



Research Article

Influence of Tire-Recycled Steel Fibers on Strength and Flexural Behavior of Reinforced Concrete

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Tire production is increasing every year due to the increase in vehicle sales. The generation and disposal of waste are inherent to life itself and have presented very serious problems to the human community in China. Recently, some research has been devoted to the use of tire-recycled steel fibers in concrete. This study is focusing on the use of tire-recycled steel fibers. Several volume ratios of tire-recycled steel fibers were used in concrete mix to fabricate and test. Reinforced concrete obtains evidence and satisfactory improvement by adding tire-recycled steel fibers, mostly in compressive strength, splitting strength, flexural tensile strength, and flexural toughness. The strength and flexural toughness of the tire-recycled steel fiber reinforced concrete are lower than those of industrial steel fibers. To obtain concrete with approximately the same strength or toughness, the content of tire-recycled steel fibers should be about 1%-2% higher than that of industrial steel fibers. In addition, the load-deflection curve tends to become fuller after the first crack, and the second peak of the load continues to increase. The steel fiber reinforced concrete is getting closer to the ideal elastic-plastic material.

1. Introduction

With the development of the automobile industry, the recycling of waste tires has received more and more attention in China. Waste tires are mainly composed of rubber, carbon, and metals. They have extremely high resource recycling value, but improper storage, regeneration, and disposal processes can cause environmental problems and affect people's health. Therefore, how to reasonably and effectively recycle and dispose of waste tires and prevent environmental pollution has become a problem that people must face.

At present, waste tires in China are mainly used for retreading tires, processing rubber, and making rubber powder, but the metal wires are not used well. Around the world, some scholars have studied the properties of tire-recycled steel fiber reinforced concrete [1–5].

Wang et al. reviewed some studies on mechanical properties of FRC by using some recycled fibers including tire wires [6]. They reported that recovered industrial fibers could have the same effect as origin fibers on mechanical properties of FRC although a higher dosage rate may be required to match the performance. Neocleous et al. evaluated the flexural properties of concrete reinforced with tire-recycled steel fibers [7]. They reported that recycled steel fibers (RSF) from waste tires have a great effect on improving the postpeak behavior of FRC. Meddah and Bencheikh investigated the mechanical properties of waste metallic fibers with different lengths in concrete [8]. They have reported that the incorporation of waste fibers in different lengths leads to the best load-carrying capacity and flexural properties. Aiello et al. studied the mechanical properties of concrete reinforced with tire-recycled steel fibers [9]. They have pointed that results obtained from using waste fibers

are comparable with industrial steel fiber reinforced concrete. Yang et al. studied the mechanical properties of UHPC reinforced with two types of recycled steel fibers from waste tires [10]. They have pointed that the recycled steel fibers without rubber particles have a slightly negative effect on the compressive strength of UHPC. Kamran and Mohammad studied the mechanical properties of 28-day reinforced lightweight concrete specimens with the waste wires [11]. According to the results, by using waste wires, flexural, tensile, and impact characteristics of concrete were effectively improved. It was concluded that waste steel wires could be used as a suitable microreinforcement in the structural lightweight concrete.

Therefore, using steel fibers extracted from waste tires in concrete would be the best way to make it more economical to manage them. Meanwhile, it is environmentally friendly besides enhancing concrete engineering properties. In order to achieve this, a study based on characteristics of reinforced concrete with tire-recycled steel fibers was done and compared with reinforced concrete with industrial steel fibers. The significance of this study is to investigate the mechanical performance of concrete with tire-recycled steel fibers, such as compressive strength, split tensile strength, flexural strength, flexural toughness, and fatigue properties. At the same time, it will make tire recycling attractive to be used mostly in engineering fields.

2. Raw Materials and Mix Proportion

2.1. Raw Materials

2.1.1. Steel Fibers. In order to compare the performance difference between tire-recycled steel fiber reinforced concrete and industrial steel fiber reinforced concrete, two steel fibers were used in the test, which are Zhitai-type I tire-recycled steel fibers and milling industrial steel fibers produced by Zhitai Steel Fibers Co., Ltd. The performance indicators of the two steel fibers are given in Table 1. The manufacturing processes used for tire-recycled steel fibers is drawing wire, cutting, and shaping.

2.1.2. Cement. The cement used in the test is Witton P.O 42.5 cement. The physical-mechanical performance indicators are given in Table 2, which meets the technical requirements of General Portland Cement GB175-2007.

2.1.3. Coarse Aggregate. The coarse aggregate is made of limestone with a particle size of 5 mm–20 mm. The gradation is given in Table 3.

2.1.4. Fine Aggregate. The fine aggregate used in the test was sand produced from the Duling River. The gradation range is given in Table 4.

2.1.5. Water. The water used in the test was drinking water in Taiyuan.

2.2. Mix Proportion. The mix proportion design of the concrete was carried out in accordance with JTG/T F30-2015 “Technical Detailed Rules for the Construction of Highway Cement Concrete Pavement” of China. The mix proportion is given in Table 5. Among them, the amount of the water-reducing agent is subject to the concrete slump of 30 mm~55 mm.

After trying and testing, when reaching the same strength, the volume ratio of tire-recycled steel fibers is higher than that of industrial steel fibers. According to the trial results, the amount of steel fibers in this test is appropriately enlarged, and the volume ratios of the two types of steel fibers proposed are given in Table 6.

3. Test and Analysis

To evaluate the performance of tire-recycled steel fiber reinforced concrete, this test prepared 42 groups of concrete specimens, including 21 groups of tire-recycled steel fiber reinforced concrete specimens and 21 groups of industrial steel fiber reinforced concrete specimens, to compare the difference in cubic compressive strength, split tensile strength, flexural tensile strength, flexural toughness, and fatigue times of two types of concrete specimens.

3.1. Test Method. The test of cubic compressive strength, split tensile strength, and flexural tensile strength of steel fiber reinforced concrete was conducted in accordance with the JTG E50-2005 of Highway Cement Concrete Test Procedures, and the test of flexural toughness was performed in accordance with the ASTM C1018. The test of the fatigue performance was carried out by using a four-point bending and stress-controlled loading method. The size of the fatigue specimen is 100 mm × 100 mm × 400 mm.

In order to facilitate the analysis of the test results, the test specimens are marked according to the type and volume ratio of steel fibers. For example, the specimen with industrial steel fibers with a volume ratio of 0.5 is marked as I-05 and the specimen with tire-recycled steel fibers with a volume ratio of 3.6 is marked as T-36.

3.2. Test Results and Analysis

3.2.1. Cubic Compressive Strength. The effects of two types of steel fibers on the cubic compressive strength of reinforced concrete are shown in Figure 1.

When the fibers volume ratio is the same, the cubic compressive strength of tire-recycled steel fiber reinforced concrete is lower than that of industrial steel fibers, and this effect is even more pronounced when the fibers' volume ratio is greater than 1.5%. For example, when the volume ratio is 2.5%, the compressive strength of the tire-recycled steel fiber reinforced concrete is 55.0 MPa, which is lower than that of the industrial steel fiber reinforced concrete 62.3 MPa.

The comparison curve of the cubic compressive strength growth rate of the two types of steel fiber reinforced concrete is shown in Figure 2. The compressive strength growth rates

TABLE 1: Performance parameters of steel fibers.

Type	Tensile strength (MPa)	Bending resistance	Equivalent diameter (mm)	Length (mm)	Manufacturing process	Shape	Remark
Tire-recycled steel fibers	1260	Up to standard	1.0	35.34	Cutoff	Indentation on the surface	Uniform, neat cuts, and a small amount of rubber adhesion on the surfaces
Industrial steel fibers	990	Up to standard	1.0	36.02	Milling	Hook at the end	Uniform, neat incision, and shiny surface

TABLE 2: Cement performance.

Fineness (m ² /kg)	Setting time (min)		Compressive strength (MPa)		Flexural strength (MPa)		Stability (boiling method)
	Initial setting	Final setting	3 d	28 d	3 d	28 d	
350	180	275	35.6	49.8	6.1	8.9	Up to standard

TABLE 3: Gradation range of coarse aggregate.

Sieve size (mm)	Remaining mass on sieve (g)	Mass percentage on sieve (%)	Cumulative mass percentage on sieve (%)
19	125	0.8	0.8
16	930	6.2	7
13.2	2870	19.1	26.1
9.5	5320	35.5	61.6
4.75	5360	35.7	97.3
0	400	2.7	100

TABLE 4: Gradation range of fine aggregate.

Sieve size (mm)	Remaining mass on sieve (g)	Mass percentage on sieve (%)	Cumulative mass percentage on sieve (%)
4.75	9	1.8	1.8
2.36	47	9.3	11.1
1.18	57	11.3	22.5
0.6	141	28	50.5
0.3	151	30	80.5
0.15	57	11.3	91.7
0	41	8.2	100

TABLE 5: Mix proportion.

Strength grade of concrete	Water (kg)	Cement (kg)	Fine aggregate (kg)	Coarse aggregate (kg)	Water-reducing agent (kg)
C40	195	460	783	998	5.8

TABLE 6: The volume ratio of the two types of steel fibers.

Type	Volume ratio (%)				
Industrial steel fibers	0.5	1.0	1.5	2.0	2.5
Tire-recycled steel fibers	1.2	1.8	2.4	3.0	3.6

in the figure are all compared with the compressive strength of concrete with a volume ratio of 0%. As the fiber volume ratio increases, the strength growth rate of both types of concrete continues to increase. In the box surrounded by the purple dotted line, the two curves are approximately parallel.

When the strength growth rate is 11%, the volume ratio of industrial steel fibers is 1.31%, while the volume ratio of tire-recycled steel fibers is 2.63%, which is about 1.32% more than the former. When the strength growth rate is 24%, the volume ratio of industrial steel fibers is 2.26%, while the volume ratio of tire-recycled steel fibers is 3.65%, which is about 1.39% more than the former. In other words, in order to achieve the same strength growth rate or strength, the amount of tire-recycled steel fibers should be increased by about 1.3% compared to industrial steel fibers, when the amount of industrial steel fibers exceeds 1.3%.

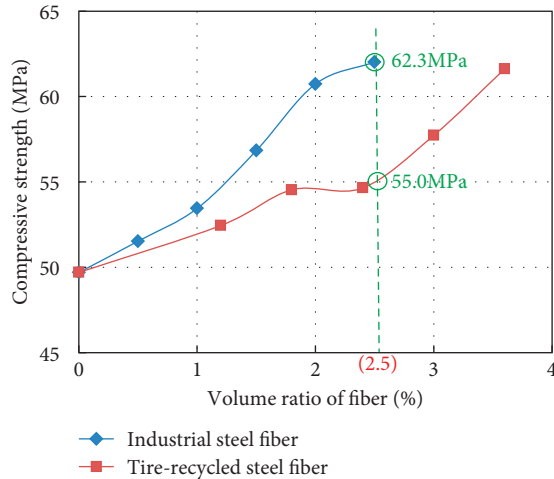


FIGURE 1: The cubic compressive strength of two types of steel fiber reinforced concrete.

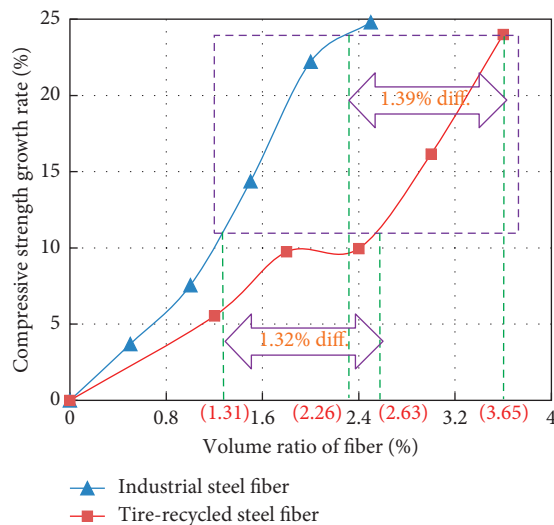


FIGURE 2: The compressive strength growth rate of two types of steel fiber reinforced concrete.

3.2.2. *Split Tensile Strength.* The effect of steel fiber volume ratio on the split tensile strength of two types of reinforced concrete is shown in Figure 3. When the fiber volume ratio is the same, the splitting strength of industrial steel fiber reinforced concrete is higher than that of recycled-tire steel fiber reinforced concrete.

As the fiber volume ratio increases, the split tensile strength of both types of concrete continues to increase. In the box surrounded by the purple dotted line, the split tensile strength growth rates of the two types of steel fiber reinforced concrete are approximately the same. When the split strength is 6.49 MPa, the volume ratio of tire-recycled steel fibers is 2.25%, and the volume ratio of industrial steel fibers is 0.98%. The difference between the two is the largest, reaching 1.27%. When the split strength is 6.86 MPa, the difference between the two is the smallest. The volume ratio of tire-recycled steel fibers is 0.91% which is higher than that of industrial steel fibers. So, in order to achieve the same split

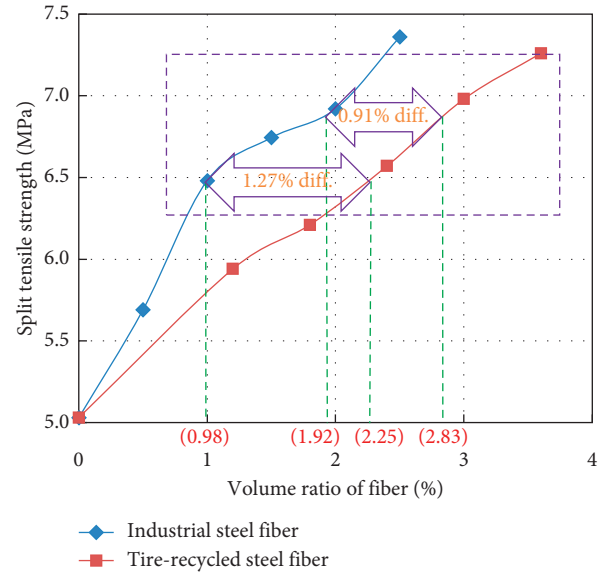


FIGURE 3: The split tensile strength of two types of steel fiber reinforced concrete.

tensile strength, the amount of recycled-tire steel fibers should be increased by about 0.9%–1.3% compared to industrial steel fibers, when the amount of industrial steel fibers exceeds 1%.

3.2.3. *Flexural Tensile Strength.* When the fiber volume ratio is the same, the flexural tensile strength of industrial steel fiber reinforced concrete is higher than that of tire-recycled steel fibers, as shown in Figure 4. This change of flexural tensile strength is similar to that of cubic compressive strength and split tensile strength.

As the volume ratio of steel fibers increases, the flexural strength of both types of steel fiber reinforced concrete continues to increase. When the amount of industrial steel fibers exceeds 1%, to achieve the same bending tensile strength as industrial steel fibers reinforced concrete, the volume ratio of tire-recycled steel fibers needs to increase by 1.1%–1.7%.

3.2.4. *Flexural Toughness.* The load-deflection curves of tire-recycled steel fiber reinforced concrete and industrial steel fiber reinforced concrete are shown in Figures 5 and 6, respectively. Once the bottom of the plain concrete specimens (T-0 and I-0) cracks, the crack quickly expands to the top of the specimens, and the concrete loses all the bearing capacity. With the addition of steel fibers, the load of the first cracking of the concrete increased greatly. After the first cracking, the specimens were still able to withstand large loads by virtue of the bond between steel fibers and concrete. Steel fibers improve the ductility and toughness of reinforced concrete and then change its failure mode from brittle to elastoplastic. Nevertheless, it can be seen from the figure that the load-deflection curves of the two types of steel fiber reinforced concrete show no signs of strain hardening. This is different from the existing research results, and this difference may be related to the fibers used in the test.

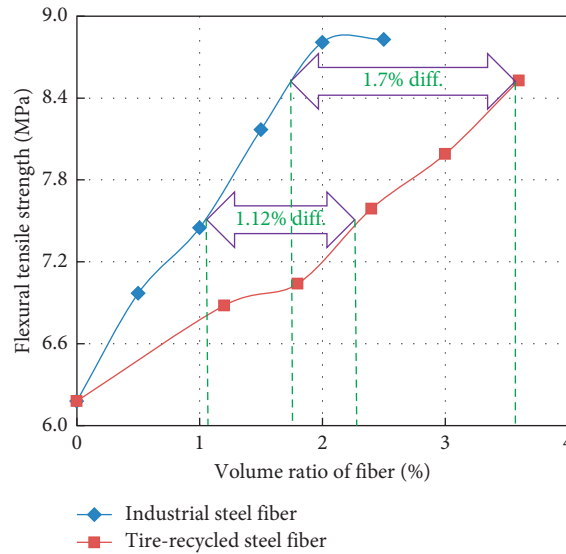


FIGURE 4: The flexural tensile strength of two types of steel fiber reinforced concrete.

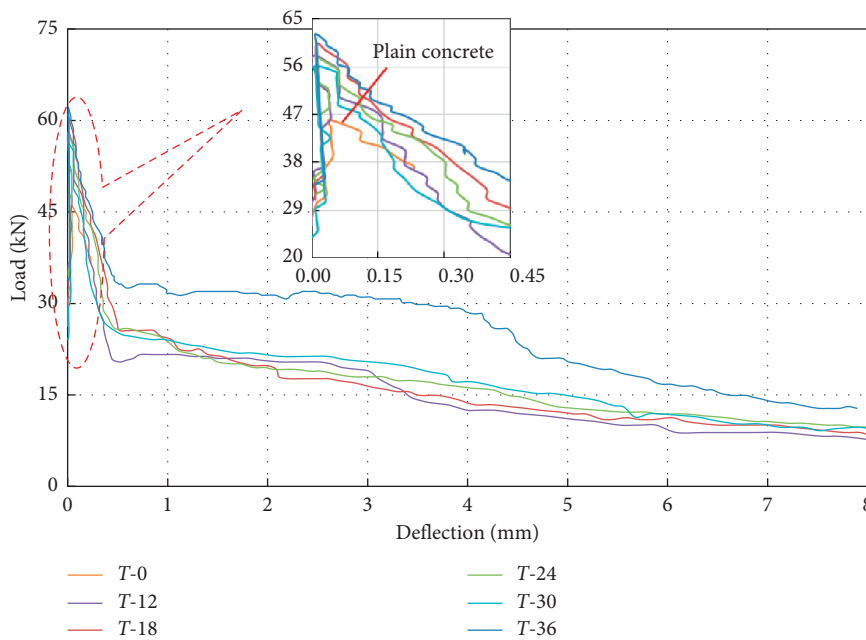


FIGURE 5: The load-deflection curves of tire-recycled steel fiber reinforced concrete.

With the increase in the amount of steel fibers, the maximum deflection of the two types of steel fiber reinforced concrete specimens continues to increase. Even if the crack eventually penetrates the entire section of the specimens, the concrete can still bear a certain load. Moreover, this phenomenon becomes more obvious as the amount of steel fibers increases. The load-deflection curve shows that the curve is fuller after the first crack and the secondary peak of the load is getting higher.

Based on the load-deflection curve, the flexural toughness index and residual strength coefficient of tire-recycled steel fiber reinforced concrete and industrial steel fiber reinforced concrete are calculated, as given in Table 7.

With the increase in the steel fiber volume ratio, the flexural toughness index of the two types of steel fiber reinforced concrete increased continuously and the growth rate of I_{30} was greater than I_{20} and greater than I_{10} , and I_5 was the smallest. That is, as the fiber volume ratio increases, the concrete becomes closer to the ideal elastoplastic material. At the same time, in the later stage of loading, the higher the amount of steel fibers, the more excellent the toughness will be. Residual strength coefficients $R_{10,30}$ are significantly larger than $R_{10,20}$ which also reflect this view.

Comparing the two types of steel fibers, it can be seen that when the volume ratio is similar, the toughness index of industrial steel fiber reinforced concrete is about 30% to 40%

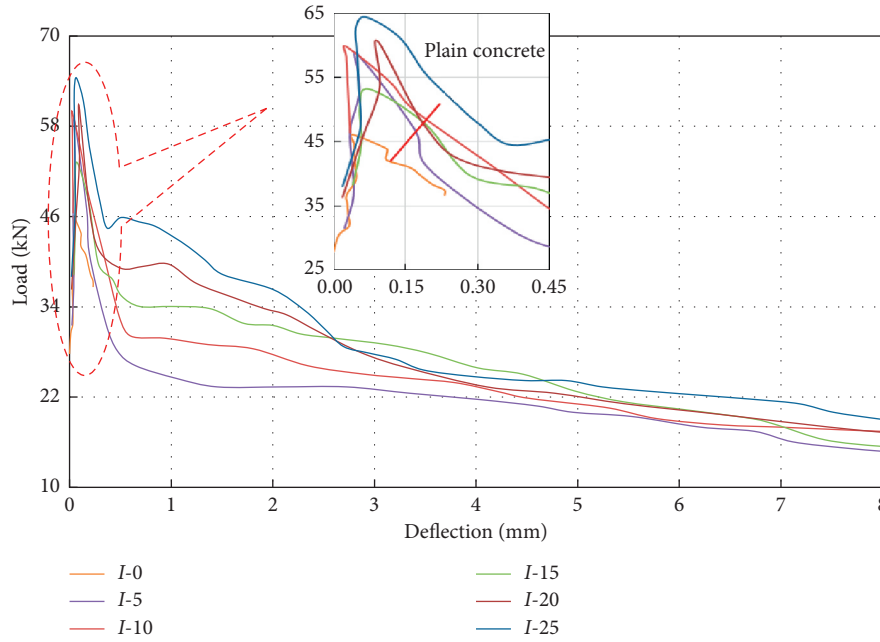


FIGURE 6: The load-deflection curves of industrial steel fiber reinforced concrete.

TABLE 7: Flexural toughness index and residual strength coefficient of steel fiber reinforced concrete.

Type	No.	Flexural toughness index				Residual strength coefficient		
		I_5	I_{10}	I_{20}	I_{30}	$R_{5,10}$	$R_{10,20}$	$R_{10,30}$
Industrial steel fibers	I-5	2.38	3.21	5.14	8.46	16.6	19.3	26.3
	I-10	2.81	3.99	7.55	14.77	23.6	35.6	53.9
	I-15	3.44	4.06	9.87	15.82	12.4	58.1	58.8
	I-20	4.56	6.48	10.80	19.15	38.4	43.2	63.4
	I-25	5.48	9.96	14.59	26.45	89.6	46.3	82.5
Tire-recycled steel fibers	T-12	2.55	3.57	5.33	7.16	20.4	17.6	18.0
	T-18	3.14	5.33	7.14	10.05	43.8	18.1	23.6
	T-24	3.87	6.03	9.87	14.71	43.2	38.4	43.4
	T-30	4.26	6.09	10.69	18.74	36.6	46.0	63.3
	T-36	4.75	8.57	14.88	23.75	76.4	63.1	75.9

higher than that of tire-recycled steel fiber reinforced concrete. To achieve similar toughness, the volume ratio of tire-recycled steel fibers needs to be increased by about 1% to 2% compared to industrial steel fibers.

4. Conclusion

In order to evaluate the mechanical properties and flexural toughness of tire-recycled steel fiber reinforced concrete, several volume ratios of tire-recycled steel fiber reinforced concrete and industrial steel fiber reinforced concrete were prepared. The cubic compressive strength, split tensile strength, flexural tensile strength, flexural toughness index, and residual strength coefficient of the two types of concrete were compared.

- 1 Tire-recycled steel fibers have a significant enhancement effect on the mechanical properties and flexural toughness of cement concrete and can be used as a green material;

- 2 When the fiber volume ratio is the same, the strength and flexural toughness of tire-recycled steel fiber reinforced concrete are lower than those of industrial steel fiber reinforced concrete. To achieve the same strengthening or toughening effect, the content of tire-recycled steel fibers must be about 1%-2% higher than that of industrial steel fibers.

- 3 As for the flexural toughness of reinforced concrete, with the increase in the volume ratio of the steel fibers, the load-deflection curve becomes fuller after the first crack and the second peak of the load continues to increase. The steel fiber reinforced concrete is getting closer to the ideal elastic-plastic material.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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