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Mechanical Properties of Steel-Fiber-Reinforced Concrete †

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Abstract: The rapid increase in a vehicle's use leads to tire waste, the management of which is of social and environmental concern. The steel wires in a tire have good application in concrete if the proper amount and distribution of steel fiber in the concrete matrix is ensured. This experimental setup evaluates the dosage effect of steel fiber with different ratios on the compressive, splitting tensile, and flexure strength of concrete. The relationship of flexure and compressive strength vs. the dosage of steel fiber is also investigated. A significant enhancement in compressive and flexure strength was found with the use of steel fiber. Moreover, the effect of the length of steel fiber on the mechanical properties of concrete is checked. A 2% dosage of steel fiber with a 3″ length showed excellent performance in compression and flexure. The first crack appeared at a 10% greater load than the control specimen. Based on detailed analysis, a 2% dosage with a 3″ fiber length can be used for the commercial production of structural concrete.

Keywords: steel fiber; mechanical properties; tire waste; flexure strength

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1. Introduction

The tire is one of the non-biodegradable materials and is globally produced at a rate of 1.5 billion per year [1]. With the population increase, the use of vehicles is increasing day by day, which leads to the production of more tire waste. The average lifetime of the tire is 50,000 km, after which it needs to be replaced [2]. This tire waste can catch fire and create hotbeds for mosquitoes, mice, etc. [3]. Tire waste comprises 85% of rubber material. Ways of carefully dealing with tire waste have attracted public interest recently due to its environmental impact and the rapid degradation of its disposal sites [4]. Pakistan is the fifth most populous country in the world, with an annual population growth of 2% [5]. The number of vehicles is increasing with the population, which ultimately leads to the production of more tire waste and requires more land for proper disposal. The management of such a number of tires is also a serious problem for the Pakistan EPA (Environmental Protection Agency) [6].

Concrete is a widely used material in the construction industry, and some researchers reported its use next to water [7,8]. Concrete is weak in tension, a quasi-ductile material, and offers low resistance to crack creation. High-performance concrete is required for skyscrapers and large-span buildings to meet the needs of the construction industry [9,10]. One of the ways to reduce brittleness and enhance the tension capacity of concrete is through the usage of fibers, which improve the tensile strength of concrete before cracking and its ductility after cracking. Fiber helps in the improvement of impact and fatigue strength and minimizes temperature and shrinkage cracking [11]. Used tires are one of the most easily available and cheap sources of steel fiber in Pakistan with high tensile strength. A large number of tires are collected annually in Pakistan due to the absence of a recycling industry for it [6,12].

Tire waste largely consists of steel fiber, the proper extraction of which would be very beneficial for the construction industry [13]. Recently, researchers and practitioners

have given great attention to the use of sustainable, environmentally friendly, and green concrete by using different recycled materials in concrete; recycled steel fiber (RSF) is one of these [14]. Recently, various studies were carried out to determine the effect of RSF, extracted from tires, on the mechanical properties of concrete, and an excellent result was found. It was reported that RSF has a negligible effect on durability, with significant enhancements in mechanical properties [15]. It reduces the probability of chemical-agent entry into concrete by minimizing the dimensions of the concrete [16]. Enhancements in flexure and compression strength were also reported by different researchers of the addition of RSF [17]. However, a high amount of SF in concrete affects workability, leading to porous concrete, which causes different durability issues [14].

The level of increase in the mechanical properties of concrete (post-cracking, shear strength, etc.) is related to the uniform distribution of SF and length factor in the concrete mix [18]. Different researchers used 0.26% and 0.46% SF by volume of normal concrete to ensure proper workability [19]. In previous research studies, it was concluded that commercial SF significantly enhances flexure strength, ductility, and resistance to post-cracking in concrete [6]. Furthermore, the brittle behavior of concrete was reduced by the bridging action of SF, ultimately leading to enhancement in post-cracking resistance through the control of crack origination and propagation [20]. Some researchers reported decreases in the compressive strength when SF was more than 2% [21]. The inclusion of SF causes workability problems and produces low-quality concrete. This issue can be resolved through proper selection of the length and dosage of SF. The amount and length of SF significantly contribute to the tensile strength of concrete.

In this study, steel fiber from tires was utilized in concrete in different dosages and lengths to select the most optimum combination from detailed scrutiny. Experiments were performed on control and Steel-Fiber-Reinforced Concrete (SFRC) specimens and the compressive, splitting tensile, and flexure strengths were evaluated. The test was performed according to different ASTM standards.

2. Methodology and Materials

The properties of the material are given in Table 1. To find the optimum amount for the mix, locally available material was used. The material's physical and mechanical properties were found in the lab of the Civil Engineering Department of the University of Engineering and Technology, Peshawar, according to the standards [22]. A total of 540 cylinders were cast with a length of 30.5 cm and a diameter of 15.5 cm. The properties of the ingredients used in concrete specimen preparation are given in Tables 1 and 2.

Table 1. Material properties.

Property	Value
Concrete	1:2:4
w/c ratio	Constant for all, 0.61
Steel fiber extraction from the tire	Manually (Figure 1b)
Diameter of SF	0.0157″ (0.40 mm)
Average tensile strength of SF	990 MPa (conforms to ASTM A370 [23])
% elongation of SF	1.30
Length of SRF	3″ (76.2 mm) and 4″ (101.6 mm)
Amount of RSF used	1, 1.5, 2, 2.5, 3, 3.5, 4% by weight replacement of concrete
Cement type	Type-1
Fineness of cement	96%
The specific gravity of cement	3.10

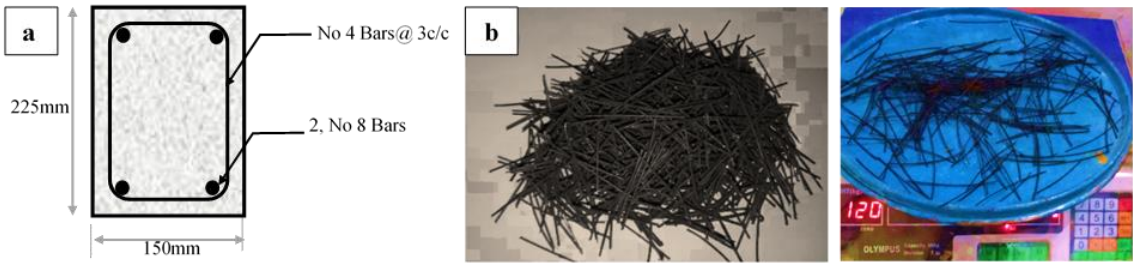

Figure 1. (**a**) Cross section of the beam. (**b**) Wires extracted from tire.

Table 2. Properties of coarse and fine aggregate.

Coarse Aggregate (20 mm)			Fine Aggregate		
Property	**Specification, Reference**	**Values**	**Property**	**Specification, Reference**	**Values**
Sieve analysis	ASTM C136, [24]	Well-graded	Specific Gravity	ASTM C128, [25]	2.72
Moisture content	ASTM C566, [26]	0.25%	Water absorption	ASTM C128, [25]	3.10%
Specific gravity	ASTM C127, [22]	2.66	Fine modulus	ASTM C136, [24]	2.84
Water absorption	ASTM C127, [22]	1.23%	Moisture Content	ASTM C70, [27]	2.40%

2.1. Compressive Strength

For compressive and splitting tensile strength, a total of 140 cylinders were prepared: 5 cylinders each with different % of SF for 3″ and 4″ fiber length. For comparison purposes, a control specimen was prepared with no SF.

2.2. Flexure Strength

For flexure strength, four specimens of the beam (Figure 1a) with dimensions of 145 × 288 × 2286 mm were cast with the proper combination of ingredients, as given in Tables 1 and 2. Minimum reinforcement was provided according to ACI 318 [28] to obtain failure at a lower load, as given by an author of [29] with the addition of an economic aspect. All beams were cast and tested as per ASTM standard procedure [30]. The load was applied as per the third-point loading method and three Linear Variable Displacement Transducers were used in the region of maximum bending moment. Two beams were constructed without RSF, acting as a control beam, while the two beams were cast with 2.5% SF.

3. Results and Discussion

The compressive strengths of the control specimens and Steel-Fiber-Reinforced Concrete (SFRC) are shown in Figures 2 and 3. The experimental results show that both the percentage content and dimensions of the RSF can affects the compressive strength of SFRC. Compressive strength increases with an increase in percentage content of SF for both the 3″ and 4″ lengths. At a fiber content of 2%, the maximum compressive strengths are found to be 20% and 16% higher than the control beams for 3″ and 4″ fiber, respectively. A further increase in the dosage of RSF causes a decrease in the compressive strength, both for the 3″ and 4″ length fibers. However, the compressive strength is higher for the 3″ fibers as compared to the 4″ fibers. Additionally, the best-fitted line was drawn through the compressive strength data, through regression analysis, and it was found that the decrease in compressive strength with a dosage of SF follows quite linear behavior for both lengths of fibers. The linear line fits best for the 4″ fiber compared to 3″. The decrease in compressive strength with an increase in the length and dosage of RSF may be due to the low workability of concrete, which results in poor-quality concrete in terms of cavities and pores, which causes a decrease in compressive strength.

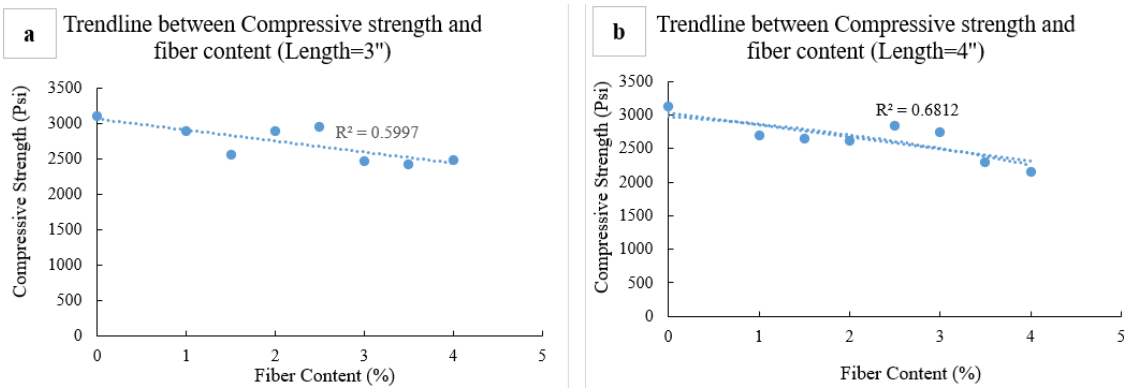

Figure 2. (**a**) Compressive strength vs. SF dosage of 3″. (**b**) Compressive strength vs. SF dosage of 4″.

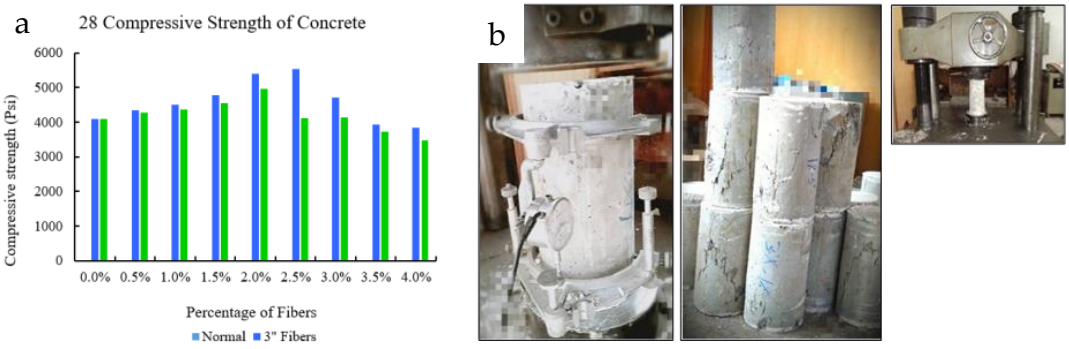

Figure 3. (**a**) 28-days compressive strength of concrete. (**b**) Testing of concrete cylinder.

The splitting tensile strength test was performed to find the capacity of SFRC in tension, which is an important mechanical parameter for plain concrete performance. Figure 4 shows the effect the of the length of fiber on the splitting tensile strength. It is obvious from Figure 4 that the splitting tensile strength is greater for the 3″ fiber compared to 4″. The splitting tensile strength increases with an increase in the dose of RSF to 2%, and after that, it decreases. The decrease may be due to the low workability of concrete at high SF levels, which produces low-quality concrete with pores and cavities. The maximum splitting tensile strength is 50 and 62% greater than that of the control specimen for the 3″ and 4″ fiber lengths, respectively. The increase in tensile strength is due to the bridging action of SF across the crack, and hence, controls the crack widening and propagation.

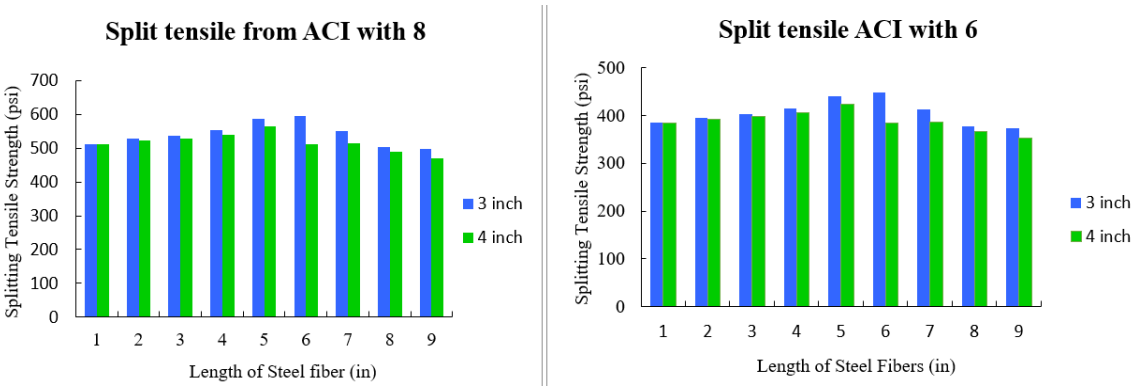

Figure 4. Splitting tensile strength vs. % dosage of SF.

Full-scale concrete beams were tested for flexure strength in the lab according to third-point loading [30] for maximum positive bending. For the constant w/c ratio, based

on workability effect on other mechanical properties, the optimum amount of SF (2%) with a length of 3″ was used for enhancement of the flexure capacity of the RC beam (Figure 5). Similarly, the flexure capacity was found at different percentages of SF for the lengths of 3″ and 4″. The test results show that the flexure capacity increases with an increase in the percentages of SF. It also shows that flexure capacity linearly increases with percentage SF dosages shown by the best-fitted line through regression analysis, with R^2 = 0.98. The maximum flexure strength is 56% and 57% more than the control specimen for the 3″ and 4″ RSF, respectively. The increase in flexure strength is due to the bridging action of RSF across the crack, and thus, controls the crack widening and propagation. Similarly, the first cracks start in control and SFRC at 3.7 and 4.9 k, respectively, which shows that the elastic behavior was enhanced by 17% and SFRC can sustain a 10% greaterload than the control specimen after the beginning of the first crack. The bridging action of SF is clearly shown in Figure 6.

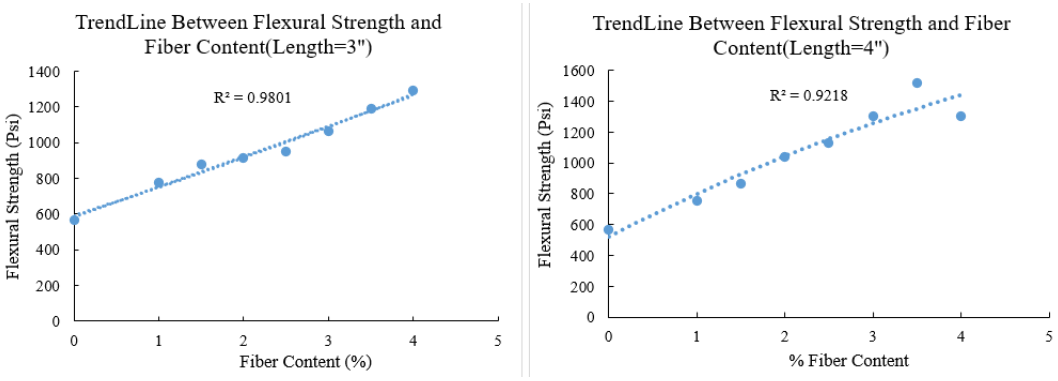

Figure 5. Trend line between flexure strength and % dosage for (**Left**) 3″ fiber length (**Right**) 4″ fiber length.



Figure 6. Bridging action of SF in concrete beam.

4. Conclusions

From the experimental findings of the current research, the following conclusion can be drawn.

- The mechanical properties of concrete are greatly affected by the length and dosage of SF.
- The maximum compressive strength was increased by 20% and 16%, respectively, for the 3″ and 4″ fiber compared to the control specimen.
- The maximum splitting tensile strength was increased by 50 and 62%, respectively, for the 3″ and 4″ fiber compared to the control specimen. The increase is shown for both lengths.
- The maximum flexure strength is 56% and 57% greater than in the control specimen for the 3″ and 4″ RSF, respectively.
- The SF with a 2% dosage with a 3″ length can be used for structural concrete.

- The decrease in compressive strength beyond a 2% dosage is due to the low workability of concrete, as it produces porous concrete.
- The increase in the flexure strength of concrete is due to the bridging action of SF across the crack, which increases resistance to crack production and propagation.

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