

Review Article

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A review on the properties of concrete reinforced with recycled steel fiber from waste tires

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Abstract: In the construction industry, fibers have been added to concrete to improve the mechanical properties of concrete for decades. Steel fiber has been widely used as an additive fiber owing to the unique properties; it provides reinforced concrete. However, the large-scale production of steel fibers generates a large amount of CO₂ and aggravates the depletion of natural resources. In response to the requirements of green environmental protection, some scholars have focused their attention on replacing industrial steel fibers with recycled steel fibers from waste tires (WTSF). It is found that WTSF can be used to reinforce the mechanical properties of concrete and even replace industrial steel fiber (ISF) in some engineering applications. The existing research results are summarized and discussed, with emphasis on the process of recycling WTSFs. This review not only has a great impact on the environment but also has fiber characteristics as well as the mechanical properties (compressive strength, tensile strength, and flexural strength) and durability of the concrete with WTSF. The purpose of this article is to review the existing literature with a critical attitude and summarize the existing related literature, which determines the research gap for those who are committed to this direction.

Keywords: recycled steel fiber from waste tires, environmental impact, mechanical properties, durability

1 Introduction

Cement concrete is a brittle material. This characteristic makes it highly sensitive to strain and prone to cracks under small strains. To address this problem, the method of adding reinforcing fibers to concrete has been widely used. Currently, the commonly used fiber materials include steel fiber, glass fiber, basalt fiber, polypropylene fiber, cellulose fiber, and mixed fiber [1–4]. Saidani et al. [5] have studied the effects of steel, macro-polypropylene, and micro-polypropylene fiber on the performance of concrete. The results show that the performance of concrete is indeed improved after adding fiber. Compared with other fibers, steel fibers play a significant role in reducing the crack sensitivity and brittleness of concrete [6]. Moreover, through the results of some researchers on steel fiber-reinforced concrete, it was found that adding steel fiber to concrete can also significantly improve the toughness, fatigue resistance, and impact resistance of concrete [7], which means that steel fibers play an important role in reinforcing the mechanical properties of concrete. Owing to its unique significance in improving concrete performance, steel fiber-reinforced concrete is most widely used among various types of concretes. In the global market, the annual sales volume of steel fiber not only exceeds 300,000 tons but also has an annual growth rate of 20%, and the reduction of carbon emissions is the main target for the fabrication of green construction [8,9]. Furthermore, nearly 90% of the industrial steel fibers (ISFs) produced every year have different shapes and surface lines [10]. In the previous application of steel fibers, only some of the geometries of steel fibers enhanced the concrete performance [11], but the majority of the other shapes cannot be used in concrete [12]. The annually increasing sales volume indicates that the production of steel fibers will continue to increase, and the corresponding consumption of ore resources and fossil fuels will also increase. Therefore, a large number of greenhouse gases will be produced during these production processes, which will have an extremely adverse impact on the environment. To slow down the deterioration of the global environment, exploration and research to find sustainable

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and green alternatives to steel fibers have been ongoing. Therefore, recycled steel fibers (RSFs) have attracted the attention of scholars worldwide because of their small impact on the environment and low recovery cost.

RSFs are mainly obtained from scrap tires; therefore, they can also be called WTSFs. The disposal of used tires has always been a major focus of waste management agencies [13]. Owing to the gradual popularization of automobiles, the number of used tires is also increasing rapidly. According to statistics, currently, there are nearly 5.2 billion tires to be scrapped [14]. Because the direct burial of tires would cause extensive land pollution, the EU banned the burial of waste tires as early as 2003 [15]. With the EU's martial law on the disposal of waste tires, new disposal modes and related regulations have also emerged [16]. A common tire comprises 47% rubber, 22% carbon, 17% steel wire, 5% fabric, and a small quantity of some other additives [17]. Their recycling value is excellent, but if they are not handled properly, they will cause not only environmental pollution but also a significant wastage of resources. Through extensive research, researchers have found that steel fibers can be extracted from these tires via crushing at a low temperature or pyrolysis [18] to separate steel wire from the combustibles such as rubber and carbon. Wang et al. [19] summarized some studies on the mechanical properties of fiber-reinforced concrete (FRC) prepared using recycled fiber values. Their article stated that WTSFs can demonstrate the same mechanical properties as the fibrils in FRC, although relatively larger amounts of fiber are required to achieve the same effect as that of fibrils. In their research, Meddah and Bencheikh [20] investigated the mechanical properties of test blocks with WTSFs of different lengths in concrete. Their final experimental results demonstrate that mixing WTSFs of different lengths can result in the best load-bearing capacity and bending properties of the test block. Kamran and Mohammad [21] mixed WTSFs into 28-day lightweight concrete specimens to determine their mechanical properties via experiments. The experimental data showed that the addition of WTSFs effectively improved the bending, tensile, and impact resistance of the concrete specimens. It also showed that the dimensions of the WTSFs were suitable for the micro reinforcement of structural lightweight concrete. Some researchers have also conducted experiments on the compressive strength [22], flexural and torsional strength [23], and drawing performance [24] of WTSF concrete. In the research on WTSF concrete in recent years, it was found that WTSFs can completely or partially replace the ISFs in FRC [25]. Therefore, steel fibers recovered from waste tires can also be added to the concrete as a reinforcement material to enhance the mechanical properties of concrete.

However, rubber and carbon separated from tires are also used as combustibles, and their high calorific value during incineration makes them suitable for use as fuels in many energy-recovery plants and the cement industry [26]. Li et al. [27] also said that the rubber recovered from waste tires also has the potential to be mixed with concrete in highway construction.

This review summarizes and discusses the main research results of WTSFs and its application in concrete materials in recent years. First, the various sources of WTSFs and their recycling processes and environmental impacts are summarized. The impact of WTSFs on the mechanical properties and durability of concrete is then discussed. Finally, the conclusion and direction of the future development of WTSF concrete are proposed.

2 Main source of WTSFs

Nowadays, the WTSFs studied by many scholars are mainly recycled from waste tires. There are two methods for obtaining recycled raw fiber: one method involves pulverizing waste tires and extracting fibers at a low temperature, and the other involves extracting them via anaerobic degradation (microwave induction and conventional pyrolysis) [28]. The crushing method involves crushing the waste tires into pieces, crushing these small pieces again to obtain fine rubber particles, and then using a magnetic force to extract the steel wire from the rubber particles [18]. The steel fibers obtained by this method are presented in Figure 1(a).

The low-temperature treatment process is as follows: first, the waste tires are cut into small pieces, and these small pieces of waste tire are placed in a refrigerator, frozen to -180°C using liquid nitrogen, and then broken using a hammer. Finally, the steel fibers and rubber are separated using a magnetic force to obtain the required steel fibers [29,30]. Because the steel wire has a brittle temperature range, the cooling temperature must be controlled well; otherwise, the produced steel fiber may be brittle [31]. From the perspective of the production process, this method can provide steel fibers from waste tires with low energy consumption, and it can thus be considered energy saving [32]. However, this method results in greater liquid nitrogen consumption and thus a higher acquisition cost. The steel fibers recovered via the low-temperature treatment are presented in Figure 1(b).

The anaerobic degradation method involves the pyrolysis of waste tires in an oxygen-free environment. In this process, steel wires and coke are produced to



Figure 1: WTSFs obtained using different recycling techniques [29]. (a) Shredding technique, (b) cryogenic technique, and (c) pyrolysis technique.

separate the steel fibers. During the normal operation, the waste tires are placed into the pyrolysis reactor, and heat treatment is carried out to heat them to the required temperature. The liquid and gas produced in the pyrolysis reaction are separated via a gas–liquid separator. Finally, the produced steel fiber and coke are separated to obtain the required steel fibers. However, some unclean coke will be found on the surface of this type of steel [33], as shown in Figure 1(c).

3 Environmental effects of WTSF applications

With the rapid development of the construction industry, the demand for the quality and quantity of buildings is increasing. In the face of this large demand, the natural resources required for construction are also rapidly reducing. According to statistics, 15% of the energy consumption of the entire building is due to the production of building materials [34]. Therefore, it is particularly important to save energy and reduce its consumption in the initial stages of the construction. Previous studies have shown that the use of recycled materials in the preparation of construction raw materials can considerably reduce the energy consumption [35]. Waste tires have a high carbon content, toxic characteristics, and high fuel value, and if they are not handled properly, they can cause significant environmental damage. Therefore, they have attracted the attention of many scientific researchers in terms of reuse and recycling.

The amount of cement used in construction projects is considerably large. Owing to the burning characteristics of waste tires, they can replace the fuels used to burn

cement in cement kilns, and the steel wires produced in the incineration of waste tires can also be used as construction fibers. Previous studies have shown that it is feasible to replace existing fuels with waste tires. The calorific value of waste tires in cement kilns is $270 \text{ MJ}\cdot\text{kg}^{-1}$, which is $26.5 \text{ MJ}\cdot\text{kg}^{-1}$ higher than existing fuels such as coal [36]. In the previous studies, it was found that only 20 lb of shredded waste rubber tires can replace 25 lb of coal [37]. Compared with the existing coal fuels, the use of waste tires can also reduce carbon dioxide emissions by 17% [38]. In terms of the cost of construction materials, by using WTSFs to replace ISFs as fibers added to concrete, the cost ratio can reach 1:0.2 [39]. At the same time, the unit energy consumption of ISF concrete (ISFC) production is $0.76 \times 10^6 \text{ kcal}\cdot\text{t}^{-1}$, while the energy consumption of WTSF concrete (WTSFC) is only about 60% [40].

If waste tires are not processed and recycled, long-term stacking will result in the breeding of a large number of mosquitoes and rodents, accelerate the spread of diseases, and threaten human health. As early as the 1940s, the United States shipped its used tires in Asia that had been infested by mosquitoes during World War II back to the United States, which caused the spread of imported diseases. For the first time, people in the United States discovered the relationship between scrap tires and disease-carrying mosquitoes [41].

In the case of long-term accumulation of waste tires, the possibility of the occurrence of a fire is high owing to their combustible characteristics. Once a fire breaks out, waste tires accumulated in the open will not only generate a large amount of heat and CO_2 , which will aggravate global warming, but also generate harmful gases such as CO and SO_2 , causing environmental damage. The oil produced by the incineration of tires is absorbed by the land and causes significant ground and groundwater pollution [42]. Some scholars have found that

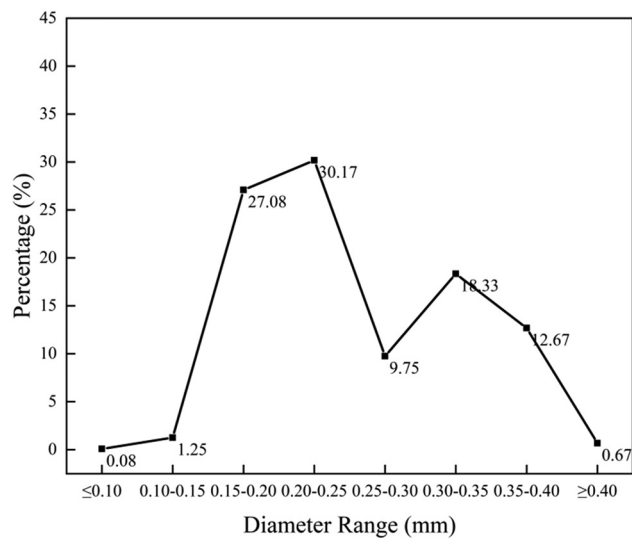
recycling about 1.2 million waste tires every year can reduce carbon dioxide emissions by 1.52 tons [43].

From the aforementioned discussion, it can be observed that the recycling of waste tires is not only financially beneficial but also protects the environment to a significant extent and responds to the call for green development. The recycling of steel fibers in tires effectively improves resource utilization, thereby protecting natural resources. Moreover, the addition of WTSFs to concrete improves the performance of concrete and, most importantly, increases the demand for the recycling of waste tires, thereby increasing the conversion rate of waste tires and preventing the long-term accumulation of a large number of waste tires. Threats such as fires and mosquito diseases are caused by open-air accumulation of waste tires.

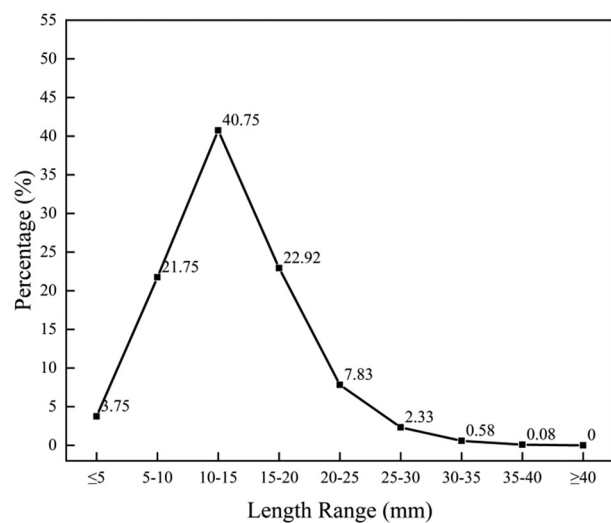
4 Characteristics of WTSFs

The steel fibers obtained from scrap tires are of irregular sizes and shapes owing to their different sources and recycling processes. From the related literature, it is found that the majority of the WTSFs recovered from scrap tires are obtained through the same pulverization process, which results in recycled fibers of varying lengths and diameters [44]. Moreover, as different types of waste tires are used in this process, the diameters of the steel fibers obtained from them are not uniform, which also affects the shape of the WTSFs [45]. Therefore, the geometric shape of the WTSFs varies widely. Therefore, we should perform a statistical analysis of the distribution frequency and average fiber size using a representative number of fibers [46].

Some scholars have conducted statistical analyses in this direction. Leone et al. [47] obtained statistics on the size of 1,200 randomly selected WTSFs. A micrometer was used to measure the diameter of the two ends of the fiber, and the average value was calculated [48]. From this measurement, the obtained average diameter of the selected fiber was 0.25 mm, the diameter range was 0.10–0.45 mm, and the coefficient of variation was 29%. Among the fibers used, those of a diameter of 0.20–0.25 mm comprised the largest proportion (approximately 30.17%), followed by fibers of a fiber diameter of 0.15–0.20 mm (approximately 27.08%), as shown in Figure 2(a). As the shape of the recycled fibers is irregular, the length of the fibers is calculated and expressed based on the length between the two ends of the fiber, which is called the equivalent fiber length [49]. The average length of the selected fiber is



(a)



(b)

Figure 2: Geometrical characterization of WTSFs [46]. (a) Proportion of the WTSF diameter and (b) proportion of the equivalent fiber length.

13.94 mm, the distribution range of its length is 1–37 mm, and the coefficient of variation of its length is 37%. The fibers of length 10–15 mm account for the largest proportion (approximately 40.75%), followed by the fibers of length 15–20 mm (approximately 22.92%), as shown in Figure 2(b).

In Figure 3, the average diameter and length of the WTSFs used in previous related studies are presented, and the relationship between the average diameter and length of the WTSFs for different recycling methods is depicted. As can be observed in this figure, the majority of the fibers have a diameter of 0.15–0.26 mm, which indicates that these fibers are obtained from scrap tires of similar vehicles and tire types. The diameter of the

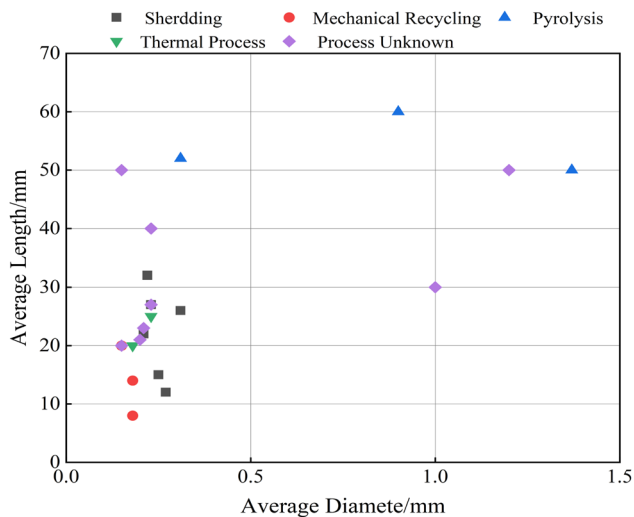


Figure 3: Average diameter and length of WTSFs [51].

steel fibers in ordinary pneumatic radial tires is generally 0.1–0.32 mm [50], but there also exist some outliers. In Figure 3, the geometric data of the WTSFs obtained from 25 experiments are represented by icons. Among them, the diameters of 21 recycled rigid fibers indicated in red are within the diameter range of steel fibers contained in passenger car tires (0.125–0.275 mm), of which only four average diameters are greater than the diameter of steel fibers contained in passenger car tires. Based on the existing data, the majority of steel fibers are recovered from passenger car tires, and some in-depth studies can be extended to the research of steel fibers obtained from trucks and heavy-vehicle tires.

In a fiber-reinforced concrete gel system, the fiber content, shape, and geometry have a significant influence on its workability and fluidity [51,52]. WTSFs have various geometric shapes and high aspect ratio, which cause WTSF concrete to exhibit an obvious balling effect [53]. When WTSFs are used in tires, the types of tires to be recycled are different, and the recycling procedures also vary. Therefore, the geometric shapes of the WTSFs are inconsistent. Some studies have found that the problem of how to avoid the spheroidization effect of WTSF concrete and maintain its workability can be solved by maintaining the geometric consistency and low aspect ratio of the recycled fibers, by using a superplasticizer to improve its workability, and by increasing the content of fiber in the mixing process. It was also found that a planetary vertical concrete mixer can effectively aid in realizing a uniform distribution of WTSFs in concrete. Using the mixer for mixing will not have any adverse impact on the workability of concrete, even when a high steel fiber content is added to the concrete. Therefore, for obtaining

WTSFs, specific standard procedures must be used, the recycling equipment should also meet the corresponding specifications, and the WTSFs should be classified and recycled according to their diameter and length. Based on the corresponding literature, it is found that when the fiber diameter and length ranges are 0.15–0.26 and 25–40 mm, respectively, it improves the mechanical properties of WTSF-reinforced concrete. Among the various fiber shapes, corrugated and irregular WTSFs can provide a superior anchorage bonding force for concrete. Furthermore, when recycling WTSFs, the impurities (rubber or other materials) on the surface of the WTSFs should be eliminated as much as possible. Recycled fibers having clean surfaces can be more effectively used in the construction industry, and they are also conducive to a more economical realization of our goal of sustainable development.

5 Mechanical properties of concrete with WTSF

5.1 Compressive strength

The amount of WTSF used in concrete has a significant impact on its strength. A content that is too small has little effect on the compressive strength of concrete [54]. Through research, it was found that, when the fiber content is less than 0.5%, its compressive strength only increases from 36.69 to 37.37 MPa. Thus, when the fiber content is low, the steel fiber content is not the main determinant of its compressive strength [46]. However, if too much fiber is added, it will have a negative impact on its compressive strength. Studies have shown that when the amount of WTSF added is 0.5%, the compressive strength increases by 5%. In contrast, when the amount of fiber is increased to 0.75%, the compressive strength reduced by 8%. This is because the increase in the fiber content results in fiber inclusions, which cause discontinuities in the body structure, thereby reducing its compressive strength [55]. ISFs and WTSFs are mixed into concrete at the same fiber–volume ratio. Figure 4(a) presents a comparison of the influence of these two fibers on the compressive strength of concrete. For the same fiber volume, the use of WTSFs improves the compressive strength of the concrete significantly less than ISFs, especially when the fiber volume ratio is greater than 1.5%. The result in Figure 4(b) is a comparison of the influence of the WTSFs and ISFs on the rate of increase in the

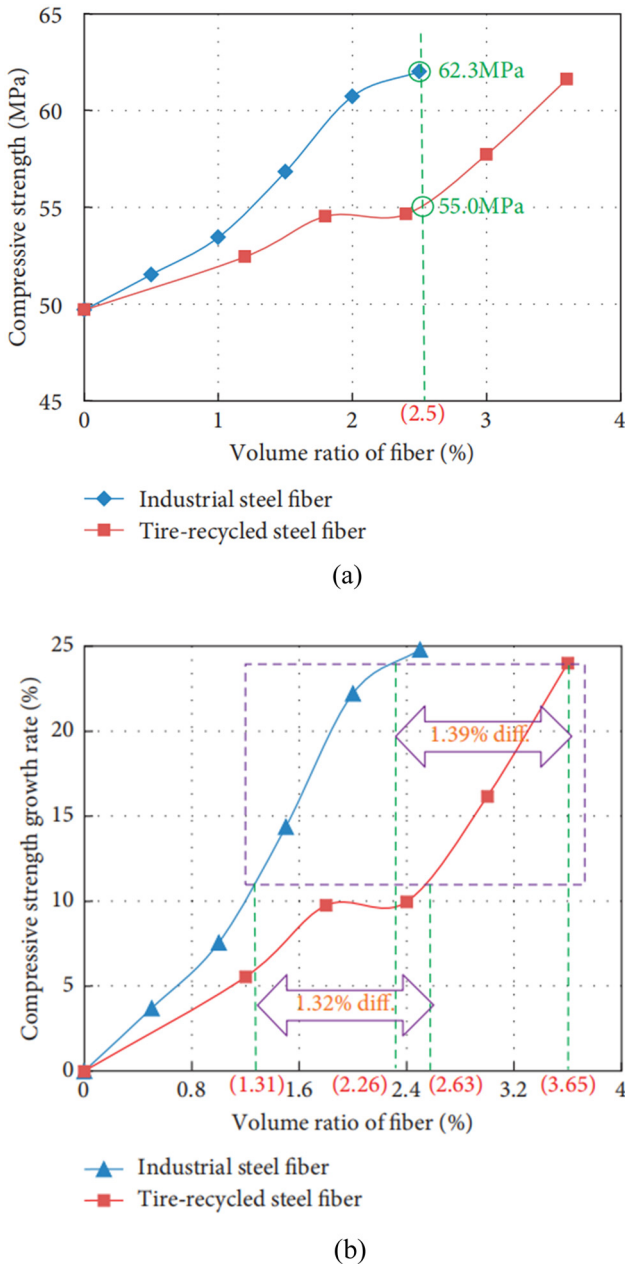


Figure 4: Comparison of the influence of two types of fibers on the compressive strength of concrete [57,58]. (a) Compressive strength at different fiber volume ratios and (b) rate of increase in compressive strength for different fiber volume ratios.

concrete compressive strength. The rate of increase in the strength of the two types of concrete increases as the fiber content increases. However, in contrast, the rate of increase in the strength of the test block comprising ISFs is significantly greater than that of WTSF concrete. In general, for the same rate of increase in strength, the WTSF content is approximately 1.3% greater than that of the ISFs [56]. Angelakopoulos et al. [57] concluded through research that the optimal content of

WTSF is 3% by mass. The results have shown that mixing fibers (ISFs and WTSFs) in a certain proportion has a significant impact on the compressive strength of concrete: ISFs and WTSFs are mixed in a ratio of 3:7, and when mixed with concrete at 1 and 1.25%, respectively, the resulting compressive strength is increased by 5–10% and decreased by 5%, respectively [58].

The fiber dispersion of WTSF concrete also has an impact on its compressive strength. Conventional concrete mixers cannot evenly disperse the WTSFs in concrete, and the enhancement of its compressive strength has thus not been fully realized. Aiello et al. [24] also showed that the mixing and dispersing effect of a vertical planetary mixer is better than that of a conventional mixer. The conventional mixer and vertical planetary mixer are used for mixing WTSF at 0.26 and 0.23%, respectively. The compressive strengths are increased by 12 and 20%, respectively. It can be observed that the dispersion of steel fibers has an important influence on the compressive strength of concrete.

Aiello et al. [24] suggested that the addition of WTSF to concrete would not increase its compressive strength significantly, and if a large amount of WTSF were added, it would have an impact on the workability of the concrete. To overcome these effects, it is necessary to add water reducing agent to concrete. The added water increases the porosity of the concrete, which has a negative impact on its compressive capacity. According to experiments, when the added high-density WTSF content is 5%, the overall compressive strength of the concrete is increased by 59% [59]. Li and Lin [60] mixed WTSFs into concrete in a certain proportion. The compressive results thus realized are presented in Figure 5. The compressive strengths were increased by 3.05, 4.70, and 9.56%, and the improvement effect was not obvious. Mastali et al. [61] found in their experiments that, when the ISFs and WTSFs are configured at ratios of 1 and 0.5%, respectively, their compressive strength was greatly improved by 50%.

The shape of the WTSFs and the impurities on their surfaces also have an impact on the compressive strength of concrete. Centonze et al. [49] found in experiments that the addition of 0.46% of irregularly shaped WTSFs effectively slowed down the propagation of concrete cracks and correspondingly increased its compressive strength by 25%. In another experimental result, the surface of the mixed fiber was not cleaned (i.e., rubber particles remained on the surface), and the compressive strength of the concrete was thus reduced from 135.5 to 130.2 MPa. In contrast, the compressive strength of the fiber composite material without rubber particles was increased from 135.5 to

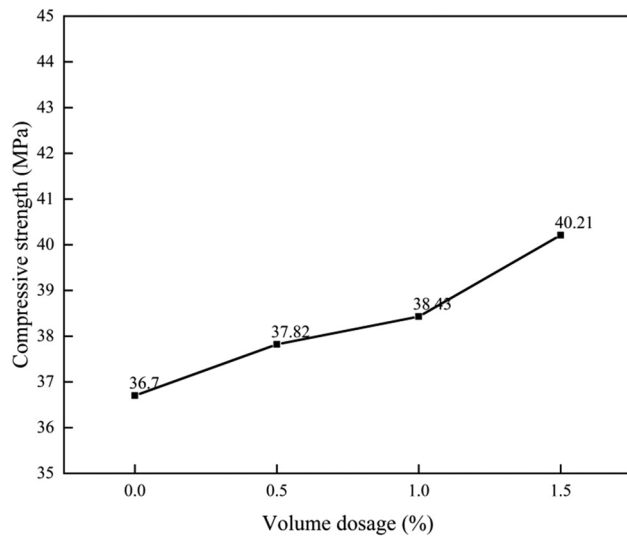


Figure 5: Effect of WTSF content on compressive strength of concrete [60].

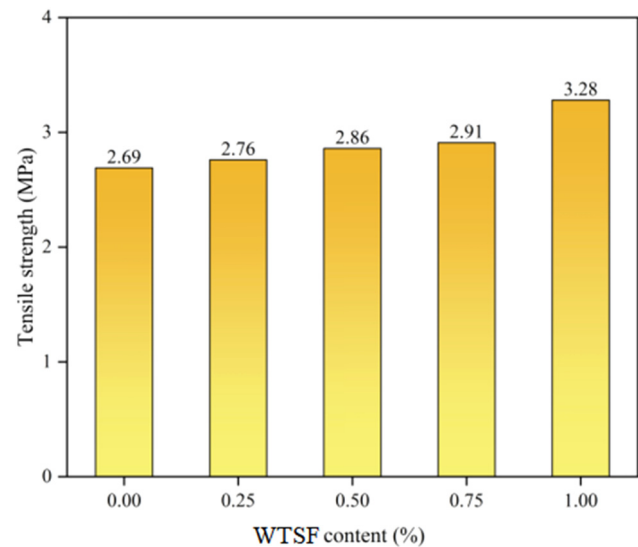


Figure 6: Comparison of tensile strength of ordinary concrete and WTSF concrete [63].

141.3 MPa [62]. It can be observed that the impurities on the surface of the WTSFs do not improve the concrete compressive strength. In contrast, the irregular shape of the WTSFs provides a good mechanical anchoring effect, which is conducive to the improvement of the concrete compressive strength.

Through research on the fiber content, optimal content, and fiber geometry of WTSFs mixed into concrete, it is found that WTSFs exhibit randomness in the improvement of the concrete compressive strength. Through experiments, it has been found that the fiber content is the main factor that enhances the compressive strength of WTSF concrete (WTSFC). In contrast, the geometry of the fiber has a weak effect on its compressive strength. In general, a higher WTSF content is conducive to improving the compressive strength of concrete. However, the existing research results are not completely unified. Therefore, it is necessary to conduct further research on the compressive strength of WTSFC.

6 Tensile strength

Tensile strength is also an important mechanical property of concrete. Fauzan *et al.* [63] mixed WTSFs into concrete in proportions of 0, 0.25, 0.75, and 1%, respectively, and tested the tensile strength after 28 days of curing. Figure 6 presents the experimental results. The results show that as the WTSF content increases, the tensile strength of the concrete also improves continuously. When 1% WTSF is

used, the tensile strength of the concrete test block is increased by 21.93% compared to that without fibers. This is because the WTSF incorporated into the concrete test block produces a large mechanical interlocking force inside the concrete, thereby increasing the tensile strength of the concrete test block. From the current research results, it is noted that the two main diameter range of the fiber used are 0.25–1.0 and 20–65 mm, respectively. Samarakoon *et al.* [64] found that when WTSFs and ISFs are mixed with concrete in the same volume fraction of 0.5 and 1%, the tensile strength of the concrete comprising WTSFs is increased by 18.3 and 14.2%, respectively, and the compressive strength of that comprising ISFs increased by 31.2 and 36.2%, respectively. Younis [65] concluded through experiments that the maximum tensile strength of concrete was increased from 3.6 to 4.6 MPa on adding WTSFs at a volume fraction of 4%. Skarzynski and Suchorzewski [66] stated in their research report that the tensile strength of WTSF concrete was 9% higher than that of ISF concrete, and the tensile strength of the concrete with WTSF was increased by 43%, while that of the concrete comprising ISFs was increased by only 30%. They speculated that this was caused by the rougher surface of the WTSFs.

Using the same method, fibers of various diameters and volume fractions are mixed into the concrete. WTSFs of diameters 0.8, 1.0, and 1.2 mm were used. When the corresponding fiber contents were 35 and 70 kg·m⁻³, the concrete tensile strengths increased by 27.8, 21.8, and 16.9% and 35, 31, and 24.5%, respectively [67]. It can thus be inferred that the smaller the diameter of the fiber,

the greater the improvement in the tensile strength of the concrete. This is because the fiber diameter reduces, and the fiber content under the same weight increases; therefore, the contact area between the fiber and concrete is increased, and the interface bonding between the fiber and concrete matrix is enhanced. Sengul [68] compared the tensile strength of WTSF concrete comprising fibers of various sizes with that of plain concrete and ISF concrete. The mix proportions of the concrete are listed in Table 1. In Table 1 and Figure 7, P indicates the plain concrete without fiber, W indicates the concrete containing WTSF, I indicates the concrete containing ISF, the numbers after R (0.3, 0.6, and 1.4) indicate the average diameter of the fiber (mm), and the numbers after “-” represent the fiber content ($\text{kg}\cdot\text{m}^{-3}$). Figure 7 presents the measured results. The results demonstrate that the addition of WTSF to concrete enhances its tensile strength, but the number and type of fibers affect the degree of improvement.

In contrast, the extant literature indicates that some scholars believe that the incorporation of WTSFs has a negative impact on the tensile strength of concrete [69–75]. Leone et al. [76] found that, when the blending amount of WTSFs was 0.46%, its tensile strength was reduced. Papakonstantinou and Tobolski [75] also found a similar situation. After adding the WTSFs, the tensile strength of the concrete was reduced. This occurred because the fibers were randomly dispersed in the concrete matrix during the tensile test. Therefore, during the tensile test, the main crack surface had a discontinuous destructive effect, and thus, the tensile strength of the concrete decreases [77]. In addition, the current technology available for recycling WTSFs cannot completely eliminate impurities from the fiber surface. Compared with the surrounding dense concrete matrix, these rubber particles have a soft characteristic that creates an elastic

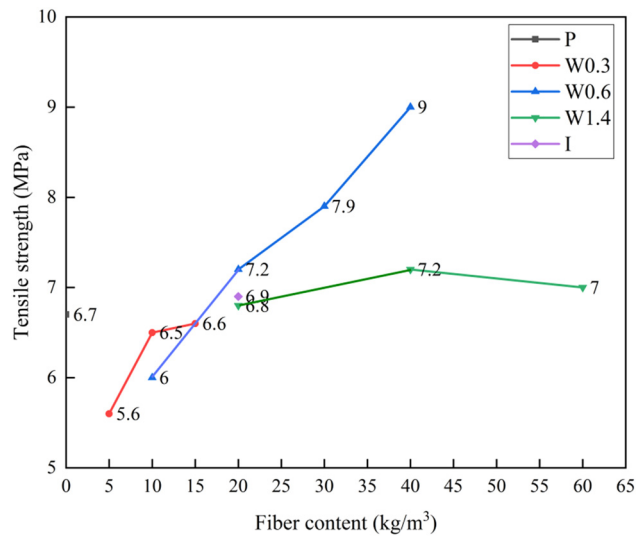


Figure 7: Influence of different fibers on the tensile strength of concrete [68].

imbalance around them, resulting in voids in the concrete matrix, which has a negative impact on the tensile strength of the concrete [67,69].

On summarizing and analyzing related articles, it is determined that WTSFs can effectively change the failure form of concrete to ductile failure, thereby enhancing the tensile and splitting strength of concrete. However, the tensile strength of concrete can be effectively enhanced only when the amount of WTSF reaches a threshold value. A fiber content lower than the lowest critical value cannot provide sufficient reinforcement. A fiber content higher than the highest critical value results in fiber dispersion in the concrete, resulting in the formation of cavities and weak points in the concrete, which causes the deterioration of the mechanical properties of the

Table 1: Mix proportions of various concrete [68]

Mixture ID	Cement ($\text{kg}\cdot\text{m}^{-3}$)	Water ($\text{kg}\cdot\text{m}^{-3}$)	Superplasticizer ($\text{kg}\cdot\text{m}^{-3}$)	Fiber ($\text{kg}\cdot\text{m}^{-3}$)	Sand (0–1 mm)	Sand (0–4 mm)	C. S. II (12–22 mm)
P	366	183	4.9	0	314	635	571
W0.3–5	365	182	4.9	4.9	312	631	568
W0.3–10	367	184	4.9	9.8	314	636	572
W0.3–15	364	182	4.9	14.8	311	629	565
W0.6–10	363	182	4.9	9.9	311	628	565
W0.6–20	368	184	4.9	19.7	315	636	572
W0.6–30	368	184	4.9	29.5	314	635	571
W1.4–20	362	181	4.9	19.8	310	626	563
W1.4–40	362	181	5	39.8	308	623	560
W1.4–60	363	182	4.9	59.7	308	623	560
I-20	364	182	5.1	20.2	310	628	555

concrete. Therefore, it is crucial to determine the optimal dosage range of WTSFs in concrete; however, the current research results do not specify a reliable optimal dosage value. The flexural and tensile strengths of WTSFC are also affected by the geometry of the fiber. The longer the fiber length, the better the reinforcement mechanism is. Accordingly, the flexural and tensile strengths of concrete are improved. Currently, pyrolysis is primarily used to recover steel fibers from tires. Because a temperature that is too high would damage the steel fiber, the low-temperature pyrolysis method is primarily used, but the low temperature also makes it impossible to effectively eliminate impurities from the surface of WTSFs. These attached impurities have an adverse impact on the mechanical properties of concrete. Therefore, when these WTSFs are treated, the impurities on their surface should be eliminated to ensure optimal mechanical properties of the WTSFC.

7 Flexural strength

In a certain sense, the flexural strength can be regarded as an indirect expression of the tensile strength. In the flexural strength test of concrete, small concrete beams are primarily used. On consulting the literature, it is found that some researchers have tested the flexural strength of WTSFC and arrived at a conclusion. Based on the related results, it can be observed that WTSFs have a positive effect on the flexural strength of concrete.

Aiello *et al.* [24] added WTSFs at a volume fraction of 0.23 and 0.46% to concrete and found that its flexural strength was 15.9 and 9.0% higher than that of ordinary concrete, respectively. This is because when the specimen is under a load, the fiber can play the role of connecting cracks, reduce the spread of cracks, and improve the flexural strength of concrete [78]. Using the same experimental method, Younis [79] added WTSFs and ISFs to concrete and compared the flexural strengths of the two types of concretes. He added the two types of fibers (WTSFs and ISFs) to concrete in the same volume fraction (2, 4, and 6%), and the flexural strength of the WTSFC was increased by 9.5, 19, and 14.3%, respectively. The flexural strength of the concrete containing ISFs increased by 14.3, 21.4, and 16.7%, respectively. He also compared the flexural strength of WTSFC for different fiber diameters and volume fractions. When the diameter and length of the WTSFs were 0.23 and 20 mm, respectively, the volume fraction mixed into the concrete was 0.2, 1, and 2%, and the flexural strength of the concrete

increased by 23.5, 54, and 80.9%, respectively. When the fiber diameter and length were 0.8–1.55 and 50 mm, respectively, and the volume fraction was 1.5, 3, and 6%, the concrete flexural strength was increased by 67.5, 111.5, and 150%, respectively [80]. Skarzynski and Suchorzewski [81] and Murthy and Ganesh [82] also conducted similar research and reached the same conclusions. These results indicate that the addition of WTSFs to concrete greatly improves the latter's flexural strength. In addition, Al-musawi *et al.* [83] experimentally found that WTSFs can improve the flexural strength of fast-hardening mortar. They incorporated $45 \text{ kg}\cdot\text{m}^{-3}$ of WTSFs in two types of mortar mixtures, which were prepared using calcium sulfoaluminate cement and rapid-setting calcium aluminate cement. It can be observed from the results in Figure 8 that the flexural strength of the mortar samples is significantly improved when the curing ages of the two mortar mixtures are 7, 28, and 365 days.

From the related research results, it can be observed that WTSFs can improve the flexural strength of concrete. However, there is an exception in one of the documents. As shown in Figure 9 (the symbol representation in the figure is consistent with Table 1), when the fiber content in concrete is 10 and $20 \text{ kg}\cdot\text{m}^{-3}$, and the fiber diameter is 0.3 and 0.6 mm, respectively, the test result indicates that the fracture modulus of the concrete decreases slightly. When the amount of WTSF is $40 \text{ kg}\cdot\text{m}^{-3}$ and the diameter is 0.6 mm, the flexural strength is increased to the greatest extent, i.e., 67.8% higher than that of plain concrete. Compared with ordinary plain concrete, the flexural strength of WTSFC with a fiber diameter of 1.4 mm when the fiber content is 20, 40, and $60 \text{ kg}\cdot\text{m}^{-3}$ increased by 21.4, 19.6,

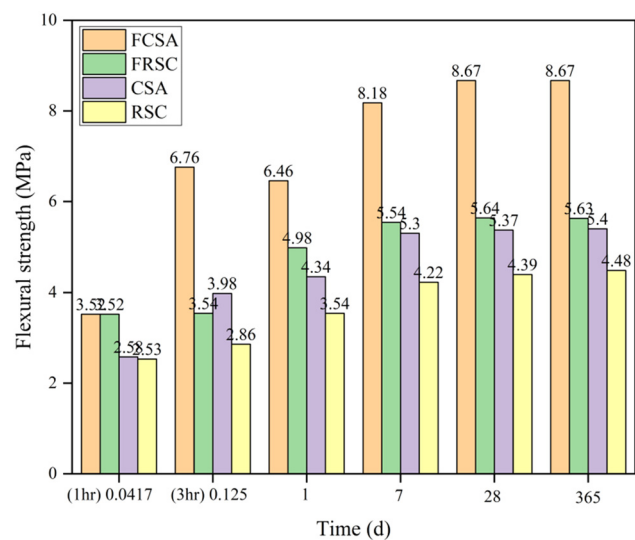


Figure 8: Flexural strength for all mixes [83].

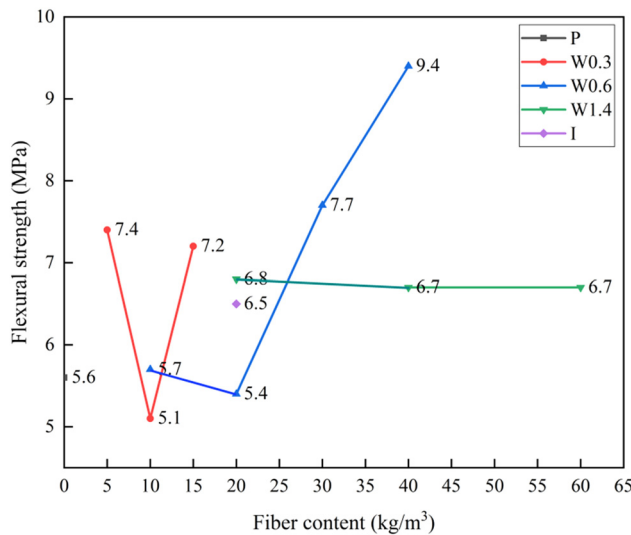


Figure 9: Influence of fibers on flexural strength of concrete [68].

and 19.6%, respectively [84]. It is also found in some documents that, although the size and content of the WTSFs used are different, the results obtained are similar [46,85].

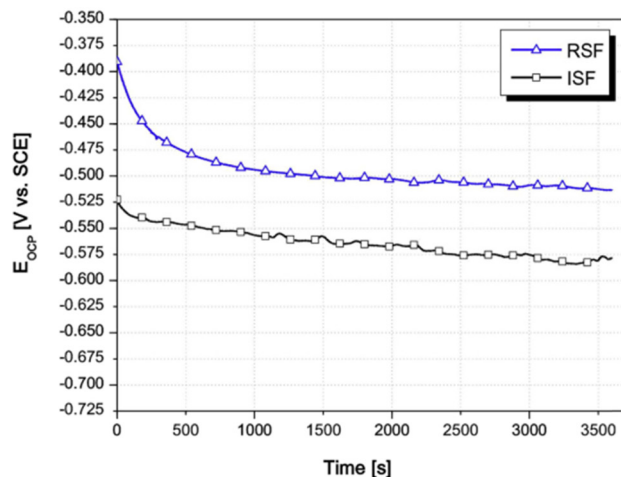
In summary, it can be observed that WTSFs have the effect of bridging and lateral cracking on the concrete matrix, and adding them to concrete can also improve the energy absorption capacity of concrete. When the recycled fiber content in the concrete is relatively low, the concrete exhibits a softening behavior. This is because the fiber content is too small, which makes the stress transfer between the added fiber and cement matrix insufficient, thus resulting in a softening reaction. Owing to the small contact surface, this increases the probability of fiber slip, which suddenly reduces the bearing capacity of the concrete after the initial crack. Therefore, the WTSF content in concrete has an important impact on its mechanical properties. Meanwhile, the aspect ratio of WTSFs also has a significant impact on the flexural performance of concrete because the former is directly related to the dispersion of the fiber effective stress transfer and its surface contact area with concrete. Therefore, to improve the flexural strength of concrete, attention should be focused on the content and aspect ratio of steel fibers.

8 Durability of WTSFC

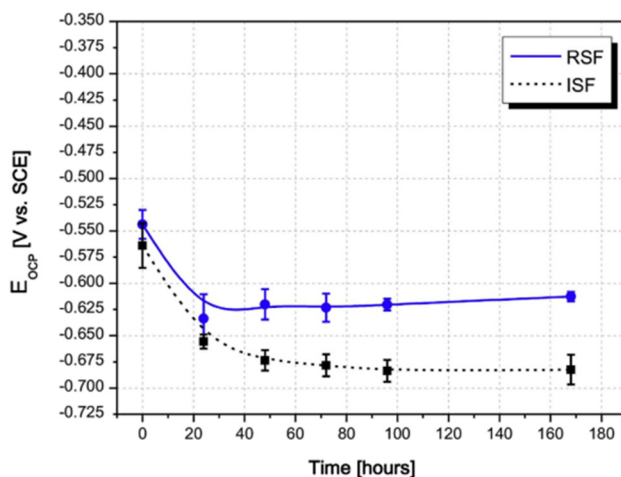
Incorporating WTSFs into concrete not only delays the expansion of cracks in concrete but also improves their shrinkage and impact resistance [86–92]. There are three main methods by which corrosive substances damage

concrete: penetration, diffusion, and capillary transportation. The main measure for preventing the penetration of harmful substances into concrete to the greatest extent is the control of the expansion of concrete cracks, which helps reduce the deterioration of the concrete and its internal steel fibers, thereby enhancing the durability of the concrete. Studies have shown that, when the crack width of concrete is maintained at 0.3 mm or maintained at less than 0.3 mm, the only damage to the concrete is the degradation of the surface fibers in a corrosive environment [93]. For example, in an environment comprising a relatively high content of chlorine, steel fibers mixed into concrete are more susceptible to chemical corrosion, which degrades the overall properties of the concrete [94]. Corrosion also seriously affects the interaction between the WTSFs and cement matrix. After the WTSF is pre-treated at 350°C, the austenite in the fiber structure is transformed into bainite, thereby enhancing the fiber hardness.

Figure 10(a) and (b) presents the average value of open circuit potential (E_{OCP}) of WTSF and ISF soaked for 1 h and 7 days in the potential experiment, respectively. The results show that the corrosion potentials of WTSFs and ISFs remain unchanged after immersion in chloride for 1 h. In the experiment of soaking for 7 days, the corrosion potential decreased rapidly after soaking for 1 day, thus indicating that the overall corrosion of the fiber increased. Subsequently, the potential of WTSFs was completely stabilized on the seventh day of immersion [95,96]. It can be observed from the results of the electrochemical experiment that, when the WTSFs and ISFs are placed in a 3.5% NaCl solution at the same time, the corrosion rate of the WTSFs is approximately 90%, which represents greater vulnerability to corrosion than the ISFs. In the potential polarization experiment of the fiber, the diameter of the fiber decreases and the surface becomes rougher, which shows that WTSFs cause corrosion product degradation in this experimental environment [95]. The technology for recovering WTSFs from waste tires has not reached a level whereby it could realize the complete elimination of impurities from the surface of WTSFs. Therefore, some scholars have also investigated whether the impurities on the fiber surface affect the corrosion resistance of WTSFs. The results of these studies indicate that residual impurities on the surface of WTSFs have no significant impact on its corrosion resistance [96]. Furthermore, the mechanical properties of WTSFC are not significantly degraded in either the wet or dry cycles of the chloride ion environment [97], and even if its exposure strength to chloride ions is strengthened, there is no obvious visual deterioration. Even if the



(a)



(b)

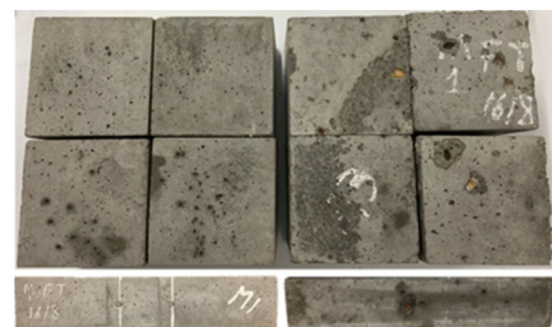
Figure 10: Changes of E_{OCP} of WTSF and ISF during immersion [95,96]. (a) Immersion period of 1 h and (b) immersion period of 7 days.

WTSF buried in the concrete is exposed to chloride, it does not exhibit serious deterioration [93]. Therefore, some researchers have stated that the addition of WTSFs to concrete can enhance the durability of the concrete matrix [98]. However, in chlorine-containing environments, WTSFs are more vulnerable to corrosion than ISFs. Rubber particles on WTSFs that cannot be completely removed would not enhance the corrosion, possibly because rubber acts as a natural barrier to water and other chlorides.

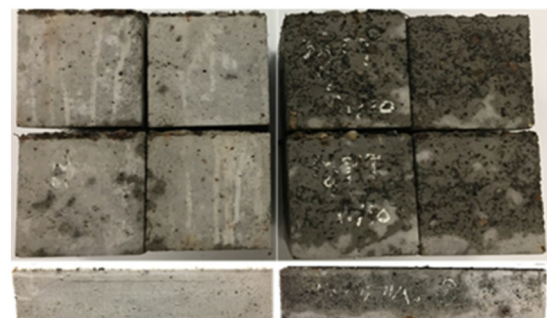
Recently, Astm [99] researched the freeze–thaw properties of WTSFC based on the procedures in the relevant literature, from the two directions of surface scaling and concrete cracking. The rubber particles remaining on the WTSFs, owing to their low density, cause the concrete matrix to have a high water absorption [100] and pore

connectivity, such that freeze–thaw cycles are generated in the concrete, which results in surface scaling and mortar shedding. In addition, the size of the remaining rubber particles is small, which causes the concrete matrix to have a large pore size and connectivity. Therefore, this reduces the compressive strength of concrete and increases the quality scaling; the changes in the concrete surface are presented in Figure 11. Figure 11(b) presents concrete comprising a 60% volume fraction of steel fiber and rubber particles for fine and coarse aggregates. However, the addition of steel fibers to concrete is very effective in enhancing its flexural strength [101].

In summary, it can be observed that the addition of WTSFs to concrete can improve its durability. Two important factors affecting the durability of concrete structures are volume stability and early shrinkage. These two factors reduce the strength of the concrete, resulting in cracks on the concrete surface. These cracks make it easier for water and other corrosive chlorides to invade the water mud matrix, thus resulting in degradation and corrosion of the reinforcement buried in the concrete. The research shows that the addition of WTSF to concrete can



(a)



(b)

Figure 11: Concrete surface condition after 56 cycles before (left) and after (right) freezing and thawing [100]. (a) Concrete with only steel fibers and (b) concrete with steel fibers and rubber particles.

enhance the volume stability of concrete and improve its durability. At the same time, mixing the WTSF evenly into the concrete can also effectively prevent the early shrinkage of concrete to enhance the durability of the concrete. Although impurities that cannot be completely eliminated from WTSFs will have a certain negative impact on the properties of concrete, its steel fibers can objectively enhance the durability of the concrete matrix. Therefore, the addition of WTSF to concrete is of positive significance to the properties of concrete.

9 Current challenges and future trends

This article presents an analysis of and looks forward to the current challenges and future development trends of WTSFC.

Currently, the processes and equipment for obtaining WTSFs from waste tires are not unified, which results in nonuniformity in the geometry of WTSFs. Therefore, it is a challenging task to evenly disperse WTSFs in concrete. To address this problem, corresponding standards should be formulated to eliminate the problems related to the geometric changes of existing WTSFs to the greatest extent to obtain qualified steel fibers. In the case of the various recycling technologies, their life cycle and environmental impact should be evaluated to determine the most reasonable and effective technology for obtaining uniform and high-quality recycled steel fibers. There also exists another problem that the present relevant data, such as the characteristics and quality, of the WTSFs in the corresponding table are relatively limited. Therefore, in the future, WTSFs obtained from different sources should be analyzed qualitatively and quantitatively to obtain detailed data.

Impurities that cannot be cleaned off the surface of WTSFs will seriously limit the contact between the cement matrix and the fiber surface. In the future, the interface between WTSFs and the surrounding matrix should be fully understood and studied in detail. In recent research, researchers have found that rubber particles attached to the surface of WTSFs are very sensitive to high temperatures. Therefore, future research should be focused on the interaction between fibers at high temperatures to better understand the behavior and specific changes of WTSFs in a concrete matrix. Furthermore, the spalling mechanism at high temperatures should also be studied in detail. In addition, WTSFs are more vulnerable

to corrosion damage than ISFs; therefore, a detailed study on their durability and corrosion sensitivity is also essential. It is found in this study that there are no specific guidelines for the design of WTSFC structural components. Therefore, when recovering steel fibers from tires, we should not only consider the quality changes and possible defects of recovered steel fibers but also expand the work to the formulation of design specifications.

10 Conclusion

On identifying and studying a large number of relevant studies, the following conclusions are drawn:

- (1) Although the concrete-reinforcement effect of WTSFs obtained from waste tires is still far from that of ISFs, it is feasible, environmentally friendly, and sustainable. It can be used as reinforcement material in different grades and applied to engineering projects with lower mechanical-property requirements of concrete compared with ISF-reinforced concrete, to achieve environmental protection and sustainability. Furthermore, the stripped rubber can be used as fuel, which can provide energy for the production of cement to reduce the use of ore fuel and reduce energy consumption.
- (2) The existing recycling technology cannot completely clean the surface of the steel fibers, which causes the rubber particles to remain on the surface of the steel fiber, which has a negative impact on the properties of WTSFs. Therefore, the recycling procedures and standards are required to be further optimized to obtain higher quality steel fibers.
- (3) The distribution of WTSFs in a concrete matrix has a significant impact on the improvement of the overall mechanical properties of concrete. The mechanical properties of concrete can be improved to the greatest extent only when the WTSF is evenly distributed in the concrete matrix. Owing to the irregular shape of WTSFs, it is easier to produce a spheroidizing effect with them than ISF. To address this problem, the steel fibers can be evenly dispersed in the concrete matrix using a planetary vertical mixer, adding superplasticizer, and using fibers of a uniform geometry and reasonable content and aspect ratio.
- (4) The WTSFs have a relatively small enhancing effect on the compressive strength of concrete. Few studies have been conducted on the interaction between WTSFs and its surrounding cement matrix and their behavior under compressive load; thus, further

research is required to be conducted on this subject in the future.

- (5) Mixing WTSFs and ISFs into concrete according to a certain proportion can provide concrete with superior mechanical properties for resisting structural loads. Under the same bending load, the reinforcement results of the WTSFs and ISFs are the same.

The research results reviewed in this article indicate that WTSFs can replace ISFs when added to concrete under reasonable conditions, and the mechanical effect of the reinforcement is identical to that of ISFs. Therefore, WTSFs can be used as an alternative to ISFs in the construction industry. It is a low-cost and environmentally friendly alternative. In addition, the recycling of waste tires and steel fibers also provides a new solution to the problem of the accumulation of waste tires, and better use can be made of waste tires, which not only provide an economical energy source but also prevents the breeding of mosquitoes, thus reducing the spread of diseases such as malaria and dengue fever.

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