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ORIGINAL ARTICLE

Transforming waste into strength with recycled tire steel fibers for superior concrete performance

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Abstract: Despite extensive research on using waste tire fibers in concrete, a detailed examination of flexural toughness, impact resistance, and optimized fiber dosage for applications in high-stress industrial floors and slabs remains limited. This study uniquely focuses on maximizing these properties by varying waste tire steel fiber content to determine the ideal mix for enhanced performance in concrete, providing a sustainable alternative to conventional steel fibers. The fibers' diameter was 0.82mm and length was equal to 50 mm with an aspect ratio of 61. A design mix with compressive strength equal to 25-30 MPa at different dosages of fibers i.e., 0.5%, 1%, and 1.5% by volume of concrete was prepared and results were compared with control concrete samples for applicability in slabs on grade and industrial floors. Workability was reduced by fiber addition, but SP was adjusted to achieve the target slump. Split tensile strength, compressive strength, and flexure strength were improved with maximum values at 1.5% fiber content. Post-peak behavior and toughness were significantly improved by adding fibers. Impact resistance results were also promising for the first crack and ultimate failure.

Keywords: Recycled tires, waste, sustainable, concrete, fibers

1 Introduction

Concrete is a major part of construction in any part of the world, till 2001, around 76 million m^3 of concrete was produced annually. Since concrete tensile strength is very low and it possesses very low ductility. Conventionally, reinforcement in the form of continuous steel bars is placed in concrete in the appropriate positions to withstand the tensile and shear stresses [1]. Reinforced cement concrete (RCC) is developed to increase the tensile strength of concrete but the problems like cracks within structures [2], their propagation [3], and ductility [4] are still under consideration. To achieve improved properties like toughness, ductility, energy absorption, cracking control, etc. reinforcement must be distributed throughout the cross-section hence, short, discrete fibers of small diameter either metallic or non-metallic are added in concrete. Various types of fibers i.e. glass fibers [5], synthetic fibers [6], natural fibers [7] and metallic fibers [8] are added to concrete but steel fibers [9] have greater potential to overcome the problems. The main purpose of steel fibers to be used in floors is to minimize visible cracking, increase shear strength and fatigue strength endurance, and to improve post crack flexure toughness and impact resistance [10]. Fiber reinforced concrete has vast structural applications i.e., slabs on grade [11], tunnels lining [12], canal linings [13], industrial floors [14], highway and bridges applications [15], shotcrete [16], and precast members [17], etc.

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The application of steel fiber reinforced concrete for industrial floors and slabs on grade is advantageous because these floors are subjected to cyclic and impact loading hence require sufficient energy absorption capacity which can be achieved by steel fiber reinforced concrete [18]. In recent years, research work for the replacement of steel fibers with waste tire steel fibers is in the process because waste tires have been a major issue [19,20]. Every year, out of 1.6 billion tires, 1 billion tires are converted to waste. Out of which, only 100 million are recycled (GTRIA, 2017-2030). The disposal of waste tires is a great concern to prevent environmental problems because tires occupy a large space, and when dumped underground, at times, rise to the surface creating waste problems and are also a major source of dengue larvae production within its empty spaces causing danger to human health as well in addition to environment. Dumping of tires requires a large area of landfill because the major portion of tires consists of voids while burning the tires adds to air pollution. In Pakistan, waste tires play a major role in environmental pollution in the way that these are either dumped in a large landfill area or utilized in brick manufacturing plants to get tire-derived fuel. Waste tires contain valuable materials like rubber & steel which can be used in different aspects one being the strengthening of structures [21]. Various methods to recycle waste tires include shredding, cryogenic process, and pyrolysis [21,22]. There is major research on concrete containing rubber crumb but steel extracted from waste tires is not utilized for new material production. Since, the steel present in waste tires is rich in tensile strength and possesses similar properties to industrial steel fibers, so waste tires’ steel fibers can be added to concrete to improve the mechanical properties of concrete [23]. It can also reduce the wastage of tire’s steel for sustainable construction.

Researchers now a days are working on the addition of waste tire steel fibers as a replacement of industrial steel fibers in concrete. It helps prevent environmental damages introduced due to disposal of waste tires and also an economical replacement of conventional steel fibers with almost comparable behavior of concrete in terms of its mechanical properties. Numerous researchers have used waste tire steel fibers in concrete to investigate its fresh & hardened state properties [24–28]. These researches mainly focus on the incorporation of waste tire fibers replacing industrial steel fibers to obtain mechanical properties of concrete within range of those obtained using industrial steel fibers. In a recent study by [29], compressive strength, flexure toughness and split tensile strength of waste tire fibers reinforced concrete were investigated. It was proposed that the mechanical properties of concrete with 1.2-3.6 % fibers content improved greatly. In comparison with industrial steel fibers at a dosage of 0.5-2.5 % content by volume, tensile strength of concrete at 2.25% recycled fibers & 0.98% industrial steel fibers content was increased from 5 MPa to 6.5 MPa. To have similar split tensile strength, waste tire steel fibers should be 0.9-1.3 % higher and for flexure strength, its increment should be 1.1-1.7 % and 1-2 % increase in fiber content to achieve similar toughness.

Sengul, 2016 carried out his research on the mechanical behavior of concrete reinforced with waste tire steel fibers [30]. Waste tire fibers with different diameters of 0.3, 0.6 & 1.4 mm and average length equal to 50 mm were added to concrete. Results were compared with commercial steel fibers of 0.9 mm in diameter and 60 mm in length. The addition of scrap tire fibers affected compressive strength negligibly with the increase of 6 MPa, 3.8 MPa increase of flexure strength and 2.3 MPa increase in split tensile strength at 40 kg/m^3 content of 0.6 mm diameter fibers but toughness and residual strength were greatly modified with waste steel fiber reinforced concrete. Samarakoon et al., 2019 tested mechanical behavior and flexural performance of concrete beams with recycled steel fibers as reinforcement and related the results with industrial steel fibers at 0, 0.5 & 1% fibers by volume of concrete [31]. Fibers’ average aspect ratio was 100±37.47 and fibers were extracted using pyrolysis process. Results showed that tensile and compressive strength increased gradually upon increasing the fibers content but recycled fibers gave comparatively lower results than industrial steel fibers. Beams with fiber reinforcement failed at maximum load slightly lesser than plain concrete but mid-span deflection was increased with fiber addition. Hu et al., 2018 conducted research on the mechanical performance of concrete by adding tire steel fibers as reinforcement material in a hybrid mix with manufactured steel fibers 32]. It was concluded that both fibers do not affect compressive strength and modulus of elasticity but tire steel fibers proved to be effective in controlling micro cracks. Further, it was proposed that in a hybrid mixture, 10 kg/m^3 of tire fibers in a total fiber dosage of 30 & 45 kg/m^3 gave significant results. Flexural behavior of prisms and round panels was also reported. In another study, direct tensile strength and single fiber pull out, compressive strength, cube strength and flexure strength using scrap steel fibers alone as well in mix with tire cords dosage of 30 kg/m^3 and 45 kg/m^3 were tested while comparing results with conventional steel fibers. Results showed that tire cords could be more effective in the post crack strength and controlling the widths of micro cracks and macro cracks than manufactured steel fibers. Results obtained from recycled tire fiber and industrial steel fibers were comparable [32].

While previous studies explored waste tire steel fibers in general concrete applications, there is insufficient focus on achieving a balance of mechanical properties for high-stress environments, particularly on industrial floors and slabs where flexural toughness and impact resistance are critical. This study addresses this gap by evaluating and optimizing fiber dosage to provide specific performance improvements in these demanding applications, distinguishing it from prior research focused primarily on general concrete performance. Thus, the main objective of this study is to investigate the mechanical properties of concrete reinforced with recycled tire steel fibers (WTSF). By evaluating the effects of different dosages of *WTSF* on compressive strength, tensile strength, flexural strength, and impact resistance. Furthermore, the study introduces a novel approach by incorporating recycled steel fibers extracted from waste tires into concrete, offering an eco-friendly and cost-effective alternative to conventional steel fibers. Unlike previous research that primarily focused on rubber from waste tires, this research emphasizes the potential of tire steel fibers to significantly improve flexural toughness, impact resistance, and overall durability of concrete. The use of WTSF provides a sustainable solution to the disposal of waste tires, addressing both environmental challenges and material efficiency in construction.

2 Materials and Mixture Design

2.1 Materials

Table 1. Chemical composition of cement

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Loss on ignition (L.O.I)
21	5.04	3.24	61.7	2.56	1.51	1.83

Fig. 1. Process of extraction of steel fibers from waste tires

Cement used in current study was locally available Ordinary Portland cement (OPC). The chemical composition of cement used is given in **Table 1.** A well graded fine sand locally known as "Lawrencepur sand" was used as fine aggregates with fineness modulus of 2.51, water absorption equal to 1.01, and specific gravity of 2.55. Well graded coarse aggregate locally known as "Margalla crush" was sued as coarse aggregates with maximum size of 12.5 mm, fineness modulus equal to 3.94 with water absorption of 0.722, and specific gravity equal to 2.66. Ultra-super plast SP-470 was added in the concrete to minimize the loss of workability upon fiber addition. The physical appearance of the admixture was brown colored liquid with specific gravity equal to 1.155.

Steel fibers used in this study were straight fibers having a diameter equal to 0.82 mm. The steel fibers were obtained by separating the steel from rubber contained in waste tires and then wires were cut into fibers of required length. The process of extraction of steel fibers from waste tires is illustrated in **Fig. 1**. To keep the aspect ratio within the range of 21-100 as specified by [33], length of the fibers was kept equal to 50 mm with aspect ratio equal to 61 and ultimate tensile strength equal to 1428 MPa.

2.2 Mixture Design

As per [10] (ACI 302.1 R-04), for industrial floors and slabs on grade, the slump value is specified equal to 100-125 mm and compressive strength equal to 25-30 MPa. Hence mix design was prepared based upon these target slump and compressive strength. The ratio of mix design was kept equal to 1:1.8:2.5 and water to cement ratio was kept equal to 0.5. Dosage of waste tire steel fibers used was 0.5%, 1% & 1.5% by volume of concrete. The details of mix design is given in **Table 2**. Overall, four different mixes were prepared at various fiber dosage in this study.

Table 2. Details of mix design

Mix #	Mix Designation	Cement	Fine Aggregates	Coarse Aggregates	Water	Waste Tire Steel Fibers	Super Plasticizer
		Kg/m^3	Kg/m^3	Kg/m^3	liter	Kg/m^3	Lit/m^3
1	Control Mix	399	720	1025	199	0	--
2	WTSF-0.5					39.3	1.56
3	WTSF-1					78.6	3.12
4	WTSF-1.5					118	4

Where, WTSF = Waste Tire Steel Fiber

2.2.1 Mixing Procedure

The process of mixing is shown in **Fig. 2**. In the process of mixing the constituents, coarse aggregates, cement and fine aggregates were added to the mixer and mixed for one minute. Then, fibers were added with the help of a sieve to avoid balling effect of fibers into the mixer following the addition of two third of water and mixing was carried out for two more minutes. Remaining water along with the superplasticizer was added and mixing ceased within 4 to 5 minutes. The detailed mixing procedure is illustrated in **Fig. 2**. Slump test was performed to evaluate the workability of the mix and then molds of required size were filled with the mix followed by external vibration. Then, samples were placed under curing at 14 and 28 days and tested for evaluation of mechanical properties of concrete.

Fig. 2. Procedure of mix preparation

3 Results and Discussion

3.1 Slump Test

Slump tests were performed to check the workability of fiber reinforced concrete. The results show that workability was reduced upon increasing the fiber content, but amount of admixture was adjusted to control the slump value. Graphical representation of slump test for all the mixes and target slump is presented in **Fig. 3**. It was observed that control mix gained the required workability i.e. 125 mm without any admixture but upon addition of fibers, for *WTSF*=0.5%, 1% & 1.5% mixes, relative amount of super plasticizer by weight of cement was 0.5%, 1% & 1.5% to gain the required slump. A mix with 2% fiber dosage was also tested for slump but it gave 50 mm slump value. So, fiber dosage was limited to 1.5%. The decreasing slump values and increased amount of super plasticizers with increasing the amount of fibers shows that due to presence of uniformly distributed fibers within the mix, flow of the mix becomes difficult resulting in lower slump value but it can be controlled by adding the admixture.

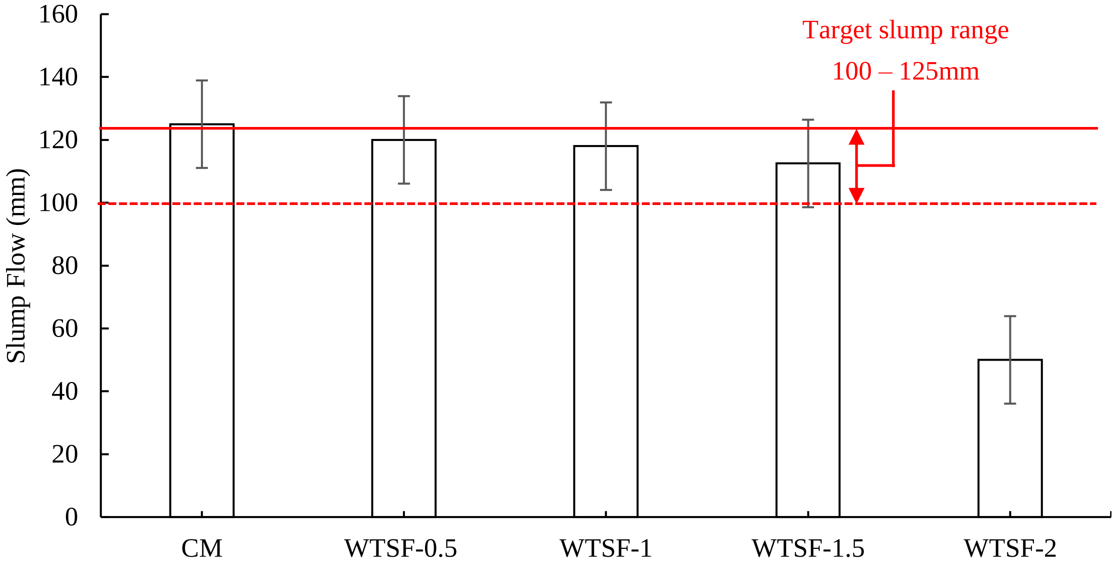


Fig. 3. Slump test results for different mixes

3.2 Compressive Strength

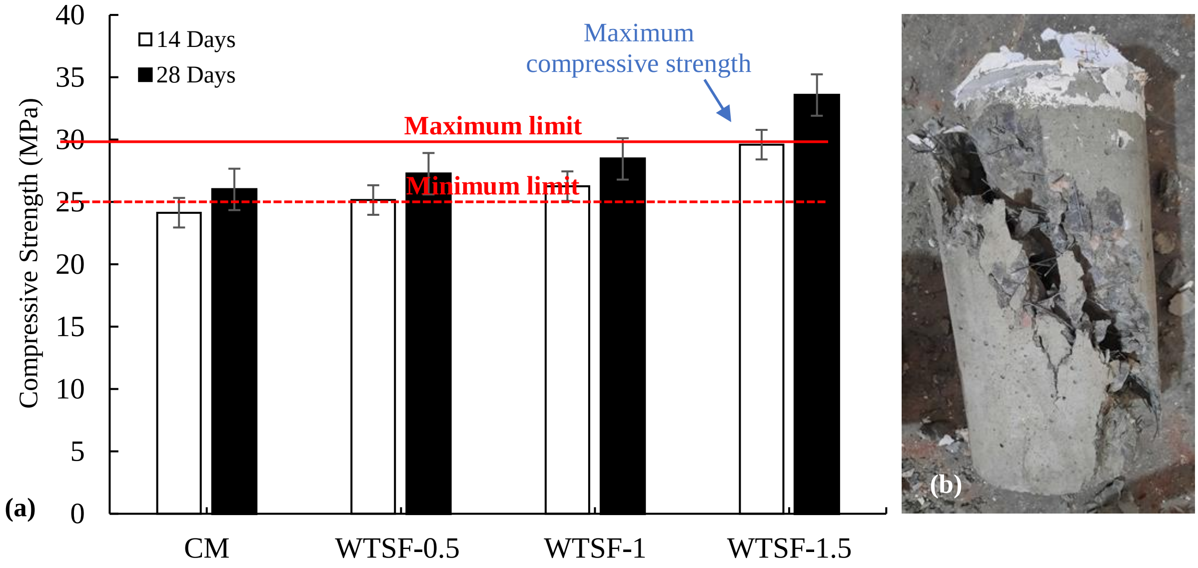


Fig. 4. (a) Results of compressive strength for all the mixes, (b) Crushed specimen

Compressive strength tests were performed as per ASTM C39 [34] on fiber reinforced concrete (FRC) specimens [35] (ACI 544.2R, 1989). Cylinders of 150 × 300 mm size at 14 and 28 days after casting and curing were tested and mean value of three specimens was taken as compressive strength of that nominal mix. The results show that adding the fibers improved the compressive strength. Graphical representation of compressive strength for all the mixes is presented in **Fig. 4**. At 14 days, strength increased from 24 MPa for control mix to 25 MPa for *WTSF*=0.5% mix, 26.3 MPa for *WTSF*=1% mix and 29.6 MPa for *WTSF*=1.5% mix. Similarly, at 28 days, strength increased from 26 MPa for control mix to 27 MPa for *WTSF*=0.5% mix, 28.5 MPa for *WTSF*=1% mix and 33.58 MPa for *WTSF*=1.5% mix. Hence, fibers addition resulted in improved strength, but the gain was almost insignificant i.e. 4.6% and 8.6% at 0.5% & 1% fiber content respectively but maximum improvement of 23% was observed at 1.5% fiber content because fibers provide binding effect to the concrete and result in improved compressive strength.

3.3 Modulus of Elasticity

Modulus of elasticity was determined as per ASTM C469 [37] where extensor meter cage equipped with strain gauges was used to record the axial deformation in concrete cylinders. From the stress-strain graph, by using Eq. 1, values of chord modulus of elasticity were calculated for all the mixes.

$$E = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - 0.00005} \quad \textbf{(1)}$$

Where;

E= Chord Modulus of Elasticity

σ_2= Stress w.r.t 40% of ultimate load

σ_1= Stress w.r.t. longitudinal strain of 50×10^{-6}m/m

$\varepsilon_2 =$ Longitudinal strain produces by σ_2

The Chord Modulus of Elasticity for control mix was 17800 MPa, and for other mixes i.e. *WTSF*=0.5%, *WTSF*=1%, and *WTSF*=1.5% it was 20200 MPa, 21600 MPa, and 24000 MPa respectively. Graphical representation of modulus of elasticity test is displayed in **Fig. 5**. Fibers addition improves the modulus of elasticity of concrete in similar manner as compressive strength with 30% improvement at 1.5% fiber content.

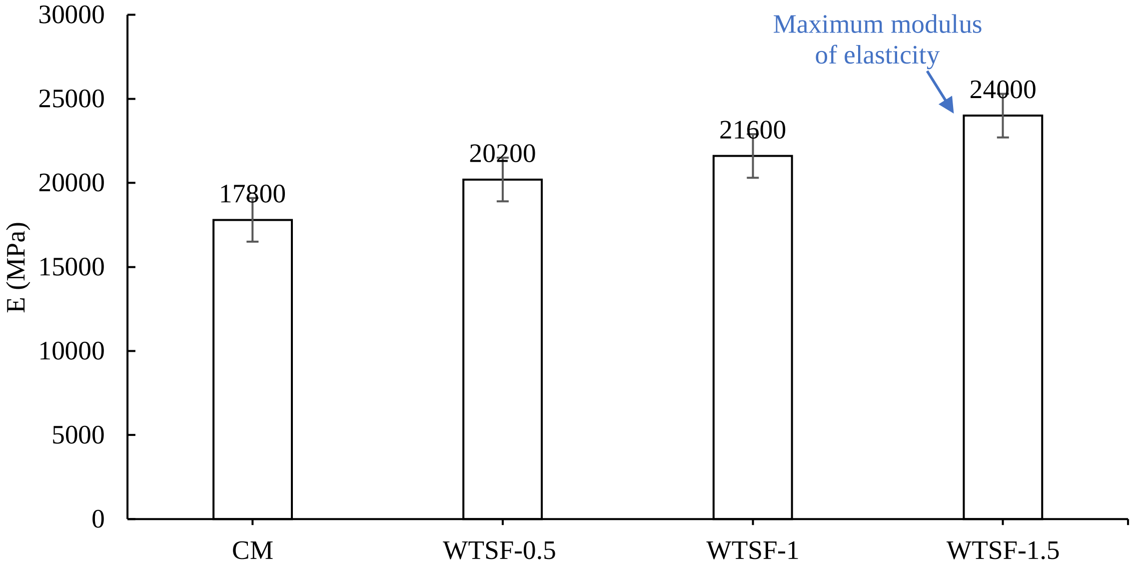
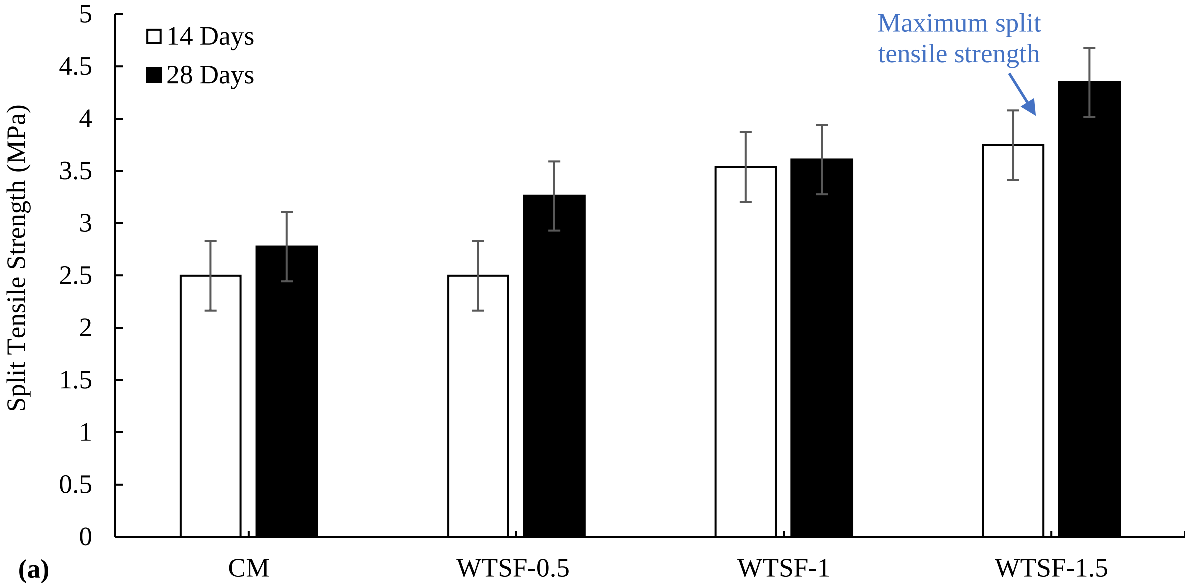


Fig. 5. Results of modulus of elasticity for all the mixes

3.4 Split Tensile Strength

Cylinders having size of 150 × 300 mm were tested for split tensile strength following ASTM C496 [38] guidelines. It was observed that the split tensile strength gradually improved by increasing the fiber content. From **Fig. 6**, it can be observed that at 14 days, split tensile strength increased from 2.5 MPa for control mix to 2.5 MPa for *WTSF*=0.5% mix, 3.54 MPa for *WTSF*=1% mix and 3.75 MPa for *WTSF*=1.5% mix with 0%, 29% & 33.4% gain respectively. Similarly, at 28 days, strength increased from 2.77 MPa for control mix to 3.26 MPa for *WTSF*=0.5% mix, 3.61 MPa for *WTSF*=1% mix and 4.35 MPa for *WTSF*=1.5% mix with percentage improvement of 14.9%, 23.1% & 36.2% respectively with respect to the control mix. Out of all mixes, maximum improvement was observed for 1.5% waste tire steel fibers content. Hence, addition of fibers in plain concrete overcome the problem of low tensile strength and it can be improved to a certain extent because presence of fibers prevents the crack opening and propagation along fracture plane.



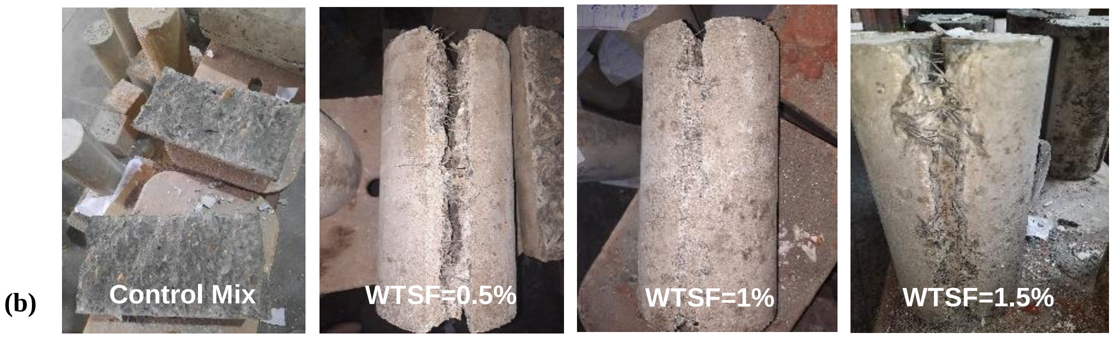


Fig. 6. (a) Results of split tensile strength for all the mixes, (b) Crushed specimen

3.5 Flexure Strength

Fig. 7. Three point loading arrangement

Prisms of 150 × 150 × 500 mm size were tested for determination of flexural strength as per ASTM C 78M using third point loading maintaining constant rate of loading equal to 0.8-1.2 MPa/min without any shock. **Fig. 7** represents loading arrangements for testing the specimen.

At 14 days, strength increased from 4.11 MPa for control mix to 4.38 MPa for *WTSF*=0.5% mix, 4.82 MPa for *WTSF*=1% mix and 5.51 MPa for *WTSF*=1.5% mix with 6%, 14.8% & 25.5% gain respectively. Similarly, at 28 days, strength increased from 4.58 MPa for control mix to 4.64 MPa for *WTSF*=0.5% mix, 5.17 MPa for *WTSF*=1% mix and 5.88 MPa for *WTSF*=1.5% mix with 1.2%, 11% & 22% gain respectively. The graphical representation of the results for all the mixes is given in **Fig. 8.** It is evident that the results of control mix are comparable to the *WTSF*=0.5% mix at 14 & 28 days with only a slight increase of almost 14% but the mix with 1.5% fiber dosage provides significant improvement of 25% at 14 days and 22% at 28 days. The **Fig. 9** gives the effect of fibers addition on flexure strength.

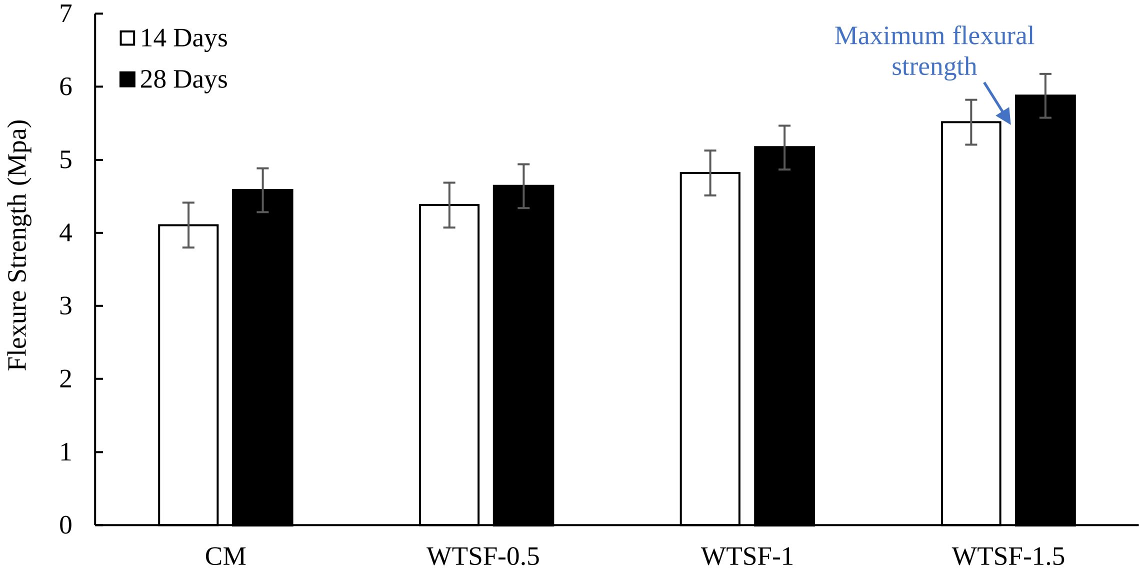


Fig. 8. Results of flexure strength for all the mixes

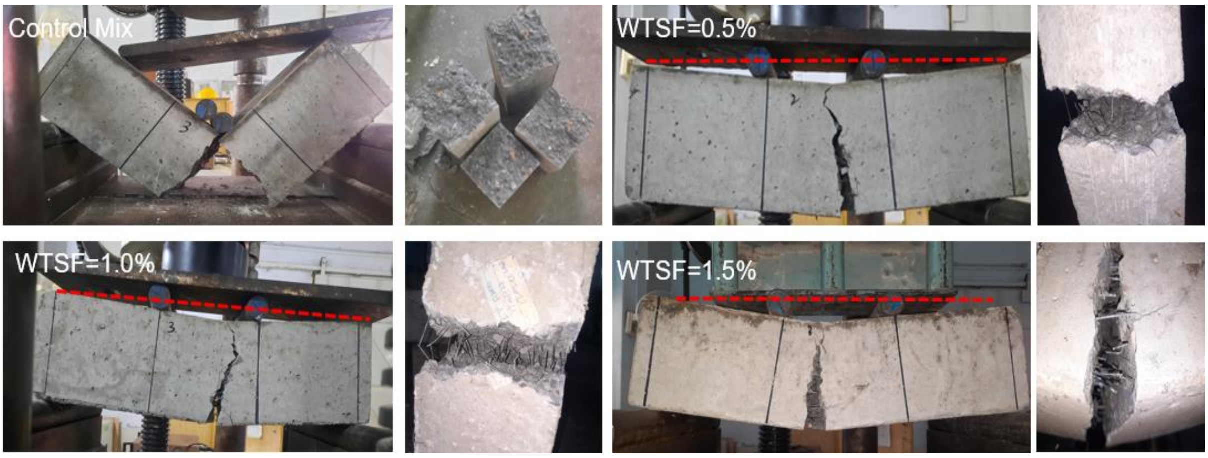


Fig. 9. Cracked specimens

3.6 Flexure Toughness

The toughness test was performed using three different standards i.e. ASTM C 1609-10, ASTM C 1018 &JSCE SF4. Energy absorption up to failure was calculated under flexure loading. As fibers play significant part in crack controlling and propagation of the cracks, hence significant toughness can be achieved by adding fibers. The behavior of samples of fiber reinforced mix and control mix under flexure loading is given in **Fig. 10** at different stages. It was observed that samples of control mix undergone sudden failure after attaining peak load while other mixes with fiber reinforcement shoed maximum crack opening and deflection without breaking. The fibers were pulled out of the matrix upon continuous application of load rather than breaking. The flexural toughness for all the mixes was calculated using different standards i.e. ASTM C1609, ASTM C1018 & JSCE SF-4. The samples were tested to get load deflection curve under third point loading. The parameters stated in different standards were then obtained from manipulation of load-deflection curve mainly specifying toughness as area under load-deflection curve up to a deflection limit of Span/150.

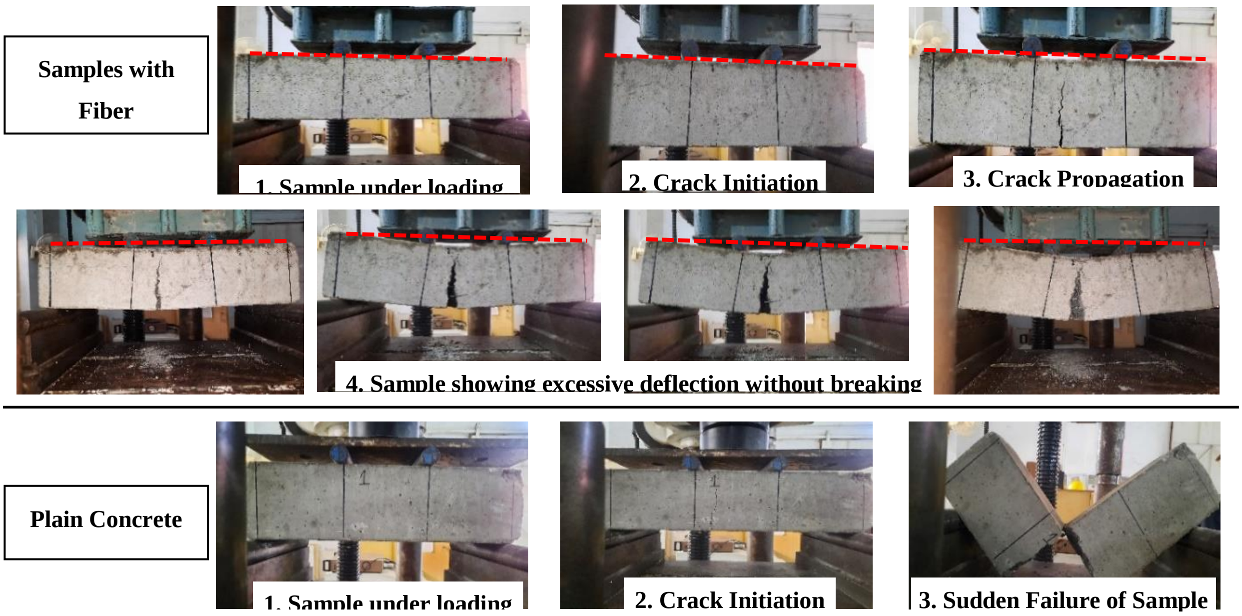


Fig. 10. Behavior of Samples under Flexure Loading

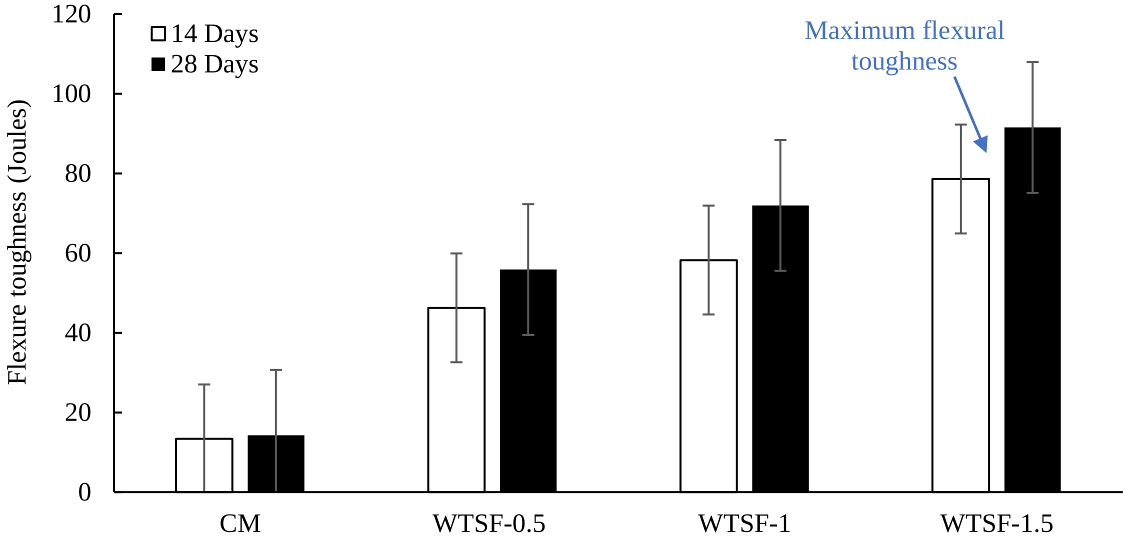


Fig. 11. 14 & 28 days results of flexure toughness

Flexural toughness of fiber reinforced concrete is significantly enhanced as compared to plain concrete. At 14 days, strength increased from 13.36 Joules for control mix to 46.26 Joules for *WTSF*=0.5% mix, 58.25 Joules for *WTSF*=1% mix and 78.59 Joules for *WTSF*=1.5% mix with 71.1%, 77.1% & 83% gain respectively. Similarly, at 28 days, strength increased from 14.25 Joules for control mix to 55.86 Joules for *WTSF*=0.5% mix, 71.96 Joules for *WTSF*=1% mix & 91.5 Joules for *WTSF*=1.5% mix with 75%, 80% & 84% gain respectively. Graphical representation of flexural toughness for all mixes is shown in **Fig. 11.**

The test results indicate that flexural toughness of plain concrete is very low and fiber addition increases the toughness significantly with maximum improvement observed at 1.5% fiber dosage. It was also observed that fibers exhibit significant tensile strength resulting in pull out failure rather than breaking during toughness test. Load deflection curve for different mixes at 14 & 28 days is shown in

Fig. 12 and **Fig. 13.** It is evident from the load deflection curve that plain concrete samples resulted in sudden drop after the peak load while the samples with fibers have shown excessive deformation. During the crack opening, fibers were pulled out of the concrete rather than breaking. At 1.5% fiber dosage, the samples shows maximum peak load and gives maximum improvement in the toughness.

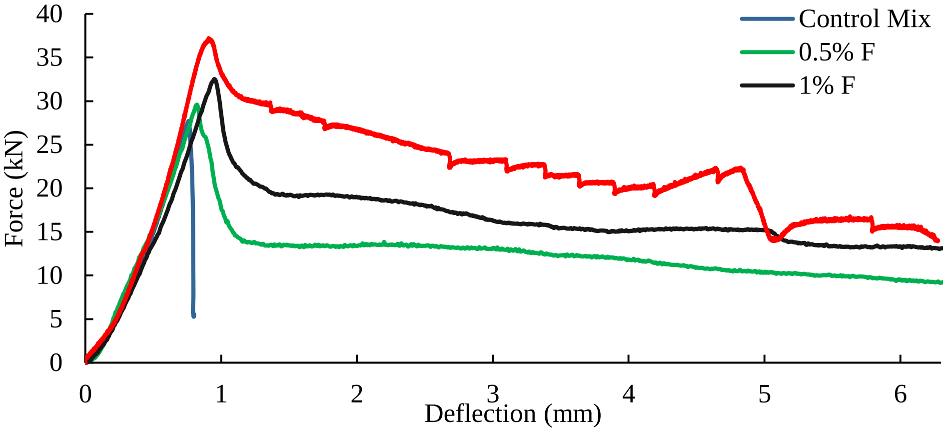


Fig. 12. Load deflection curve at 14 days

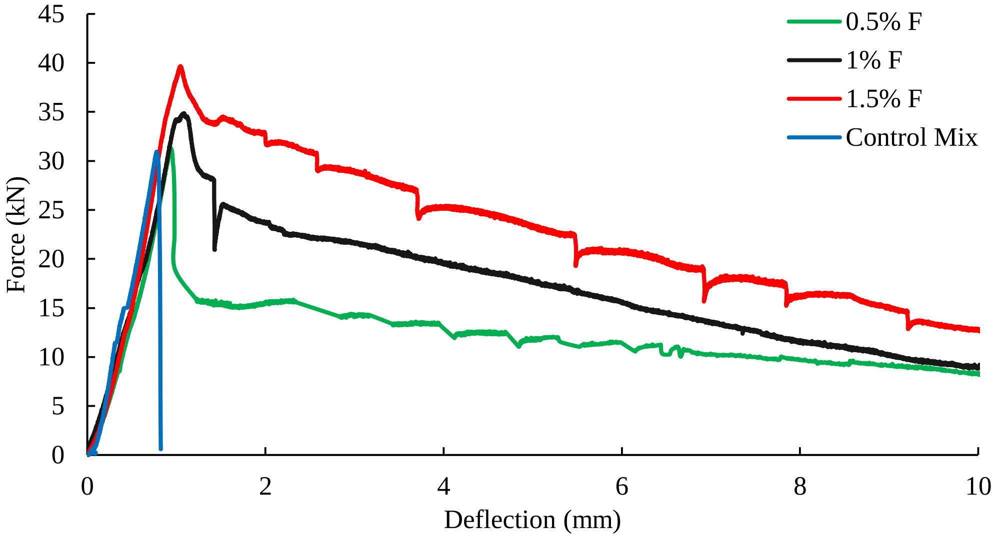


Fig. 13. Load deflection curve at 28 days

i. ASTM C-1018

As per ASTM C 1018, toughness indices I_5, I_{10}, I_{20}, I_{30}, I_{40}, I_{50} etc. were assessed by dividing the area up to a deflection of 3, 5.5, 10.5, 15.5, 20.5, 25.5 times the first crack deflection by the area up to first crack, respectively. Additionally, the residual strength factors represent the remaining strength in fiber reinforced concrete derived from the toughness indices. The residual strength factors are determined as $R_{5,10}= 20(I_{10}-I_5)$, $R_{10,20}= 10(I_{20}-I_{10})$, $R_{20,30}= 10(I_{30}-I_{20})$, $R_{30,50}= 5(I_{50}-I_{30})$, and $R_{10,50}= 2.5(I_{50}-I_{10})$ etc. (A.Jihad et al., 2019).The point where curvature of load deflection curve increases sharply followed by visible change in its slope is the first crack point. Because of such a subjective definition, the location of first crack point may vary from person to person. In this study, the first crack point was examined visually from the load deflection curve and located on it. Energy absorption up to first crack point i.e. δ_{FC} and a multiple of the first crack points i.e. $3\delta_{FC}$ and $5.5\delta_{FC}$ were estimated from area under curve up to specified deflections and toughness indices I_5, I_{10} & I_{20} were calculated as given in **Table 3**.

Table 3. Results of toughness test as per ASTM C 1018

Mix Designation	P (1st crack load)	First Crack (δ_{FC}) Location (mm)	Energy Absorption (Joules)				Toughness Indices			R5,10	R10,20
			δ	3δ	5.5δ	10.5δ	I5	I10	I20		
Control Mix	29.72	0.55	10.22	15.34	20.87	50.24	1.50	2.04		0.54	
WTSF=0.5%	28.9	0.76	15.23	43.18	73.49	106.8	2.83	4.82	7.01	1.99	2.19
WTSF=1%	29.75	0.81	13.44	52	94.35	150	3.86	7.01	11.14	3.14	4.13
WTSF=1.5%	34.3	0.61	11.86	45.39	91.71	157	3.83	7.73	13.24	3.9	5.5

It can be observed that toughness indices gradually increase by increasing fiber content with respect to the control mix. However, parameters obtained vary because of definition of first crack point and often load deflection curve lack a distinct point because of micro cracks and occurrence of subsequent multiple cracks prior to the peak load.

ii. ASTM C-1609

As per ASTM C 1609-10, the beam specimens of size 150 × 150 × 500 mm and tested in third-point loading arrangement following ASTM C 78 procedure. First-peak load, and residual loads at stated deflections are marked to calculate various parameters from load deflection curve. T_D^{150} is calculated as area under the load-deflection curve up to a deflection limit of Span⁄150. This standard specifies the deflections as L/600 & L/150 and loads and toughness values are calculated at these specified deflections form load deflection curve as listed in **Table 4**.

Table 4. Results of toughness test using ASTM C1609

Mix Designation	Ppeak	PD600	PD150	f peak	fD600	fD150	TD600	TD150
Control Mix	30.93	0.437	0.312	4.58	2.15	1.53	12.87	14.25
WTSF=0.5%	31.3	26.65	9.12	4.63	3.94	1.35	14.5	55.86
WTSF=1%	34.87	22.46	21.25	5.16	4.33	4.1	9.69	71.95
WTSF=1.5%	39.65	32.09	27.75	5.87	3.83	3.31	11.01	91.52

The results show that control mix gives minimum values of peak load and toughness at corresponding deflections because the samples break suddenly without certain deflections. The values of peak loads and toughness improve by increasing fiber dosage. It can also be observed that the deflection limit of L/600 achieved before the curve reaches the peak load and then drops gradually with a certain increase in deflection and hence load values at L/600 are lower than peak loads and load values are further reduced at deflection limit of L/150. But toughness increases significantly because area covered under load deflection curve is more at L/150.

iii. JSCE SF-4

Table 5. Results of toughness test using JSCE SF-4.

Mix Designation	Flexural Strength (σb)	Δtb	Flexural Toughness (Tb)	Flexural Toughness Factor (σb)
Control Mix	4.58	0.333	14.25	0.000634
WTSF=0.5%	4.63	0.333	55.86	0.00248
WTSF=1%	5.16	0.333	71.95	0.00319
WTSF=1.5%	5.87	0.333	91.52	0.00406

As per [40] (JSCE SF4, 2005), area under the load-deflection curve up to a specified deflection of L/150 mm is termed as toughness. JSCE SF-4 gives relatively simple toughness results as compared to American codes. Only maximum deflection limit of L/150 is specified and corresponding flexural strength and toughness are calculated, and results specified in this standard are given in **Table 5**.

As evident from the results, flexural strength and toughness values are lowest for the control mix and increase with fiber dosage. Both flexure and toughness values are maximum for *WTSF*=1.5% mix and similar trend is observed for flexure toughness factor.

3.7 Impact Resistance

Impact resistance is given as number of blows applied to obtain a specified size of distress i.e. scab/perforation/crater. Various methods are available to govern the impact resistance of FRC and most common method is drop weight test. Test is carried out as per ACI 544.2R-89. Test samples with thickness of 63.5 mm and 152 mm dimeter are prepared in the molds. At specified level of distress, the number of blows represents a qualitative measure of energy absorption (ACI 544.2R, 1989). This test was performed at 28 days and results were presented as energy absorbed by the sample in the form of initial crack and final failure. Number of blows at the stage when first crack appeared on the concrete surface and a pin needle could be inserted and the stage when final failure corresponds to the disintegration of samples into parts were calculated. **Fig. 14** shows graphical representation of impact resistance of average of all the mixes.

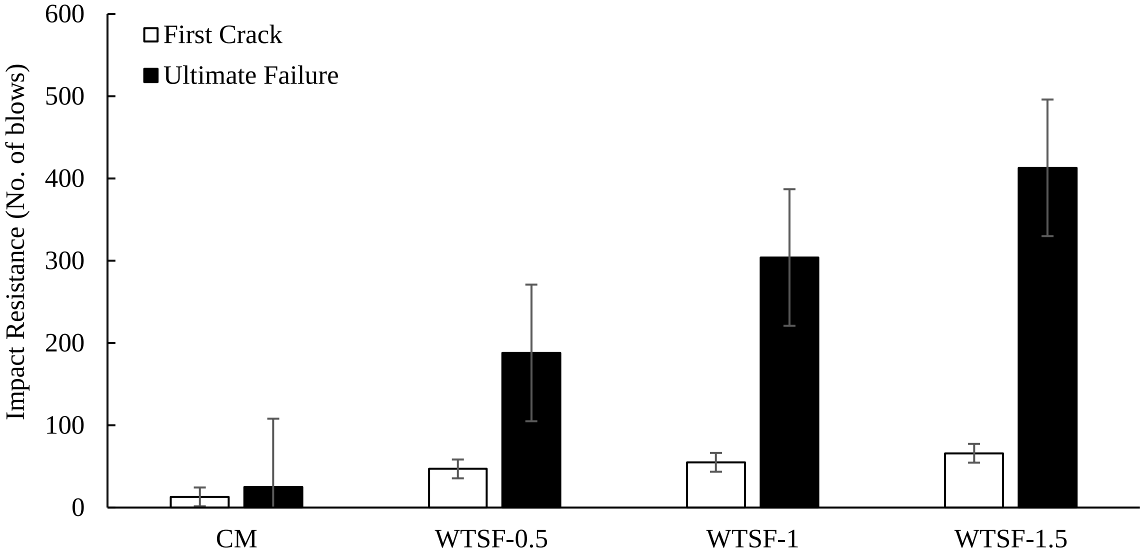


Fig. 14. Average impact resistance for all the mixes

It is clear from the figure that only 13 blows were required for the first crack to appear on the sample of control mix while the number of blows increased from 13 to 47 for *WTSF*=0.5%, 55 for *WTSF*=1% & 66 for *WTSF*=1.5%. Similarly, the ultimate failure occurred at just 25 blows for control mix, 188 number of blows for *WTSF*=0.5%, 304 number of blows for *WTSF*=1% & 413 number of blows for *WTSF*=1.5%.

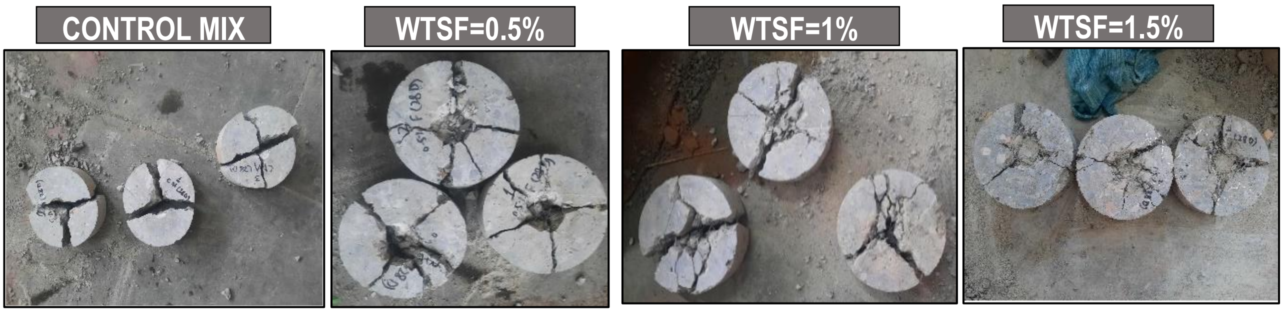


Fig. 15. Failure pattern of samples under drop-weight test

From the results, it is concluded that control mix gives minimum impact resistance while fibers addition increases the impact resistance significantly with maximum improvement observed at 1.5% fiber dosage. Failure pattern for the mixes is presented in **Fig. 15.** It is clear from that samples of control mix were separated into pieces while samples with fiber reinforcement do not separate but show significant disintegration during repeated blows. Mostly samples have shown Y-shaped failure while some of the samples from the mixes show center split failure.

4 Conclusions

In this research, the impact of adding waste tire steel fibers in to the plain concrete was investigated for its fresh and hardened state properties. The conclusions drawn from the study are as follows:

1) Waste tire steel fibers can be efficiently utilized to incorporate waste tires by product in concrete.

2) The required workability of control mix was achieved without addition of admixture, but gradual addition of fibers reduced the workability hence admixture was added to get the specified slump. At 1.5% fiber content, the required slump of 100-125 mm was obtained by adding 1.5% super plasticizer (by weight of cement)

3) Compressive strength improved by almost 4.6% to 30% from 0.5%-1.5% fiber dosage. Addition of fibers improved the compressive strength to some extent because fibers provide a bonding effect. Split tensile strength increased to 36% from 2.7 to 4.4 MPa in the control mix and *WTSF*=1.5% mix.

4) Flexure strength gradually increased by increasing the fiber dosage and mix with 1.5% fibers content improved flexure strength by 22% w.r.t control mix.

5) Impact resistance was significantly higher for both first crack and ultimate failure points. Since more energy was required to pull out the fibers from matrix, *WTSF*=1.5% mix proved to be more effective for first crack and ultimate failure strength.

6) Finally, the findings of this study suggest that waste tire steel fibers have promising potential as an eco-friendly alternative for enhancing concrete's mechanical properties. Specifically, they show effectiveness in improving flexural toughness and impact resistance under controlled conditions. However, further research is needed to confirm these benefits in diverse environments and applications.

Limitations and Future Research

While this study demonstrates the potential of waste tire steel fibers to improve certain mechanical properties of concrete, it is limited to specific fiber dosages, mix designs, and laboratory-controlled conditions. Field applications, long-term durability studies, and the effects of environmental exposure (e.g., freeze-thaw cycles, chemical attacks) remain unexplored. Future research should examine these aspects, along with assessing different fiber processing techniques to improve compatibility and performance in diverse concrete applications.

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CRediT authorship contribution statement

All authors contributed equally to the study conception and design. Material preparation, data collection and analysis were performed by Asif Hameed, Maryam Nosheen, Ratan Lal and Ali Murtaza Rasool. The first draft of the manuscript was written by Ali Murtaza Rasool, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Maryam Nosheen: Investigation, Formal analysis, Writing – original draft. **Asif Hameed**: Conceptualization, Funding acquisition, Supervision, **Ratan Lal**: Investigation, Formal analysis, Writing – original draft. **Ali Murtaza Rasool**: Investigation, Formal analysis, Writing – original draft. **Asad Ullah Qazi**: Writing – review & editing.

Conflicts of Interest

The authors declare that they have no conflicts of interest to report regarding the present study.

Data Availability Statement

Some or all data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

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