete in structural design. This test was obtained by averaging three specimens cast for each concrete mix and tested at the same age as the beams, according to BS 1881:part116, ASTM C78/C78M-15a and ASTM C496/C496M-11 [19–21]. The results of the tests are shown in Table 3 and Figure 5.

1. The steel fiber (RSF) for all ratios (0.5–2%). These results show that adding steel fibers resulted in only moderate gains in compressive strength. The fibers operate as a specifically shaped aggregate due to their limited proportions in the process materials. The RSF of 2% enhanced the compressive strength to a maximum of 11%.
2. Because the presence of steel fibers increases the experimental (f_t) values of the mixes with RSF, which is 0.5, 1, 1.5, and 2%, they are greater than the same mixes without steel fibers. The hardness of concrete parts under load and the ductility of concrete after micro-cracks appear will increase. As a result, tensile strength increased by 16, 30.5, 35, 38.9%, respectively.
3. The steel fibers increase the ductility of concrete. The mixture with steel fibers has higher flexural strength values than those without steel fibers. Adding steel fibers of 0.5, 1, 1.5, and 2% results in the greatest increase in flexural strength by 18.4, 23.2, 44.7, and 48.5%, respectively.

Table 4: Cracking load and ultimate load of tested beams

Beams' notation	RSF%	P_{cr} (kN)	P_u (kN)	P_{cr}/P_u (%)	M_{cr}
N F0 – Cont.1	0	19	86	22.1	4.75
N F0 – Cont.2	0	28	135	20.74	7
N FD0.5	0.5	22	95	23.15	5.5
N FD1	1	25	106	23.58	6.25
N FD1.5	1.5	27	115	23.47	6.75
N FD2	2	28	120	23.33	7
N F0.5	0.5	30	150	20	7.5
N F1	1	36	167	21.55	9
N F1.5	1.5	40	180	22.22	10
N F2	2	43	191	22.5	10.75

This is the largest increase in compressive and tensile strength, so the inclusion of steel fibers considerably improves the tensile characteristics and the ductility of concrete. This finding is consistent with the results obtained in the literature [12–14], the compressive strength increased by more than 10%, flexural strength increased by more than 50%, and split-tensile strength increased by more than 30% [14].

4.2 Cracking load and moment

The cracking moment is the first visible surface crack on the member's surfaces. The results of the cracking load and ultimate load are shown in Table 4. It is obvious that as the ultimate load increases, so does the cracking load. The cracking load to ultimate load ratio (P_{cr}/P_u) was typically between 20 and 23.58%. In comparison, the cracking moment increases with the ratio of the fibers, as shown in Figure 6.

$$M_{cr} = (P_{cr} \cdot L/6), \tag{1}$$

where M_{cr} is the cracking moment in kN m, P_{cr} is the cracking load in kN, and L is the length of the beam (m).

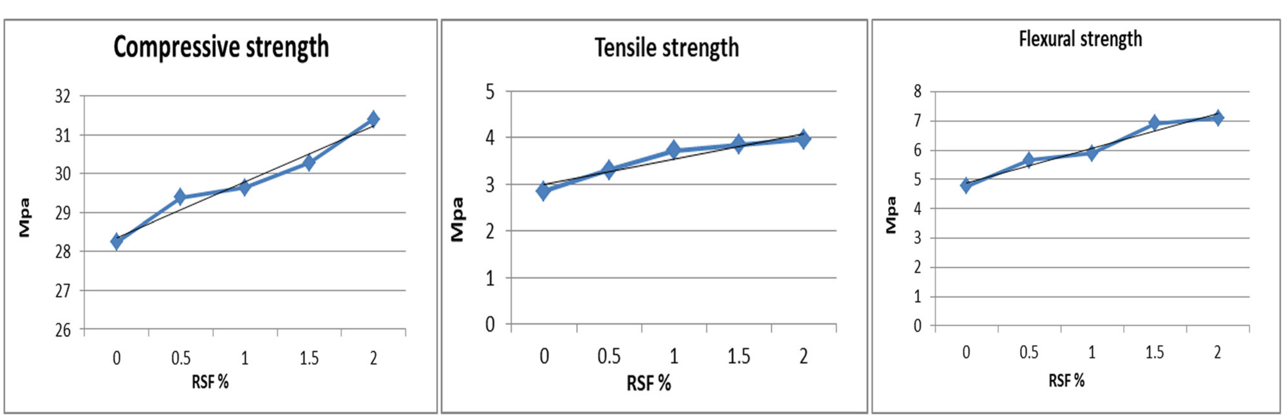

Figure 5: Relationship between f'_c, f_t, f_r and RSF%.

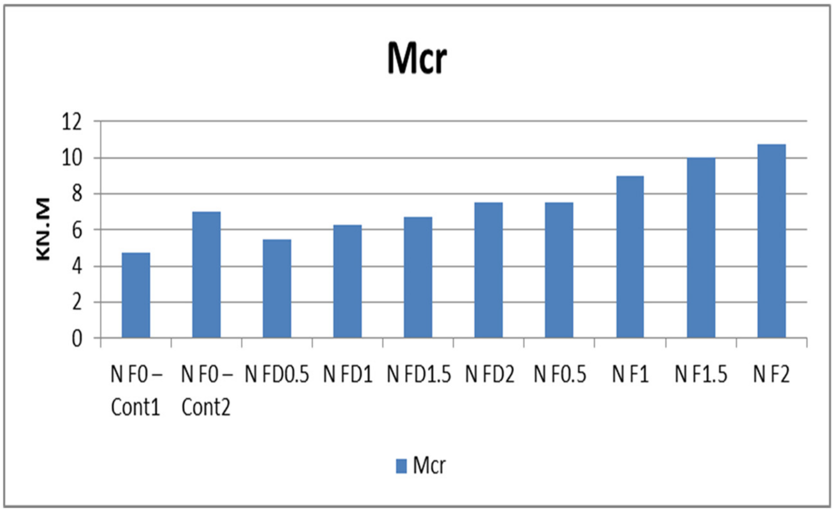

Figure 6: M_{cr} for tested beams.

In comparison, there is a noticeable increase in the cracking moment of the beam by 47.3% in the presence of transverse reinforcing steel (stirrup) even if the distance is greater than the upper limit distance (d/2). As expected, the tested RSF beams exhibit significant cracking moments compared to other beams without steel fibers. This reinforcement is primarily due to the presence of steel fibers because adding steel fibers increases the stiffness of the beams; thus, the cracking moment increases by 53.6% when the RSF added was 2%.

4.3 Ultimate shear strength

Ultimate shear is the maximum shear that denotes a force that acts perpendicular to the length of a beam. The theoretical equations for calculating the ultimate shear without and with stirrups and steel fibers are shown below. The results are shown in Table 5.

$$V_u = P_u/2. \quad (2)$$

For normal concrete (NC) without stirrups: ACI 318M-2019 [22].

$$V_u = V_c = (0.17\sqrt{f_c'})b_w \times d \quad (3)$$

$$V_u = V_c = (0.66\sqrt{f_c'} \times (\rho_w)_{1/3}) \times b_w \times d. \quad (4)$$

For NC with stirrups: ACI 318M-2019 [22]

$$V_u = V_c + V_s, \quad (5)$$

$$V_s = (A_v \times F_{yv} \times d/S). \quad (6)$$

For FRC without stirrups: Khuntia [23]

Table 5: Experimental and theoretical shear strength

Beam notation	V_u (exp.) kN	V_u (theoretical) kN					V_u exp./V_u theo.
		ACI 318M-2019			Khuntia et. al. [23]	Foster et. al. [24]	
		V_c	V_s	V_u			
Cont1	43	29.13	—	29.13	—	—	1.47
Cont2	67.5	29.13	24.86	54	—	—	1.25
N FD0.5	47.5	29.71	—	29.71	33.72	—	1.4
N FD1	53	29.84	—	29.84	36.22	—	1.46
N FD1.5	57.5	30.16	—	30.16	38.98	—	1.47
N FD2	60	30.72	—	30.72	42.12	—	1.42
N F0.5	75	29.71	24.86	54.57	—	84.01	0.89
N F1	83.5	29.84	24.86	54.7	—	91.4	0.91
N F1.5	90	30.16	24.86	55	—	96.91	0.92
N F2	95.5	30.72	24.86	55.58	—	98.14	0.97

$$V_u = [V_c + V_f] = [0.167e + 0.25F]\sqrt{f'_c} \times d \times b_w, \quad (7)$$

$$F = (L_f/D_f \times \rho_f \times \mu_f). \quad (8)$$

For FRC with stirrups: Foster [24]

$$V_u = [V_c + V_s + V_f], \quad (9)$$

$$V_C = [0.9 \times \mathrm{Kv} \times \sqrt{f'_c} \times d \times b_w], \quad (10)$$

$$V_s = [1.238 \times (A_v/S) \times F_{yv} \times d], \quad (11)$$

$$V_f = [0.991 \times \mathrm{Ft} \times d \times b_w], \quad (12)$$

$$\mathrm{Kv} = \left(\frac{200}{1{,}000 + 1.17d}\right), \quad (13)$$

where V_u is the ultimate shear strength, kN, A_v is the area of shear reinforcing bars, mm^{2,} f_{yv} is the yield stress of shear reinforcing bars, MPa, f'_c is the compressive strength of concrete, MPa, d is the effect depth, mm, ρ_w is the ratio of longitudinal bars, d/a is the effect depth/shear span $e = 1.0$, when $(a/d) \geq 2.5$ and $e = (2.5 \times d/a)$, when $(a/d) \leq 2.5$, S is the space of shear reinforcing bars, mm. Ft represents the residual tensile stress provided by fibers' three-point prism bending test, $\mathrm{Ft} \leq 0.231\sqrt{f'_c}$, MPa, F is the fiber factor, μ_f = 1.0 for fibers with deformed ends and μ_f = 0.67 for round fiber, b_w is the width of the beam, mm, ρ_f is the percentage of steel fibers, L_f is the length of fibers, mm, D_f is the diameter of fibers, mm.

1. The American code (ACI 318M) [22] provides a high safety factor in the concrete design equations. The equations for calculating the shear strength without the stirrups (V_c) did not include the effect of all influences on the shear strength, and they consider the maximum distance between stirrups as (d/2). Therefore, it is noticed that the theoretical values are lower than the experimental values. As for the use of steel fibers (RSF) with stirrups, it was noted that there is a convergence in the results of the experiment with the results in the equation (Foster) [24].
2. The effect of stirrups: The presence of transverse reinforcing steel (stirrups) increases the shear resistance of the beam even when the distance is greater than the upper limit distance (d/2). The stirrup distance is 250 mm. Shear resistance increased by 56.9%, and the failure type is also a shear failure, but it is less severe. The stirrup is primarily designed to resist shear forces, so shear resistance increases with the increase in the transverse reinforcing steel.
3. The effect of steel fibers (RSF) without stirrups: When steel fibers are added to the beams in different proportions (0.5, 1, 1.5, and 2%), the shear resistance increases by 10.5, 23, 33.7, and 39.5%, respectively, compared with the beam (cont.1). The type of failure remained a shear, but it is less severe.
4. The effect of steel fibers (RSF) with stirrups: When different proportions of steel fibers (0.5, 1, 1.5, and 2%) are added to the beams, a gradual increase in shear resistance by 11.1, 23.7, 33.3, and 41.4%, respectively, is noticed concerning the beam cont.2. The failure type is changed to a gradual flexure.

As expected, the beams containing steel fibers demonstrated higher ultimate shear than those tested without steel fibers. This enhancement is primarily due to steel fibers, which created hardness in the beam before the first crack and the ductility after that, thereby increasing the ultimate shear. This finding is consistent with the results obtained in the literature review [8–11], which is significantly close to the results obtained and the amount of steel fiber used in the previous study [10].

4.4 Load–deflection curve behavior

The load vs deflection curves are commonly used to explain structural behavior. In this work, the deflection is taken at the mid-span. All the tested beams' load–deflection curves display the following three stages:

1. The first stage (O–A), as shown in Table 6 and Figure 7, "is the elastic behavior or uncracked concrete section (constant slope)," which runs from the zero load point to the first crack load point, and the beam has a relatively higher flexural rigidity at this stage. The stiffness of the beams was defined as the slope of the line in this stage ($\Delta P_{cr}/\Delta_{cr}$) [25].
2. For stage (A–B), the vertical flexural cracks begin in the beam cross-section's tensile area at the maximal bending moment area and extend to the material of the neighboring matrix in the second stage, followed by inclined cracks in two shear spans. These cracks progress as loading increases, causing a matching shifting in the locations of the neutral axis in the direction of the compression face and, as a result, a constant decrease in the moment of inertia of the cracked section. When a shear beam fails, inclined cracks extend in the direction of or beyond the point load and horizontally in the longitudinal reinforcement level, causing failure.
3. The ductility is very clear in the third stage (B–C). When the beam fails by flexural, the cracks develop gradually and increase crack up perpendicular until the final failure, resulting in less rigidity due to the development of flexural. The ability of an element to exhibit non-

Table 6: Deflection in the center of beams

Beam notation	P_{cr} (kN) flexure	Δ_{cr} (mm) flexure	P_{cr} (kN) shear	Δ_{cr} (mm) shear	Δ_u (mm)	*(Kt)	**(ψ)
Cont.1	19	1.32	52	3.63	6.82	14.4	5.16
Cont.2	28	1.4	85	5.21	10.15	20	7.25
N FD0.5	22	1.35	60	3.95	7.37	16.3	5.46
N FD1	25	1.39	68	4.45	7.98	17.98	5.74
N FD1.5	27	1.43	74	4.86	9.1	18.88	6.36
N FD2	28	1.4	80	5.1	9.83	20	7.02
N F0.5	30	1.38	100	6.25	12.28	21.73	8.89
N F1	36	1.45	140	9.97	13.65	24.82	9.41
N F1.5	40	1.5	—	—	15.19	26.66	10.12
N F2	43	1.52	—	—	16.58	28.3	10.9

*Kt = The stiffness of beam = Crak load (Δ_p)/deflection at P_{cr} (Δ_{cr}).
**ψ = The ductility ratio of beam = Maximum deflection (Δ_u)/deflection at P_{cr} (Δ_{cr}).

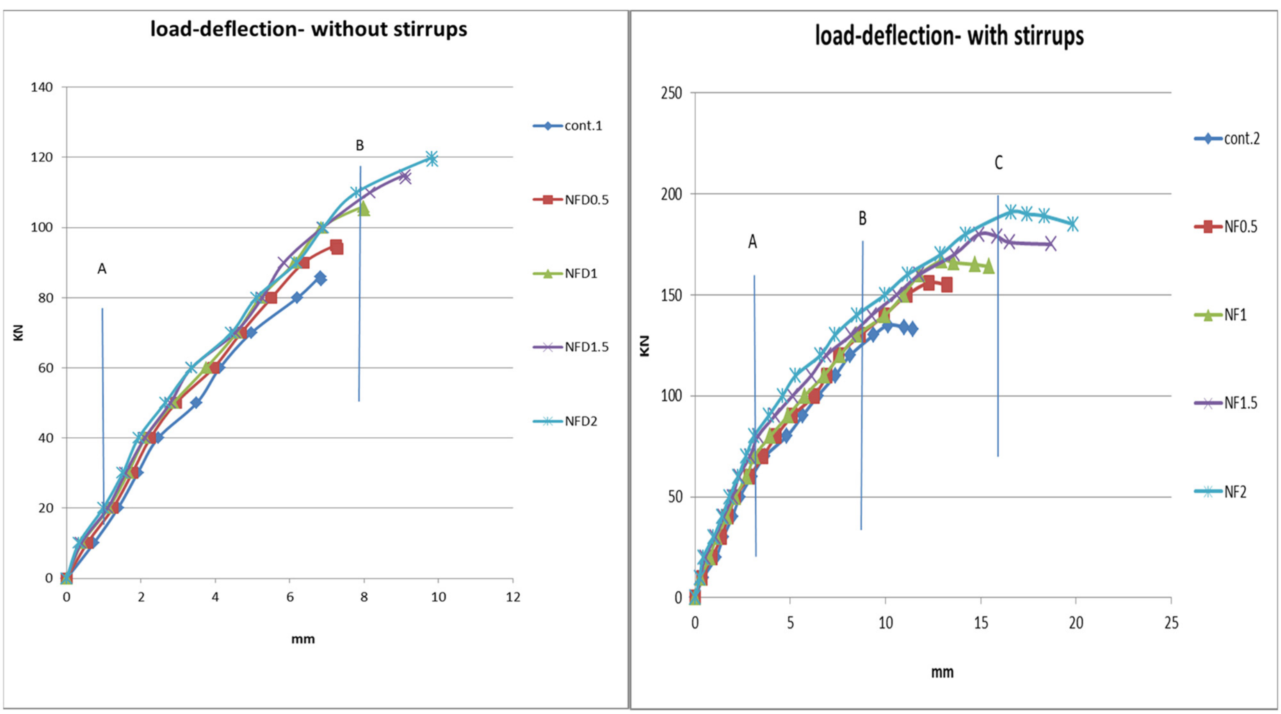

Figure 7: Comparison between cont.1 and cont.2 for variable RSF%.

elastic behavior and absorb energy is measured by its ductility. The ductility ratio was calculated by dividing the mid-span deflection at ultimate load by the mid-span deflection at the first crack (Δ_u/Δ_{cr}) [26].

The capacity of a material to absorb energy before failure is referred to as toughness. However, it depends on combining ductility and strength into a single measurable property and necessitates a careful balance between them [27]. To be tough, the material needs to be both strong and ductile. A strong material with little flexibility is not tough, just as a highly ductile material with little strength is not tough. To be deemed tough, a material must withstand high stresses and strains. The area under load–deflection curves is a measure of toughness.

The results of load–deflection curve:

1. Effect of web reinforcement: The stirrup reinforcement increases the shear resistance, which means the deflection at the final load of the beam (cont.1) is lower than that of the beam (cont.2), the reason for this is attributed

to the fact that the presence of the stirrup, even if it is higher than the upper limit (*d*/2), increases the bond between the lower and upper parts of the beam, and thus the stiffness and ductility ratio increased by 38.8 and 40.5%, respectively.

2. Effect of RSF without stirrups: The presence of fibers reduces deflection at cracking load while increasing deflection at ultimate load. Adding the steel fibers at 0.5, 1, 1.5, and 2% increased the stiffness and ductility ratios by 13.2, 24.86, 31.1, and 38.8% and 5.8, 11, 23, and 36%, respectively, due to the presence of steel fibers when compared to the beam (cont.1).
3. Effect of RSF with stirrups: When there is a stirrup, this effect will be greater. The presence of fibers reduces deflection at cracking load while increasing deflection at ultimate load. On adding the steel fibers at 0.5, 1, 1.5, and 2%, the stiffness and ductility ratio increased with the presence of steel fibers by 8.65, 24.1, 33.3, and 41.5% and 22.6, 29.7, 39.6, and 50.3%, respectively, when compared to the beam (cont.2).

This behavior may be explained by the fact that the addition of RSF to beams led to an increase in the ultimate load and deflection, which resulted in an increase in the area under the load–deflection curve (toughness) [27].

The addition of steel fibers significantly increases the ductility of normal-strength concrete beams. When adequate and efficient steel fibers are used, this ductile behavior is crucial in seismic regions to avoid brittle and disastrous failures, which have been observed in numerous earthquake-prone regions worldwide [28–31].

Table 7: Crack width and modes of failure

Beam notation	P_{cr} (kN) flexure	P_{cr} (kN) shear	P_u (kN)	Max crack width (mm)		Mode of failure
				Shear	Flexure	
Cont.1	19	52	86	1.2	0.3	Shear
Cont.2	28	85	135	0.7	0.5	Shear
N FD0.5	22	60	95	1.2	0.3	Shear
N FD1	25	68	106	1.1	0.25	Shear
N FD1.5	27	74	115	1.1	0.25	Shear
N FD2	28	80	120	1	0.2	Shear
N F0.5	30	100	150	0.65	0.4	Shear
N F1	36	140	167	0.5	0.45	Shear-flexure
N F1.5	40	—	180	—	0.4	Flexure
N F2	43	—	191	—	0.4	Flexure

4.5 Crack patterns and modes of failure

Crack patterns and modes of failure of the tested beams are shown in Table 7 and Figure 8. In this study, ten beams were designed without and with stirrups, and all beams fail to shear by producing tensile steel bars. The presence of RSF affected the rate of crack growth and crack widths significantly.

Using steel fibers without stirrups does not change the type of failure, but it reduces the severity of the shear failure and crack width before failure with an increase

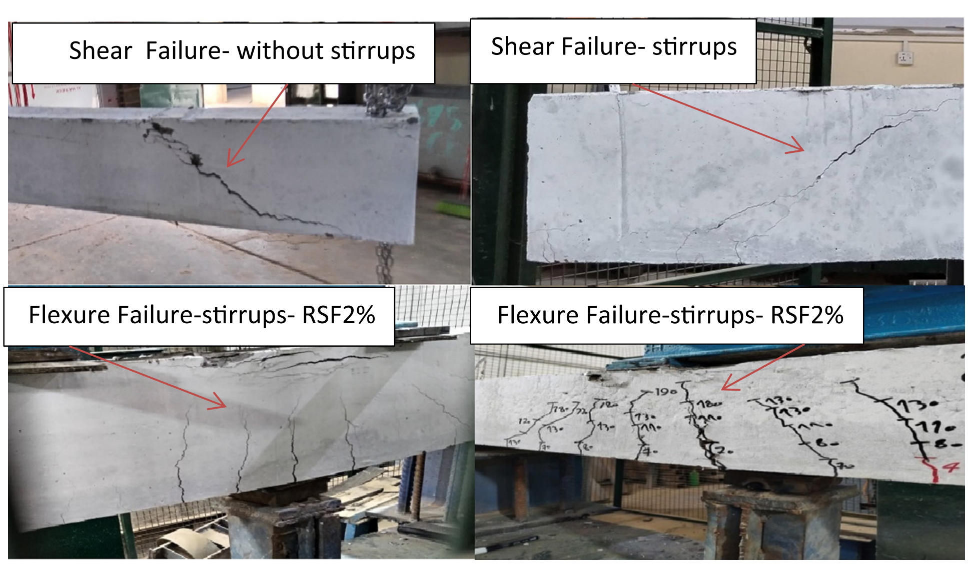

Figure 8: The failure modes of the samples.

in shear resistance. But when using minimum shear reinforcement and the steel fiber content is 1.5–2%, the failure type is changed to a gradual flexure failure.

4.6 Crack width

The crack width was measured by using the crack meter. Due to the lack of RSF reinforcement to prevent the spread of its cracks, the control beam specimens' (cont.1 and cont.2) crack width increased more than the other strengthened beams. And in all beams, the first crack started at the bottom of the mid-span and grew upward or changed to a diagonal crack. The results of the crack width are shown in Table 7.

1. Shear crack width: Shear cracking is a load that first becomes noticeable in the shear span as an inclined diagonal tension crack. Crack distribution and propagation during loading have been studied. Throughout the test, the width of the first crack was measured as the load increased and continued until the models of the beams were about to fail. Before the final failure, the width of the cracks in the case without stirrups was reduced from 1.2–1 mm by the addition of RSF of 2%. In the presence of stirrups with RSF of 1%, the width of the crack reduced from 0.7–0.5 mm, as shown in Figures 9 and 10.
2. Flexure crack width: Cracks begin to appear gradually and grow in number and width until the final failure, when only the bending cracks remain, and no diagonal cracks

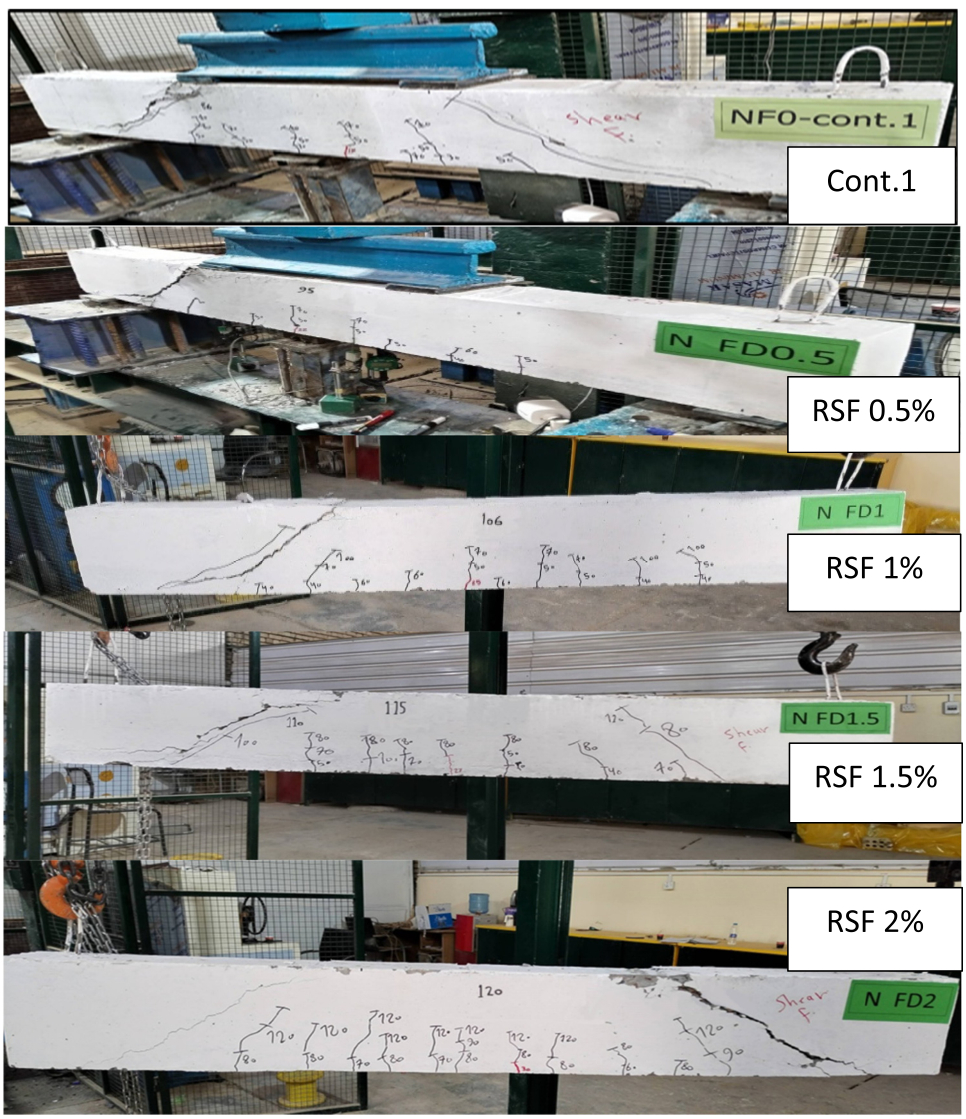

Figure 9: Crack pattern and failure modes of beams without stirrup.

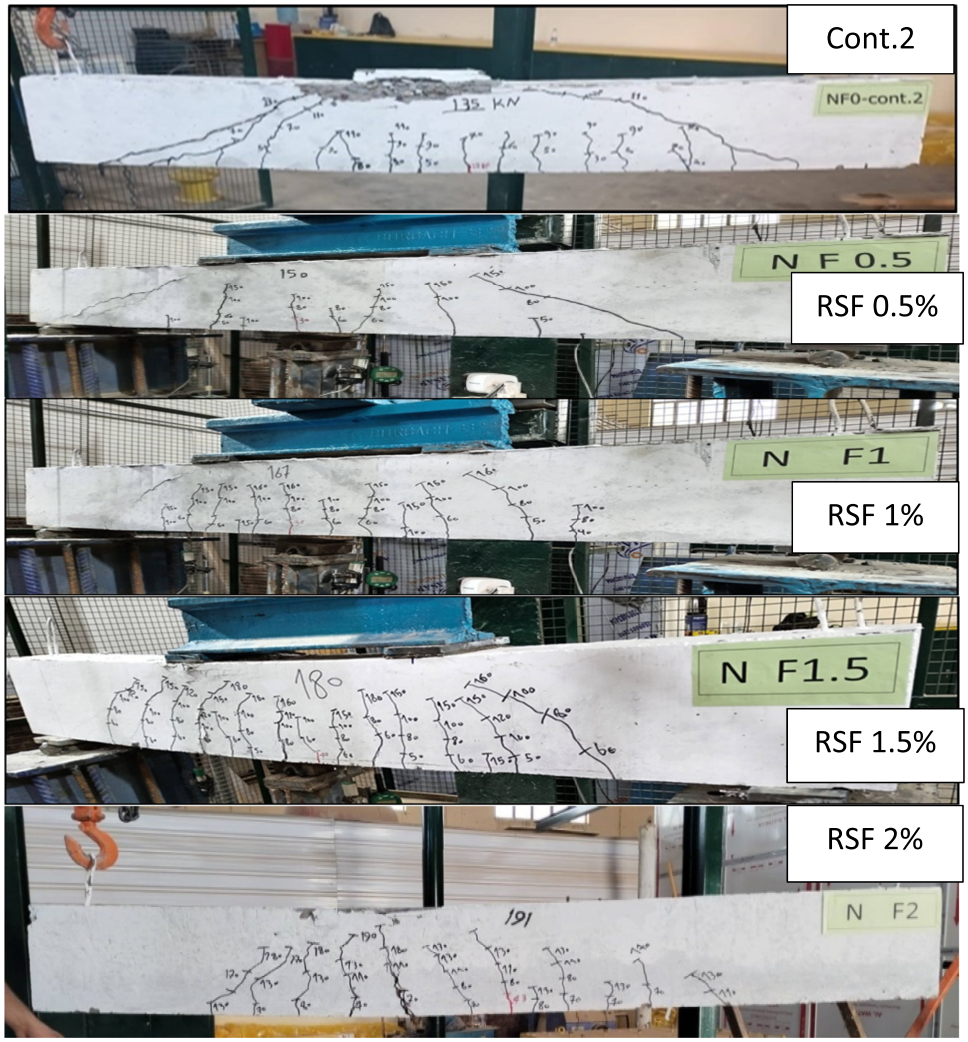

Figure 10: Crack pattern and failure modes of beams with stirrup.

appear, Table 7 and Figure 10. The increased amount of steel fibers decreased the crack width when using stirrups with the highest limit. In the presence of steel fibers (RSF = 2%), the width of the crack reduced from shear crack width of 0.7 mm to flexure crack width of 0.4 mm.

5 Conclusion

1. In The mixtures containing RSF, there is a loss in workability which must be compensated by increasing the proportion of cement and water, and the proper preparation of the mixtures is very important. Hence many experimental mixtures were made, and several factors, such as fiber length, amount of steel fibers, maximum size of aggregate, amount of cement, and water were varied to achieve a good mixture and to understand the contribution of the fibers to the resistance of normal strength concrete.
2. By testing the strength of concrete, it became apparent that when steel fibers were used, the strength of concrete (compressive, tensile, and flexural) increased by 11, 38.9, and 48.5%, respectively, due to the presence of steel fibers of 2%. By comparing the results obtained with the results of previous studies, it is noticed that there is a convergence.
3. The presence of steel fiber made the beams stiffer to resist M_{cr}, which is why the value of M_{cr} for beams made with steel fiber is greater than other beams.
4. The shear resistance increases when RSFs are added to the beam in variable ratios without using stirrups, but the beam does not reach the ductility stage.
5. The shear strength is increased better by adding RSF with ratio 2% and using the least amount of stirrups,

in which the contribution by steel fibers was only 41.4%, and the contribution of steel fibers with stirrup together was 122%, when compared with the control beam. Also, the failure turned from shear failure into a gradual flexural with a significant increase in the ductility of the beam. By comparing the results obtained with that of previous studies and equations, it is noticed that there is a convergence.
6. The beams containing RSF, with the least amount of stirrups, have maximum deflection values greater than those without steel fiber and lesser cracking deflection. The presence of steel fibers in the samples made the concrete more flexible to resist the loads, so the percentage of ductility ratio increased by about 50.3%. The crack width decreased by 42.8% due to the addition of steel fibers at the optimal ratio of 2%, compared with the reference beam.
7. The best percentage of RSF that can be used for good workability were determined to be 2% of the total concrete weight by testing the properties of hardened concrete and strengthening of beams for shear capacity.

6 Recommendations

The steel fibers recycled from tires can be used to strengthen reinforced concrete beams to be resistant to shear and reduce the amount of transverse reinforcing steel (stirrups). Because recycling helps reduce energy use and air and water pollution (in landfilling), this type of RSF obtained from tires can be used in future projects as an alternative, which protects and preserves the environment compared to traditional waste disposal. To preserve the environment and save money, the government and businesses must support and assist in achieving and obtaining the recycling program's aforementioned benefits and conduct more research in this field.

Acknowledgements: Thanks to all the staffs of Civil Engineering Department, College of Engineering, University of Kufa, for their facilities and assistance throughout this study.

Conflict of interest: The authors state no conflict of interest.

Data availability statement: Most datasets generated and analyzed in this study are in this submitted manuscript. The other datasets are available on reasonable request from the corresponding author with the attached information.

Statements and declarations: We declare that the manuscript was done by the personal effort of the authors, and there is no funding effort from any organization, as well as no conflict of interest with anyone related to the subject of the manuscript or any competing interest.

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