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REVIEW

Waste tires steel fiber in concrete: a review

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Abstract

The emergence of waste tire steel fiber (WTSF) which is an undervalued resource was borne out of the need to extract the useful materials in waste tires considering the sheer volume of this resource that is disposed of in landfills globally. These fibers find applications in tunnel linings, hydraulic structures, bridge decks, pavements and slope stabilization. The fiber length has positive influence on compressive strength (increased by more than 10%), flexural strength (increased by more than 50%) and split-tensile strength(increased by more than 30%) while slump and flow (increased by more than 80%) were reduced but can be avoided through careful mixing, reduction of coarse aggregates and utilization of short fibers. Utilization of WTSF contributes to the sustainability of the construction industry. This paper focuses on reviewing the contemporary management of waste tires, fresh and hardened properties of steel fibers extracted from the waste tires, usage of the steel fibers and the durability of concrete containing these fibers.

Keywords Waste tire · Steel fibers · Concrete · Sustainability · Civil engineering · Construction

Introduction

Concrete is a composite material, brittle in nature with applications in many architectural structures, foundation, walls, bridges, roads, dams and reservoirs [1]. As a result of these various applications, a lot of research efforts have been made to improve concrete properties for better applicability [2–4]. One of such attempts to improve concrete properties was the introduction of steel into the concrete. These conventional reinforcements are in form of steel reinforcing bars placed at specific positions in the structure to resist imposed tensile and shear stresses [5, 6]. The incorporation of steel fibers on the other hand is usually discontinuous and randomly dispersed in the concrete mix. For concrete mix where the fibers are well dispersed they play a major role in minimizing the occurrence of cracks which may occur due to changes in temperature and relative humidity. The inclusion of fibers in the concrete mix enhances the engineering behavior of mortar and concrete. Although the role of fiber may not necessarily be in the form of strength increase it has a significant positive influence on the toughness, ductility and concrete resistance to dynamic loading [7–9]. These results corroborate the findings of previous researchers [10–14].

The fiber reinforcement is not a replacement for the conventional steel reinforcing bars since fibers and steel bars play distinct but complementary roles in enhancing the performance of concrete [6]. The incorporation of short discontinuous steel fibers into concrete matrix during mixing is referred to as Steel Fiber-Reinforced Concrete (SFRC) [15]. The main ingredients of SFRC are cement, aggregate (fine and coarse) water and well dispersed discontinuous steel fibers. SFRC may also contain pozzolana and admixtures depending on targeted applications [7]. The need for a

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sustainable environment and improved concrete performance has made waste tires a center of attraction for researchers [16–26].

The interest in this area of research is borne out of the continuous increase in population, rapid urbanization and improved standard of living. All these factors have increased vehicular ownership which has an indirect impact on the environment. However there is an increasing need to strike a balance between economic development and environmental preservation [27]. According to Thomas et al. [17], the average life of vehicular tires was estimated to be 10 years after two threading, by this estimate the number of waste tires in India was put in the order of 112 million per annum. The generation, handling and disposal of these waste tires are of great importance to the environment. It constitutes menace in most developing countries with insufficient landfill, inadequate facilities and technical know-how to process and recycle them into valuable products. Discarded tires provide an avenue for breeding of mosquitoes which transmits the malaria parasite [18], the malaria parasite has been reported to be responsible for hundreds of thousands annual deaths worldwide [28]. This makes the recycling of waste tires in developing countries a point of research interest.

In the last three decades, SFRC has been found useful in many applications such as tunnel linings, hydraulic structures, slabs, bridge deck, foundation, refractory concrete fiber shot-crete and precast elements [9, 29]. The application of this material in concrete depends on the creativity of the engineer since the use of 1% industrial steel fiber (ISF) automatically doubles the material cost of the concrete [15]. This has made the use of steel fiber extracted from waste tires a good alternative for producing SFRC. It has been observed that concrete reinforced with these fibers has similar performance with industrially produced steel fibers. This promotes an environmentally friendly means of handling some of the problems associated with waste tire generation. It also serves as a means for promoting sustainability in the construction industry [18].

In addition, steel fibers are also useful in the areas of highway pavement and precast applications resulting in high flexural strength, decrease in the overall pavement thickness and increases the resistance to impact and repeated loading [30]. SFRC has high resistance to erosion caused by the movement of water at high speed when used in hydraulic structures. The fibers hotcrete are particularly useful in rock slope stabilization lining of tunnels and repair of bridges. Fibers used in refractory concrete can withstand higher thermal stress, thermal cyclic and thermal shock when compared to their unreinforced refractory concrete [9]. This paper explores the prospect and challenges of waste tires steel fibers in concrete and as well highlight its potentials for better applicability. This paper is focused on reviewing the contemporary management of waste tires, fresh and hardened properties of steel fibers extracted from the waste tires and the durability of concrete containing these fibers. Such information will help to provide up-to-date knowledge on the properties of the fibers and spur more research toward its practical applications.

Waste Tire Management

According to Pilakoutas et al. [29], over a billion waste tires are generated worldwide. The accumulation of these tires poses a major challenge since the component materials of tires are highly complex which makes natural degradation very difficult to accomplish [23]. Waste tire generation remains an environmental problem in both developed and developing countries due to their cheap availability and bulk resilience. In Nigeria for instance, waste tires are stockpiled in undeveloped lands at different locations across the country due to nonavailability of landfill for proper disposal. These stockpiled tires provide an excellent breeding space for pests and insects [31]. It is estimated that 11.8 million vehicles ply Nigerian roads either for commercial or personal purposes annually [32]. Sadly, a large majority of vehicle owners depend on used tires imported from other countries with an estimated life of 2 years. This implies that the probable number of estimated discarded tires at the end of every 2 years life span is over 80 million. This makes it imperative for the proper management of this huge waste. Several ways by which waste tyres can be managed include material recovery, energy recovery, retreading, export and disposal to landfill [29].

The emergence of improved technologies to retrieve the components of waste tires has renewed interest in waste tires steel fiber (WTSF) recycling. The various derivable products from waste tiress include nylon fibers, nylon pellets, steel wires, rubber crumbs, rubber powder and steel beads and are displayed in Fig. 1. The introduction of industrially manufactured steel fiber into concrete has been investigated with far-reaching recommendations in favor of steel fibers [33–39]. However, for a developing country like Nigeria with no visible presence of a viable steel manufacturing company it becomes imperative to look inward for alternative means of obtaining steel fibers. One of such alternatives is the extraction of steel fiber component of waste tires. This will help curb the environmental problem associated with waste tire management and as well provide an avenue for improving the mechanical properties of concrete.

According to Bulei et al. [31], the component of a tire consist of rubber content, carbon black, steel insert, oil and vulcanizing agents, inserts synthetic yarns and textiles ranging between 46 and 48%, 25–28%, 10–12% and 3–6%, respectively. WTSF have been found to possess mechanical properties comparable to industrial fibers and have been

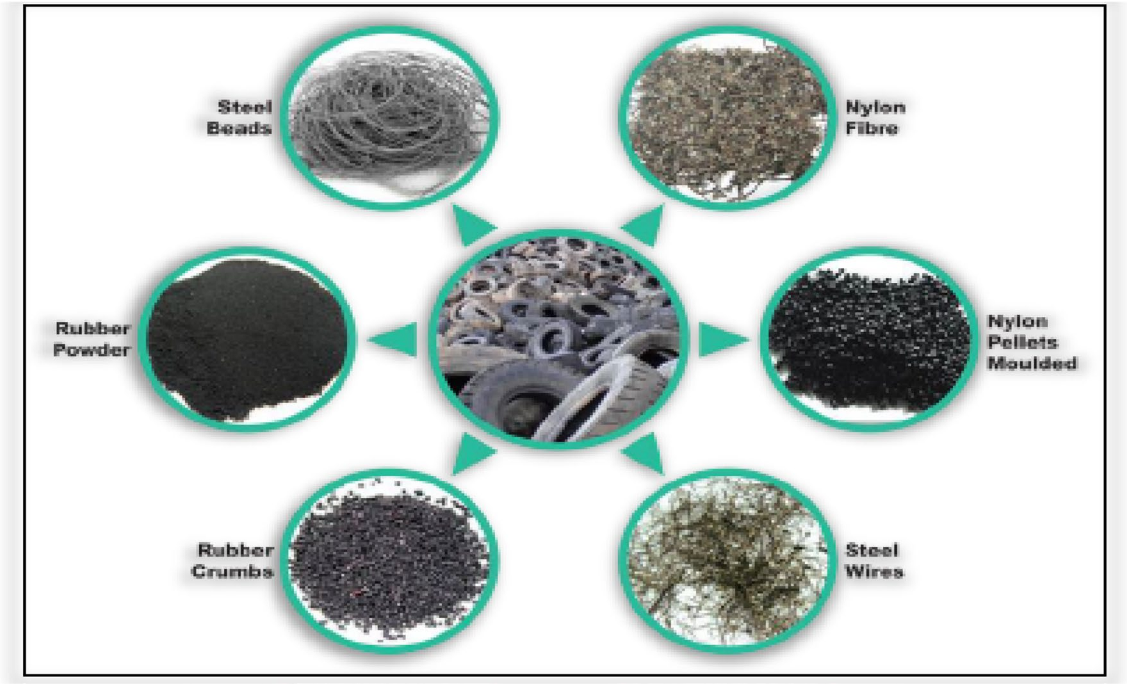

Fig. 1 Materials obtained from vehicular waste tire [31]

recommended for fiber reinforcement in concrete [40–43]. However, Martinelli et al. [44] reported that ISF cannot be replaced with the same quantity of recycled steel fibers due to post cracking behavior under flexural loading. The recovery of steel fiber from wastes tires are usually in the form of shredding, cryogenic and anaerobic thermal degradation processes [29]. The quantity of steel fiber extracted from waste tire is dependent on the type of tires. Lightweight vehicles contains up to 15% of steel component while trucks contains up to 25% steel component [29].

Characteristics of Steel Fibers from Waste Tires and Method of Mixing SFRC

The steel fibers obtained from waste tires can be described as straight or slightly deformed. The diameter of these fibers ranges between 0.23 and 1.8 mm depending on the method of extraction [29, 45]. Fibers extracted through the process of shredding was found to have a diameter of about 0.23 mm while those extracted through the microwave-induced pyrolysis process were found to have ranged between 0.8 and 1.5 mm [29]. Conversely, steel fiber extracted from waste tires can be described as either smooth surface or crimped base [46]. Fibers can be categorized as macro or micro based on their length [47]. Macrofibers have a length which varies between 19 and 60 mm, and they are effective in crack bridging and providing structural support in hardened concrete [36]. Conversely, the length and diameter of microfibers are usually between 2–10 mm and 0.1-1 mm. respectively. A comparison between typical properties of WTSF and ISF is presented in Table 1. Steel fibers are usually discrete, short length and defined by the aspect ratio (length to diameter). The aspect ratio irrespective of the diameter is usually in the range of 20–100 [48]. Since these fibers are sufficiently

Table 1 Comparison of typical properties of steel fibers

Fiber types	Length (mm)	Diameter (mm)	Tensile strength (MPa)	Elastic modulus (GPa)	Authors
WTSF	23	0.22	2570	200	Hu et al. [12]
WTSF	20,40,60	1.15	1054.7	–	Ndayambaje [9]
WSTF	40	0.15	2000	–	Mastali [50]
ISF	55–60	0.8- 1	1050–1450	200	Hu et al. [12]
ISF		0.25–1	280–2800	200–250	Shi et al. [51]

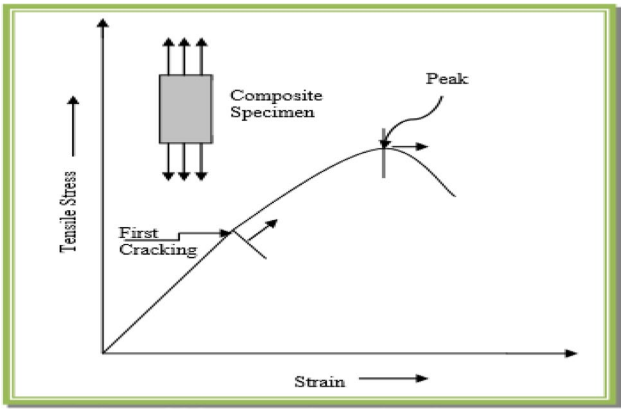

Fig. 2 Ductile nature of steel fiber-reinforced concrete [9]

small they can be easily and randomly dispersed in the concrete mix [49].

Amuthakkanna [52] identified the homogenous dispersion of fibers during concrete mixing as a vital factor for enhanced mechanical performances. Enhanced performance is achieved through combined adhesion, friction and mechanical interlock. Bentur and Mindess [53] described fiber-reinforced concrete as a composite material comprising of two phases concrete, namely the concrete which represents the matrix phase, while the fiber constituents represent the inclusion phase. According to Nasir [15], the matrix strength, fiber modulus, fiber types, fiber aspect ratio, fiber strength, fiber surface bonding characteristic, fiber orientation, fiber content and aggregate size effects were identified as factors that improve the post-elastic property of concrete. The fibers are included in the concrete mix to improve early age tensile and flexural strength which provides tensile resistance against dry and plastic shrinkage [46]. The ductile nature of SFRC is presented in Fig. 2.

Chanh [54] reported that the cement and aggregate contents required for steel fiber-reinforced concrete are higher than that required for conventional concrete. This implies that the mix design applicable to both concrete differs. To reduce the cement required in the mixing process supplementary cementitious materials such as fly ash, silica, limestone, steel slag powder, rice husk ash, metakaolin, granulated blast furnace slag can be partly used as a replacement for cement [51]. The level of cement replacement and type of supplementary cementitious materials is usually determined by the relative availability of the replacing material. The steel fiber component is usually introduced as the last constituent to be added during concrete mixing as presented in Fig. 3. The most common mixing process of concrete containing steel fiber is illustrated in Fig. 3 [39, 51]. The ACI committee [55] proposed a range of proportion for normal weight fiber-reinforced concrete as presented in Table 2.

This table shows a variation in mix compositions as the sizes of coarse aggregate changes. Reduced water-cement ratio, increased quantity of cement, steel fiber, aggregates and water cement ratio are required as aggregate sizes increases. This mix design was based on the fact that smaller aggregate sizes have a much greater combined surface area than large aggregates. This mix composition has been found useful for both industrially manufactured steel fibers and steel fiber extracted from waste tires [15, 54, 56, 57]. However, it is important to

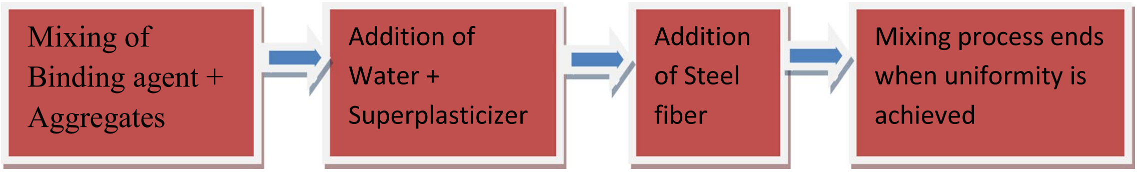

Fig. 3 Mixing procedure for fiber-reinforced concrete

Table 2 A range of proportion for steel fiber-reinforced concrete [55]

Properties	9.5 mm Maximum aggregate size	19 mm Maximum aggregate size	38 mm Maximum aggregate size
Cement (kg/m^3)	355 -590	300 – 535	280–415
Water cement ratio	0.35–0.45	0.4–0.5	0.35–0.55
Fine/ coarse aggregate (%)	45–60	45–55	40–55
Entrained air (%)	4–7	4–6	4–5
Fiber content (%) by volume			
Smooth steel	0.4–1.0	0.3- 0.8	0.2–0.7
Deformed steel	0.8–2.0	0.6–1.6	0.4–1.4

avoid undesirable conditions such as formation of balls which can be attributed to the presence of too many fibers (volumetric fraction of fiber content exceeding 2%), rapid addition of fibers to mixture, wrong sequence of the mixing procedure (making fibers the first constituent to be added) and the presence of too many coarse aggregates.

Properties of Concrete in the Fresh State

Workability (slump)

The efficacy of all fiber reinforcement is predominantly dependent on the ability to achieve homogenous dispersion of the fibers in the concrete matrix. It has been generally reported that the presence of fibers reduces the workability of concrete [9, 15, 50, 54, 58–68]. Atis and Karahan [65] observed reduced workability with increase in steel fiber content. Mohammadi et al. [67] investigated the effect of aspect ratio on SFRC. They observed a uniform decrease in workability with an increase in aspect ratio. This observation is collaborated by Figueiredo and Ceccato [69], who recommended a reduced aspect ratio to enhance aggregate movement and material mobility. It is important to achieve a workable fiber-reinforced concrete as this will ensure proper placing, consolidation and finishing with less effort. Often, the freshly prepared SFRC appears relatively stiffer and unworkable than the conventional concrete even with the use of appropriate water cement ratio. This has led to the introduction of high range water reducing admixture or superplasticizers to allow for proper workability and easy placement [18, 54, 63, 70]. Also, Wafa [71] observed that the slump values of fiber-reinforced concrete reduce with increase in fiber content from 0 to 2%. Syaidathul and Izni [63] incorporated steel fibers extracted from waste tires into concrete mix. The workability of the freshly prepared concrete mix was observed to reduce with increasing in fiber content. It could be inferred that both industrially manufactured steel fiber and waste tires steel fiber have a similar influence on workability.

Table 3 presents slump values obtained from previous studies on concrete reinforced with steel fibers obtained from discarded tires. The variation in the results for slump values observed in the Table could be attributed to the disparity in the fiber diameter and volumetric fraction considered by the different authors. In general, a similar trend of reduction in slump values with increase in fiber content and length was observed. This implies that both parameters play an important role in determining slump value of freshly prepared SFRC.

Segregation and Bleeding

According to Mastali and Dalvand [50] the slump flow test and the V-funnel test can be used to access the state of freshly mixed concrete containing recycled steel fibers extracted from tires. The authors observed that for a well-dispersed fiber, no segregation takes place between the fibers and the constituents of concrete. Figueiredo and Ceccato [69] have identified the presence of fiber as a hindrance to flow in concrete. The intensity of this mobility loss can be reduced with the use of short fibers. Libre et al. [72] observed that polypropylene fibers had less effect on segregation compared to steel fibers. They concluded that the presence of fibers generally reduces the segregation due to their blocking action. Chen and Liu [73] also observed that the presence of fibers in the concrete mix has a holding effect which prevents segregation of aggregates, surface bleeding and as well encourages uniformity of the mix. The use of short steel fibers can be a strategy to control segregation and bleeding of freshly prepared SFRC.

Properties of Concrete in the Hardened State

Compressive Strength

Nasir [15] investigated the effect of fiber length and fiber volumetric fraction on the compressive strength of concrete reinforced with steel fiber extracted from discarded tires. The fiber length was varied at 20 mm, 40 mm and 60 mm, while the volumetric fraction was varied at 0%, 0.5%, 1% and 1.5%. From the results, 1.5% volumetric fraction with a fiber length of 40 mm was observed to give the highest compressive strength. Similarly, Ndayambaje, [9] experimented steel fiber extracted from discarded tires, these fibers were varied at different lengths (20 mm, 40 mm, 60 mm) and volumetric fraction (0%, 0.3%, 0.5%, 1% and 1.2%). Their effect on the compressive strength of concrete containing rubber crumbs as aggregate was examined. The results showed that the fiber length of 40 mm at a volumetric fraction of 1.2% gave the best result.

Mastali and Dalvand [50] also investigated the effect of volumetric fraction (0%, 0.25%, 0.5%, 0.75%) on the compressive strength of steel fiber-reinforced self-compacting concrete extracted from discarded tires at the same fiber length (40 mm). The highest compressive strength was observed at 0.75% with a fiber length of 40 mm. Syaidathul and Izni [63] also examined the effect of volumetric fraction (0%, 0.2%, 0.4%, 0.6%, 0.8%, 1%) and randomly distributed fiber length varying between 20 and 99 mm on compressive strength. Their results showed that the volumetric fraction of 0.4% WTSFs gave the best results for compressive strength.

Table 3 Results of slump values obtained from using waste tire steel fiber

Authors	Type of concrete	Mix design	Steel fiber diameter (mm)	Steel fiber length (mm)	Slump value (mm)
Nasir [15]	SFRC	SF 0%	–	–	91
	W/C = 0.42	SF 0.5%	0.72–0.89	20	74
	TS =	SF 0.5%	0.72–0.89	40	55
	970.2 MPa	SF 0.5%	0.72–0.89	60	43
		SF 1.0%	0.72–0.89	20	58
		SF 1.0%	0.72–0.89	40	19
		SF 1.0%	0.72–0.89	60	5
		SF 1.5%	0.72–0.89	20	54
		SF 1.5%	0.72–0.89	40	8
		SF 1.5%	0.72–0.89	60	0
Ndayambaje [9]	SFRCCRA	SF 0%	–	–	84
	W/C = 0.5	SF 0.3%	1.15	60	61
	TS = 1054.7 MPa	SF 0.9%	1.15	60	34
		SF 0.6%	1.15	60	47
		SF 1.2%	1.15	20	29
		SF 1.2%	1.15	40	18
		SF 1.2%	1.15	60	11
Mastali and Dalvand [50]	SCSFRC	SF 0%	–	–	630
	W/C = 0.44	SF 0.25%	0.15	40	610
	TS = 2000 MPa	SF 0.5%	0.15	40	600
		SF 0.75%	0.15	40	580
Syaidathul and Izni [63]	SFRC	SF 0%	–	–	55
	W/C = 0.52	SF 0.2%	0.2–1.39	20–99	60
	TS = NA	SF 0.4%	0.2–1.39	20–99	30
		SF 0.6%	0.2–1.39	20–99	10
		SF 0.8%	0.2–1.39	20–99	30
		SF 1.0%	0.2–1.39	20–99	10

SFRCCRA—Steel Fiber-Reinforced Concrete containing 12.5% of Crumb Rubbers as Aggregate

SCSFRC- Self Compacting Steel Fiber-Reinforced Concrete, SF- Steel Fiber, W/C –Water Cement ratio, NA = not available

Table 4 Results of compressive strength obtained from using WTSF

Author(s)	Type of concrete	SF (%)	SF diameter (mm)	SF length (mm)	W/C	Fiber tensile strength (MPa)	CS (MPa) at 28 days
Nasir [15]	SFRC	1.5	0.72–0.89	40	0.42	970.2	43.94
Ndayambaje [9]	SFRCCRA	1.2	1.15	40	0.5	1054.7	35.25
Mastali and Dalvand [50]	SCSFRC	0.75	0.15	40	0.44	2000	66
Syaidathul & Izni [63]	SFRC	0.4	0.2–1.39	20–99	0.52	–	59.17

SFRCCRA—Steel Fiber-Reinforced Concrete containing 12.5% of Crumb Rubbers as Aggregate

SCSFRC- Self Compacting Steel Fiber-Reinforced Concrete, SF- Steel Fiber, W/C –Water Cement ratio, CS – Compressive Strength

Details of previous studies are presented in Table 4. The disparity in the results obtained could be attributed to the variation in steel fiber content, diameter and tensile strength.

Flexural Strength

There are several design codes [74–78] available as well as methods adopted by different researchers in understanding the flexural behavior of SFRC [79–81]. These methods include the three (3) and four (4) point bending tests for prisms and square slabs. From the flexural strength data, it was generally inferred that the presences of steel fibers provide about 50–70% in strength when compared to an unreinforced concrete matrix in the 3 points bending test. This strength increase can further be enhanced by higher fiber volume, center point loading and the user of long fibers aligned in the longitudinal direction [79–81].

Stiel et al. [82] observed significant differences from the 3 point bending test results between beams cast horizontally and those casts vertically. The splitting and flexural strengths results showed that the vertically case beams were only 25 and 34% of the horizontally cast ones, respectively. They attributed it to the alignment of the fibers in a direction normal to the casting direction. The use of deformed bars at lower volumetric fraction can also improve flexural strength due to their improved bond characteristics [8]. For SFRC, previous researchers [7, 83, 84] have also identified flexural strength test as a preferable test in determining the post cracking residual, flexural tensile and toughness compared to uniaxial tension test due to the difficulties experienced in conducting the test and interpreting the results obtained.

Nasir [15] investigated the effect of fiber length and fiber volumetric fraction on the flexural strength of concrete reinforced with steel fiber extracted from discarded tires. The fiber length was varied at 20 mm, 40 mm and 60 mm, while the volumetric fraction was varied at 0%, 0.5%, 1% and 1.5%. From the results obtained at each level of volumetric fraction, the longest length of the fiber (60 mm) was observed to give the highest flexural strength. Ndayambaje [9] carried out an experiment on concrete containing rubber crumbs and as well reinforced with steel fibers obtained from discarded tires. The fibers were varied at different length (20 mm, 40 mm and 60 mm) and volumetric fraction (0%, 0.3%, 0.5%, 1% and 1.2%). The results showed that fiber length of 60 mm at a volumetric fraction of 1.2% gave the best result.

Mastali and Dalvand [50] also investigated the effect of volumetric fraction (0%, 0.25%, 0.5%, 0.75%) on the flexural strength of steel fiber-reinforced self-compacting concrete. The steel fibers used in the study were extracted from discarded tires. A constant fiber length of 40 mm was considered for all concrete mix. The highest flexural strength was achieved using a volumetric fraction of 0.75%. Syaidathul and Izni [63] examined the effect of volumetric fraction (0%, 0.2%, 0.4%, 0.6%, 0.8%, 1%) and randomly distributed fiber lengths varied between 20 and 99 mm on flexural strength. From the results obtained it was observed that the volumetric fraction 0.4% gave the best results for flexural strength. A summary of flexural strength values obtained from different studies is presented in Table 5. The reason for the disparities in the flexural strength values could also be attributed to variation in steel fiber content, diameter and tensile strength.

Split Tensile Strength

According to Mastali et al. [85], the splitting tensile strength of concrete containing recycled steel fibers was found to have increased to about 30% due to the bridging action of the fibers. Mastali et al. [86] also observed an increase in the split tensile strength with increase in volumetric fraction of recycled steel fibers from 0.5 to 1%. This implies that the volumetric content of steel fiber has a notable effect on split tensile strength irrespective of the types of binder used.

Ndayambaje [9] experimented steel fiber obtained from discarded tires, these fibers were varied at different length (20 mm, 40 mm, 60 mm) and volumetric fraction (0%, 0.3%, 0.5%, 1% and 1.2%). Their effect on the split tensile strength of concrete containing rubber crumbs as aggregate was examined. The results showed that fiber length of 60 mm at a volumetric fraction of 1.2% gave the best result. Mastali and Dalvand [50] also investigated the effect of volumetric fraction (0%, 0.25%, 0.5%, 0.75%) on the split tensile strength of steel fiber-reinforced self-compacting concrete extracted from discarded tires at a same fiber length (40 mm). The highest split tensile strength was observed at 0.75% with a fiber length of 40 mm.

Syaidathul and Izni [63] examined the effect of volumetric fraction (0%, 0.2%, 0.4%, 0.6%, 0.8%, 1%) and randomly distributed fiber length varying between 20 and 99 mm on split tensile strength. From the results obtained, it was observed that the volumetric fraction of 1% gave the best

Table 5 Results of flexural strength obtained from using WTSF

Author(s)	Type of concrete	SF (%)	SF diameter (mm)	SF length (mm)	W/C	Fiber tensile strength (MPa)	FS (MPa) at 28 days
Nasir [15]	SFRC	1.5	0.72–0.89	60	0.42	970.2	14.79
Ndayambaje [9]	SFRCCRA	1.2	1.15	60	0.50	1054.7	5.74
Mastali and Dalvand [50]	SCSFRC	0.75	0.15	40	0.44	2000	5.60
Syaidathul & Izni [63]	SFRC	0.4	0.2–1.39	20–99	0.52	–	7.49

SFRCCRA—Steel Fiber-Reinforced Concrete containing 12.5% of Crumb Rubbers as Aggregate

SCSFRC-Self Compacting Steel Fiber-Reinforced Concrete, SF-Steel Fiber, W/C–Water Cement ratio, FS–Flexural strength results for split tensile strength. Table 6 presents the results for split tensile strength obtained from previous study using steel fibers extracted from discarded tires. From this table it could be inferred that variation in fiber content, diameter, length and tensile strength has negligible effect on the split tensile strength.

Impact Resistance

The impact resistance of SFRC is one of its unique attributes. The repeated drop weight method, instrumental impact test and projectile impact test are ways of measuring impact resistance. The use of repeated drop down weight method has been applied by researchers in determining the first and final crack resistance [9, 15, 34, 50, 86]. It has been generally observed that fiber increases both the fracture energy and the peak load under impact [87]. Following the recommendations of ACI committee [7], impact resistance should be measured in terms of repeated blows received by the test specimen. The first impact strength is measured as the number of blows required for visible initial cracks while the ultimate strength is measured as the number of blows that causes the failure of the test specimen. The presence of steel fibers has a positive influence on the impact resistances because it increases the fracture energy, peak loads, resistance to abrasion and impact resistance [87]. The impact resistance of SFRC is dependent on the length and volumetric fraction of the fiber in the concrete mix [15, 86].

Nasir [15] investigated the effect of different lengths (20 mm, 40 mm and 60 mm) and volumetric fraction (0%, 0.5%, 1% and 1.5%) of steel fiber on the impact resistance on SFRC. From this investigation, it was observed that the number of blows required for the ultimate crack of test specimens increased with increasing fiber length and volumetric fraction. The highest number of blows was observed at 60 mm fiber length and 1.5% volumetric fiber which signifies the highest impact resistance.

Ndayambaje [9] examined the impact resistance of steel fiber extracted from discarded tires. The fibers were varied at different lengths of 20 mm, 40 mm and 60 mm, while the volumetric fractions was varied at 0%, 0.3%, 0.5%, 1% and 1.2%. All mix constituents of SFRC contained 12.5% crumb rubbers as part replacement for coarse aggregate. The highest impact resistance as indicated by the number of blows was observed at 60 mm fiber length and 1.2% volumetric fraction. Mastali and Dalvand [50] also studied the impact résistance of self-compacting steel fiber reinforced containing varying volumetric fraction of steel fibers (0%, 0.25%, 0.5% and 0.75%) and constant fiber length of 40 mm extracted from discarded tires. The highest impact resistance measured in terms of the number of blows was observed at 0.75% volumetric fraction. Table 7 presents a summary of impact resistance values obtained from previous research. From this Table it was also observed that SFRC is better at resisting impact loads when compared with SFRCCRA and SCSFRC. The behavior of SFRC subjected to impact

Table 6 Results of split tensile strength obtained from using WTS

Author(s)	Type of concrete	SF (%)	SF diameter (mm)	SF length (mm)	W/C	Fiber tensile strength (MPa)	STS (MPa) at 28 days
Ndayambaje [9]	SFRCCRA	1.2	1.15	60	0.5	1054.7	3.10
Mastali and Dalvand [50]	SCSFRC	0.75	0.15	40	0.44	2000	4.60
Syaidathul & Izni [63]	SFRC	1.0	0.2–1.39	20–99	0.52	–	4.44

SFRCCRA—Steel Fiber-Reinforced Concrete containing 12.5% of Crumb Rubbers as Aggregate

SCSFRC- Self Compacting Steel Fiber-Reinforced Concrete, SF- Steel Fiber, W/C –Water Cement ratio, STS- Split tensile strength

Table 7 Results of impact resistance obtained from using WTSF

Author(s)	Type of concrete	SF (%)	SF diameter (mm)	SF length (mm)	W/C	Fiber tensile strength (MPa)	Ultimate crack impact resistance (blows)
Nasir [15]	SFRC	1.5	0.72–0.89	60	0.42	970.2	1248
Ndayambaje [9]	SFRCCRA	1.2	1.15	60	0.5	1054.7	143
Mastali and Dalvand [50]	SCSFRC	0.75	0.15	40	0.44	2000	81

SFRCCRA—Steel Fiber-Reinforced Concrete containing 12.5% of Crumb Rubbers as Aggregate

SCSRC- Self Compacting Steel Fiber-Reinforced Concrete, SF- Steel Fiber, W/C –Water Cement ratio loadings like any other mechanical properties is essential for a proper understanding of the performance of this material.

Fracture Toughness

The energy absorption of a material is a measure of the material's resistance to fracture when static strain or impact (dynamic) loads are applied. This is known as toughness [7]. Toughness is usually determined as the area under the load–displacement curve. It is estimated as the energy absorption until failure occurs calculated from the trapezoidal rule. According to Nasir [15], the addition of different fiber lengths (20 mm, 40 mm and 60 mm) and fiber volumetric fraction (0%, 0.5%, 1% and 1.5%) had a positive influence on the energy absorption capacity of concrete reinforced with steel fiber extracted from discarded tires. The highest energy absorption (in joule) was observed using fiber length of 60 mm and volumetric fraction of 1.5%.

Similarly, Ndayambaje, [9] examined the effect of steel fiber extracted from discarded tires, varied at different lengths of 20 mm, 40 mm and 60 mm and volumetric fractions of 0%, 0.3%, 0.5%, 1% and 1.2%. The SFRC contained 12.5% crumb rubbers as part replacement for coarse aggregate in all mix. The highest energy absorption was observed using fiber length of 60 mm and volumetric fraction of 1.2%. A trend of progressive increase in the energy absorption capacity of the SFRC was also observed with increase in fiber length and volumetric fraction.

Mastali and Dalvand [50] also investigated the effect of varying volumetric fraction (0%, 0.25%, 0.5%, 0.75%) at a fiber length 40 mm on self-compacting steel fiber-reinforced concrete extracted from discarded tires. The energy absorption capacity of SFRC was found to increase with an increase in volumetric fraction. Table 8 presents the result of fracture toughness for three categories of SFRC. From the previous studies it could be inferred at an increase in volumetric fraction of the steel fiber in a concrete mix will the energy absorption capacity of the concrete.

Durability

According to Nasir [15], the durability performance of SFRC is as important as the mechanical properties of the concrete. Most often the strength of the concrete determines the durability. A close relationship has also been observed between the pore structure of concrete and durability [88]. Concrete with more openings in its pore structure, is likely to be susceptibility to degradation caused by penetrating substances from the surrounding environment [89][89][89][89]. This results in physical and chemical reactions within the concrete internal structure, thereby leading to irreversible damage to the concrete [89]. It has been generally observed that dense concrete are usually impermeable while fiber-reinforced concrete exhibits less permeable when compared to plain concrete [9]. Although this is not the only factor that affects the overall durability of the concrete, it can also reduce the rate of corrosion of the steel fibers. In addition to this, the concrete environment is highly alkaline in nature with a pH between 12 and 13. This results in the formation of insoluble oxide film on the surface of steel fibers. However, this may sometimes be destroyed by the formation of weak carbonic acid resulting from the reaction between atmospheric carbon dioxide and water. In all, it has been found that corrosion is usually confined to the skin of the concrete, while the interior fiber enjoys the protective cover of the alkaline environment [15].

Future Trends and Application of Steel Fiber

SFRC has been found useful in many applications such as pavement, tunnel linings, hydraulic structures, slabs, bridge deck, foundation, refractory concrete fiber shot-crete and precast elements [9, 29]. All the application of this material in concrete depends on the creativity of the engineer since the use of 1% ISF automatically doubles the material cost of the concrete [15]. This has made the use of steel fiber extracted from waste tires a good alternative for producing SFRC. In recent years to come, the recycling of steel fibers from waste tires will experience deliberate processing so as

Table 8 Results of Fracture toughness obtained from using WTSF

Author(s)	Type of concrete	SF (%)	SF diameter (mm)	SF length (mm)	W/C	Fiber tensile strength (MPa)	Energy absorption (Joule)
Nasir [15]	Pure concrete	1.5	0.72–0.89	60	0.42	970.2	36.51
Ndayambaje [9]	CRAC	1.2	1.15	60	0.5	1054.7	77.60
Mastali and Dalvand [50]	SCC	0.75	0.15	40	0.44	2000	1.616

SF Steel fiber, *W/C* Water cement ratio to put an end to the challenge different fiber properties. This will surely provide processed steel fibers with predetermined strength and standard for the production of SFRC.

Conclusion

The reviewed literature broadly identifies the potentials of utilizing steel fibers extracted from waste tires as a means of achieving a sustainable environment and in turn sustainability in the construction industry. The paper also identified a wide variation in the properties of fresh and hardened concrete containing steel fiber extracted from waste tires. The different fiber content, length, diameter and tensile strength could be considered as the reason of the variation. It is worthy to note that the fiber content and length in the mix can be easily modified to achieve uniformity, however the variation in fiber diameter and tensile strength can be a difficult factor to control since the steel fiber source is not industrially manufactured but a recycled product.

In addition, the reviewed fresh and hardened properties of concrete reinforced with steel fibers obtained from waste tires signify that the orientation and dispersion of the steel fibers were done randomly in order to promote homogeneity of the concrete mix. The effect of fiber alignment during placing can be considered for further investigation. The fiber orientation ratio, top and bottom alignment angles of fibers can be studied for better applicability and acceptability of this material. Generally, the application of steel fibers extracted from waste tires in concrete could be a useful material in the construction industry.

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