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Review

The recent progress of recycled steel fiber reinforced concrete

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HIGHLIGHTS

- Up-to date literature on recycled steel fiber reinforced cement-based systems.
- Used and end-of-life tires were found to be major source for recycled steel fibers.
- Tire recycling for steel fibers is sustainable, energy efficient and health friendly.
- Source, recycling technique and geometry effect the efficiency of recycled fiber.
- Hybrid inclusion of recycled and industrial steel fibers provide better results.

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ABSTRACT

Environmental issues such as exhaustion of natural resources and generation of enormous amounts of waste and their dumping are currently steering the modern civilization to sustainable construction. Steel fiber reinforced concrete has been in application for many decades because of its capability in arresting crack and introducing ductility to structural concrete. Concerning about natural resources and adverse environmental impact of CO_2 emission during the production of industrial steel fibers at a larger scale, significant research efforts have been made towards sustainable, resource conservative and recycled alternatives to replace these high-cost commercially available steel fibers with recycled steel fibers (RSFs). Recycled steel fiber reinforced cement mixtures behaves differently in fresh and hardened states compared to plain and industrial steel fiber reinforced cement mixtures. This review provides a brief overview of the recycled steel fibers from different sources, their characteristics, and application in the production of various cement-based composites. Effect of RSFs on the different properties of concrete in fresh state including workability, porosity, bulk density, and volumetric stability has been addressed. Detail discussion on the mechanical properties of various cementitious systems has been included, comprising compressive and flexural strength, tensile splitting strength, toughness, resistance to impacts and durability of RSFRC. This study aims to critically examine the currently reported literature and to identify research gaps for those who intend to further study of behavior of recycled steel fiber reinforced cementitious systems for various applications.

Contents

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1. Introduction

Cement composites are brittle, which make them vulnerable to cracks at the very low strain level. Steel bars, mats, meshes, and fibers have extensively been used as reinforcement to overcome this issue. A large and growing body of literature has investigated the application of different fibers in cement-based composites for many decades [1–6]. To date, several attempts have been made to investigate the effectiveness of fibers for their crack arrest capability and the post-crack energy absorption capacity in reinforced concrete [7–9]. Steel fiber reinforced concrete is one of the promising modern structural material, utilizing randomly distributed steel fibers of different shapes and geometries into the cement matrix, to address the issues related to crack susceptibility and brittleness of cementitious composites [10]. Worldwide over 0.3 million tons of steel fibers are commercially sold every year, and it is estimated, this amount will increase by 20 percent each year [11]. It was further added that almost 90% of these industrial steel fibers are available in different shapes, geometries, and surface textures [12]. In the past years, some of the geometrical shapes of steel fibers proved to be beneficial and adopted in the production of engineered concrete [13] while most of them were retreated [14]. A large number of steel industries are currently operating all over the world and each of them not only utilizing rigorous energy and fossil fuels but also causing greenhouse gas emissions during the production of steel [15]. Concerning natural resources and adverse environmental impact due to CO_2 emission during the production of steel fibers on industrial scale, significant research efforts have been made towards sustainable and efficient alternatives to replace these high-cost steel fibers. Over the last fifteen years, the application of recycled steel fibers (RSFs) found to be an encouraging substitute for industrial steel fibers with limited environmental impact and less recycling cost [16–18].

In the past few years, disposal of worn and end-of-life tires has emerged as a critical issue for waste management agencies [19]. According to estimates, around 1.3 billion automobile vehicles are currently being used all over the world, and about 5.2 billion tires will be at the verge of disposing of after being exhausted by these vehicles [20]. In 2003, the European Union restricted the destruction of waste tires into the landfills, and later on, their derived products were also banned in 2006 [21]. Tire industry in Europe was forced to change the waste management procedures for end-of-life and used tires, and European environmental regulatory also implemented specific regulations in European states [22]. During this tenure (2004), members of Tire Recovery Association (TRA) decided to reuse all scrap tires by applying suitable collection and recycling processes [23]. High carbon content of tires attracted many energy recovery plants and cement industries to utilize scrap tires as fuel [24–27]. Recycled steel fiber reinforced concrete (RSFRC) not only address the issues related to high carbon footprint but also provide promising mechanical properties for structural applications.

Adverse environmental impact and health hazards caused due to generation of tremendous amount of end-of-life tires and recent developments in the field of cement-based composites reinforced with recycled steel fibers have led many researchers to a renewed interest [28–33]. There have been many investigations on the influence of waste and recycled steel fibers on the fresh properties of concrete [34–36]. While significant results are reported on the mechanical properties of concrete by the inclusion of recycled steel fibers (RSFs) in concrete [37–40]. RSFs can replace the industrial steel fibers (ISFs) up to some extent, many of the studies have been dedicated to comprehend the hybrid effect of industrial and recovered steel fibers on different characteristics of fiber-reinforced concrete [41–43]. Recycled steel fibers also presented profound capability in making rubberized concrete panels for non-structural use as a sound barrier [44].

The novelty of this review is that it provides a state-of-the-art summary of published literature in the field of recycled steel fiber (RSF) application in concrete. Up to date summary of different sources, fiber geometry and recycling process used in different studies are given along with a discussion on the effect of different recycling process on the geometry of recycled steel fibers recovered from tires. Influence of RSF on the fresh and hardened properties of concrete is included in this review, and based on available limited literature, the durability of recycled steel fiber reinforced concrete is discussed. In the end, based on extensive literature review, possible future research areas are identified, and conclusions are drawn.

2. Review significance and methodology

2.1. Review significance

Systematic literature review on recycled steel fiber reinforced cement composites will identify the prevailing achievements and compile the existed research gaps for future studies. Latest literature review on hardened properties and durability of cement composites incorporated recycled steel fibers will be summarized. Properties of cement based matrix incorporating recycled steel fibers have been an object of research for more than two decades [45]. Recently the enhanced mechanical properties and durability of concrete incorporating sustainable steel fibers recycled from waste tires have been reported in various studies [34,46]. It is essential to summarize the current advancement and review the persistence among critique of findings made by various researchers. Worldwide, investigators focused on different objectives when investigating the effect of recycled steel fibers in cement composites. Thus, critically combining findings by different researchers is essential to deliver a broad perspective of the current research level.

Industrial and recycled steel fibers from various sources hold some similarity in mechanical and physical attributes because of the same constitutive material. Hence research practices and testing protocols can be mutually employed among these two groups of steel fibers. Mostly, properties of industrial steel fiber reinforced cement composites have been summarized time to time by various researchers [47,48] but the literature review solely focused on the recycled steel fibers, and their effect on different properties of cement-based composites have not been conducted. The last decade has seen rapid development and emergence of sustainable recycled steel fibers as a construction material as depicted by Fig. 1. This work attempts to review the essential and seminal developments of recent research efforts by different researchers on the recycled steel fibers incorporated in cement-based composites, delivers a summary of their main contributions and discusses possible future development trends. Therefore, summarization of fresh and hardened characteristics of cement-based composites reinforced with recycled steel fibers and environmental impact of tire recycling to recover steel fibers accentuate the significance of this review.

2.2. Review methodology

This review about the recycled steel fibers reinforced cement-based composites began with the collection and assessment of relevant literature published in the past. For data collection, well known bibliometric database sources like Web of Science, SCOPUS and Google Scholar were utilized. The initial keyword search comprised the search strings "Recycled Steel Fiber" AND "Cement", "Recycled Steel Fiber" AND "Concrete" as well as "Waste Steel Fiber" AND "Cement". After the preliminary assortment of data, the scope of each article was identified by searching keywords in title and abstract and later, papers were included or excluded for further analysis and inclusion in this review article. After searching and including all research articles limited to scope of this review from each source database, EndNote library was used to identify the duplicates in research papers database. Since recycled steel fiber reinforced concrete is an developing field a cross-reference "snowballing" approach was employed during the process of review. Through this technique, bibliography of papers or citations to the research articles were utilized to extend the scope of relevant information about the topic. The complete search resulted in a list of more than 150 references on recycled steel fiber reinforced cement-based composites and their properties, on which the systematic review of literature is based.

3. Major source, environmental impact and characteristics of recycled steel fibers

Reinforcing ability and crack arrest capability of synthetic fibers make them prominent as one of the practical solutions for improving the hardened properties of the plain cement-based composites. Among the commercially available fibers, steel fibers are one of the primitive and the most persuasive materials for enhancing the flexural performance and resistance of concrete against impact loads. Application of steel fibers in the construction sector demands enormous amount of raw materials for the production of these steel fibers at the industrial scale, which results in extreme environmental concerns about carbon footprint. During recent years, sustainability, resource conservation, and recycling become one of the main concerns for the policymakers and attracted researchers to find alternative ways to address issues related to environmental impacts during the production of industrial steel fibers. Recent developments in the application of recycled steel fibers have successfully addressed the issues related to high cost, dumping of waste, and environmental impacts of industrial steel fiber production [49,50].

Tires being one of the essential components of automobiles, depending on various factors have an average life-span of 5 years [51]. Waste tires are the primary source for recovering the steel fibers and these steel fibers have been successfully employed in the construction industry for structural application with environmental and economic benefits [52–54]. Recycling of steel fibers from waste tires mainly done by the cryogenic or shredding process termed as mechanical recycling. While pyrolysis process includes anaerobic thermal decomposition and microwave-induced degradation of waste tires to recover steel fibers [55]. Shredding and cryogenic processes are mostly acquired for recycling of tires because of valuable and serviceable end products as compared to pyrolysis [56]. Shredding at ambient temperature results in relatively large rubber particles, while during cryogenic, usually small rubber particles with sharp edges and less surface area are available for further applications [57]. Steel fibers recycled by mechanical process get damaged but still provide effective

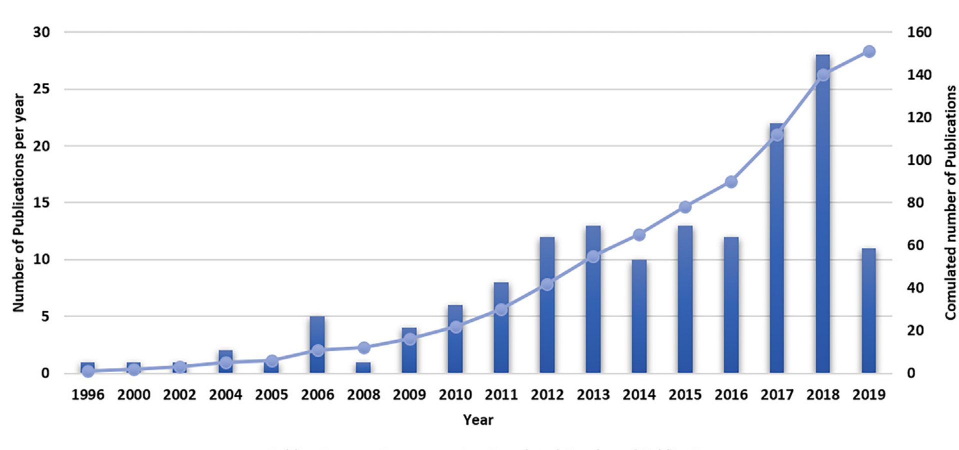

Fig. 1. Yearly Publications on Recycled Steel Fiber Reinforced Cement Composites.

stress transfer due to irregular shape [55,58]. In contrast, pyrolysis recycling of tires results in carbon black powder, decomposed organic compounds, oil, and steel fibers as end products [59,60].

Quality of recycled steel fibers from waste tires has been underestimated till now; industries use high tensile strength steel wires in the production of tires and quality of these steel fibers recovered from waste tires still found to be superior to fibers available in the market. Due to better quality of raw steel used in tire production, recycled steel fibers possess more ductility and higher tensile strength when compared with engineered steel fibers available in the market [61].

3.1. Source

Table 1 provides an overview of main sources for steel fiber recycling, employed by different researchers. Waste or end-of-life tires were found to be the primary source for recycled steel fibers because of their availability in large quantities (approximately 17 Million tons) every year [62] and other end-products that can also be adopted for sustainable construction [63–66]. In 2000, the directive of the Council on end-of-life vehicle suggested that tires should be removed from the vehicle before demolition and dumping into landfills [67]. Automobiles provide safe and comfortable transportation means, resulting in overall increase in production of motor vehicles. By contrast, less life span of tires as compared to vehicles, a large number of used and waste tires are disposed to landfills and cause land pollution and waste of valuable land in terms of landfills [68]. Around one thousand million tires ended up their life and discarded as waste annually, and it is estimated that by the year 2030, this value will rise by 20% [69–71].

The main useful products from the recycling of tires comprise rubber, textile fibers, and steel fibers. In a typical tire Fig. 2 rubber makes most of the part and comprises almost 47–48% by weight of the complete tire followed by black carbon (22%), 15–17% of steel cords, 5% textile fabric, additives (8%), and 1% of zinc oxide and sulfur each [108–110]. Due to high carbon content, tires can provide higher energy level as compared to coal, and calorific value of fuel obtained from tires also found to be higher than coal [111] with less amount of Sulphur content [112]. Apart from steel fibers recycled from waste and used tires, some researchers also used steel fibers recycled from other materials, i.e., industrial waste, steel wires used in construction reinforcement, Un-vulcanized rubber

Table 1
Recycled Steel Fibers Used in Different Studies.

Reference	Year	Recycling Method	Dimensions/Shape	Sources
[72]	2015	Cryogenic	Variable geometry and shape	Waste Tires
[73]	2012	Mechanical Recycling	Irregular shape and Dimension	Waste Tires
[74]	2012	Shredding	0.24 mm dia, 31.4 mm Length (average of 2000 fibers)	Waste Tires
[75]	2012	Mechanical Recycling	0.2 mm dia, length of 90% of fibers ranges 3–22 mm	Used Tires
[58]	2013	Mechanical Recycling	0.18 + -0.029 mm dia, 9 mm length with Irregular shape	Waste Tires
[76]	2013	–	–	Waste Tires
[77]	2013	–	–	Used Tires
[78]	2013	Warm Milling and Machining process	–	Industrial Waste
[79]	2014	Shredding	Avg. 16.5 mm Length	End-of-Life Tires
[80]	2015	–	Avg. 1.2 mm dia, 50+–10 mm length	Previously used Waste Steel wires from reinforcement and formworks
[81]	2015	Shredding	Avg. 0.27 mm dia, avg. 12 mm length	Waste Tires
[82]	2015	–	Avg. 0.27 mm dia, Average of 2000 fibers	Used Tires
[83]	2015	–	1 mm dia and 30, 35 mm length for Hooked and crimped fibers	Waste Tires
[84]	2016	–	Avg. 0.15 mm dia, Avg. 20 mm length with irregular shape	Waste Tires
[50]	2016	Shredding	Avg. 0.31 mm dia, avg. 25.5 mm length, average of 1000 fibers	End of Life Tires
[85]	2016	–	Avg. 0.25 mm dia, avg. 40 mm length	
[86]	2016	Pyrolysis and Mechanical Recycling	0.3 mm dia and 52 mm length, 0.9 mm dia and 60 mm length, 1.37 mm dia and 50 mm length	Scrap Tires and industrial waste
[87]	2017	Shredding	<0.3 mm dia, 15–45 mm length	Waste Tires
[88]	2017	Mechanical recycling without sorting and cleaning	0.18 mm dia, 0–15 mm length with irregular shape	Waste Tires –
[89]	2017	–	Avg. 0.25 mm dia, avg. 26.17 mm length	Waste tires
[90]	2017	–	Irregular shape and dimensions	Waste turnery steel fibers
[52]	2017	Mechanical recycling	0.15 mm dia, 20 mm length with irregular shape	–
[91]	2018	Thermal recycling	0.18 mm dia, 20 mm length	Waste Tires
[92]	2018	Thermal recycling	0.26 mm dia, 25 mm length	Waste Tires
[93]	2018	–	Avg 0.2 mm dia, avg. 35 mm length	Waste Tires
[94]	2018	Shredding	–	Old Tires
[95]	2018	Manual Cutting	Avg. 0.28 mm dia, avg. 25.4 mm length	Waste Tires
[96]	2018	–	Avg. 0.22 mm dia, Avg. 23 mm length	End-of-life Tires
[97]	2018	Shredding	0.22–0.27 mm dia, 30–60 mm length with irregular shape	Waste Tires
[98]	2018	Shredding	Avg. 0.25 mm dia, Avg 13.94 mm length, average of 1200 fibers	Scrap Tires
[17]	2018	–	Avg. 0.15 mm dia, Avg. 50 mm length, average of 156 fibers	–
[99]	2018	Shredding followed by heating	50 mm length with 50 aspect ratio	Waste Tires
[100]	2018	Mechanical recycling	Ranges from 0.18 to 2 mm dia, 41–114 mm length	Waste Tires
[101]	2018	Shredding at ambient temperature	Avg. 0.25 mm dia, avg. 26.17 mm length	Waste Tires
[102]	2019	–	0.2 mm dia, 21 mm length	Un-vulcanized rubber belts
[103]	2019	Shredding	0.25 mm dia, 5–43 mm length	Waste Tires
[34]	2019	–	0.18–1.25 mm dia, 0.8–55 mm length	Waste Tires
[104]	2019	–	Avg. 0.15 mm dia, avg. 20 mm length	Waste Tires
[105]	2019	Shredding	Avg. 0.22 mm dia, 23 mm Length	Waste Tires
[106]	2000	–	–	Used Tires
[107]	2006	Pyrolysis, Shredding	–	Used tires

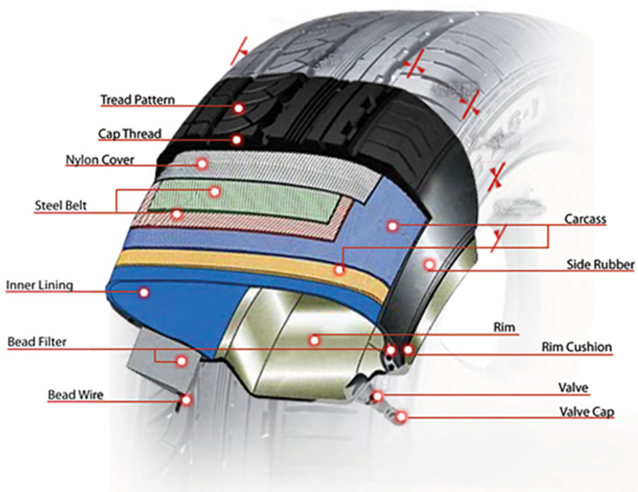

Fig. 2. Structure of Typical Radial Tire [115].

belts, steel cans and waste turnery steel fibers [90,102,113]. Also, an attempt was made to recover steel fibers from ultra-high performance fiber reinforced concrete [114].

To limit the scope of this review and available literature only steel fibers as the recycled product of waste tires are discussed here, their environmental impact during recovery from tyres and effectiveness as reinforcement in cementitious composites will be analyzed.

3.2. Environmental impacts of recycled steel fiber recovered from tires

Construction industry is one the fastest growing sectors and to meet the demand, an enormous amount of construction materials is required that results in exhaustion of natural resources. Almost 15% of the total energy of a building life cycle consumed just during the generation of virgin construction materials [116], and part of this energy consumption can be decreased by the application of recycled materials in the construction industry [117]. Waste tires not only possess high value in market due to their fuel properties, but their toxic and hazardous nature seek the attention of researchers to utilize this material rather than dumping or disposal. Economy and environmental aspects of sustainable construction are significantly influenced by the type and quality of recycled steel fibers because the load carrying capability of structural concrete is directly related to dosage and quality of recycled steel fibers.

Burning of tires in cement kiln not only provide energy for cement production but also generate valuable by-products, i.e. steel wires that further can be used in the construction industry as fibers. Several studies [118–122] proposed the burning of tires as sustainable, cost effective source of energy in the production of cement because to their high calorific value and low carbon footprint as compared to available fuels. Lower heating value as 27 MJ/kg for waste shredded tires in cement kiln was reported which is more than the value of for coal, i.e. 26.5 MJ/kg [118]. Literature reports that 25 lb of coal can be replaced by only 20 lb of shredded tire rubber from waste tires [119]. On the other hand, utilization of tires as fuel in cement industry resulted in 17% reduction of CO_2 emission [120]. In addition to this, annually, a revenue of 118.125 € can be generated by recovering the materials from ELF tire while disposal cost of 63€ can be saved each year. The cost ratio of 1:0.2 can be achieved when industrial steel fibers are substituted by recycled steel fibers from post-consumed tires in production of cement mortar with 0.35% of fibers [123]. In addition to this, landfill sites for dumping and stockpiling of waste tires are indicated as breeding sites for mosquitoes and rats which adversely affect the environment and ultimately put serious threats to human health [119,124–126]. On the other hand, disposal tires in large quantities to stockpiles are always at the verge of ignition. Burning of tires not only results in global warming but also pollute the environment by the emission of toxic gases, i.e. CO, SO_2, etc. during the fire. Burning of tire stockpiles also produces oil that gets absorbed by the soil and pollutes the ground surface and causes groundwater pollution [125]. Similarly, the carbon footprint is one of the critical benchmarks to assess the environmental impact of sustainable development [127]. By recycling of tire, yearly 1.52 tons of CO_2 emissions can be stopped to enter the green environment [128].

Therefore, recycling of tires and recovering steel fibers is not only sustainable, economical but also provide valuable by-products, i.e. rubber and textile fibers that can be used in the construction industry. Tire recycling for steel fibers will save valuable land for dumping, decrease global warming due to the burning of tires in open area, and most significantly we can reduce the possible breeding sites for mosquitos by recycling those tires rather than dumping into stockpiles. So, recycling steel fibers from tires and utilizing them in the fiber reinforced concrete which will not only enhance the mechanical characteristics of concrete but also provide another possible stream to utilize waste tires.

3.3. Composition and size of various recycled fibers

Depending on the primary source and recycling technique, fibers can be of irregular shapes and different dimensions. Literature revealed that mostly shredding process was used for recycling the steel fibers from waste tires, and fibers recovered with different lengths and diameters. Diameter of recycled steel fibers recovered from tires depends on the type of tire while recycling technique influence the length of the fibers [81,129,130]. Due to a wide range of geometrical variation of recycled steel fibers, statistical analysis is necessary for given numbers of representative fibers for frequency distribution and the average size of fibers [82,98,131].

To serve the purpose, Leone et al. [98] used 1200 randomly selected representative fibers for geometrical analysis, as shown in Fig. 3**(a)**. Average of both end diameter of fibers was measured by micrometer [132]. The average diameter of fibers was found to be 0.25 mm with 0.10 mm and 0.45 mm as lower and upper limits with 29% of the coefficient of variation (C.o.V). Highest of the population (30.17%), was in the range of 0.20 mm–0.25 mm followed by 27.08% of 0.15–0.20 mm diameter as represented in Fig. 3**(b)**. Due to irregular shape and undulations, length of fibers was represented as the distance between outer ends and termed as equivalent fiber length [74,98,133]. A typical representation of equivalent fiber length is shown in Fig. 3**(c).** Average equivalent fiber length was recorded as 13.94 mm with 1 mm and 37 mm as lower and upper bound, and the coefficient of variation was calculated as 37% for fiber length. Highest population range was found to be 10–15 mm with 40.75% occurrence followed by 22.92% for 15–20 mm equivalent fiber length as shown in Fig. 3**(d)**.

Graphical representation of average diameter and length of recycled steel fibers used in different studies is represented in Fig. 4**.** The figure depicts the relation between type of recycling process and range of average diameter and length of recycled steel fibers. Most of the fiber's diameter ranges in between 0.15 and 0.26 mm which illustrates that most of the tires were from a similar vehicle and tire type. In a typical pneumatic radial tire steel cord having a diameter of 0.1–0.32 mm are commonly used [134], and the steel fibers are mostly within this range with some outliers. Geometrical data of recycled steel used in 25 studies is shown in Fig. 4, 21 of recycled steel fiber diameter (highlighted in red) were in the range of pneumatical tires for passenger vehicles, i.e. 0.125–0.275 mm [135] while only 4 having the average

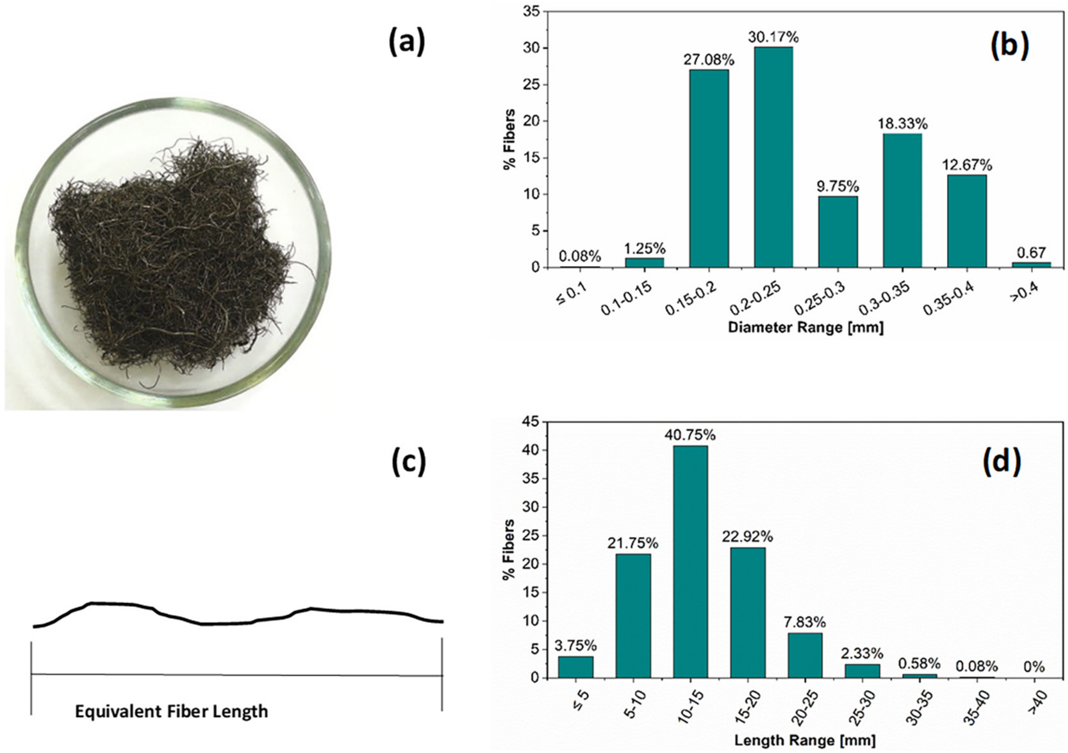

Fig. 3. Geometrical Characterization of recycled Steel Fibers. (a) representative fiber sample (b) Frequency distribution of Fiber diameter (c) Fiber Length represented by equivalent fiber length (d) Frequency distribution for equivalent fiber length [82,98].

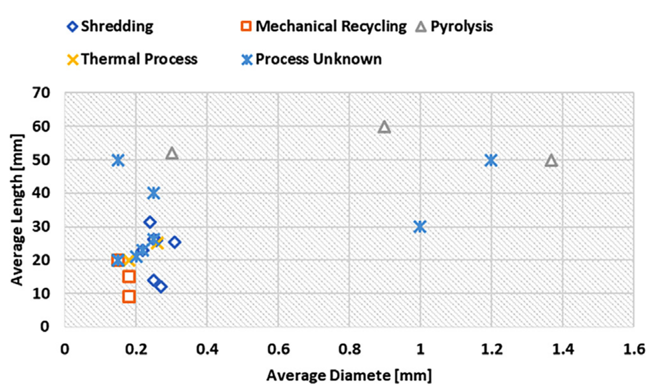

Fig. 4. Average Diameter and Length of Recycled Steel Fibers used in different Studies as shown in Table 1.

diameter larger than steel wires used in passenger vehicle tire. Available data represents that mostly steel fibers were recycled from passenger vehicle tires and further research can be extended to steel fiber recycled from a truck or heavy vehicles tires.

In contrast, the length of recycled steel fiber (RSF) varied in the range of 9–60 mm which mainly depends on the technique of recycling. Fig. 5**(a)** shows steel fibers recycled by using the cryogenic technique, steel fibers were free from large rubber particles as compared to fibers recycled by using shredding technique Fig. 5 **(b).** Large rubber particles were also attached to the steel fibers when using shredding and different lengths with uneven geometry and surface of fibers can also be observed. In the pyrolysis process mostly, larger fibers can be recovered and then cut to desired uniform length while fibers recovered using shredding were of small variable lengths as shown in Fig. 5.

4. Fresh properties of cementitious systems incorporating recycled steel fibers

4.1. Workability and flowability

In fiber reinforced concrete workability is one of the major constraints towards the better performance of concrete in the hardened state. Towards the development of most suitable concrete mix, workability of concrete is the key parameter, and it is

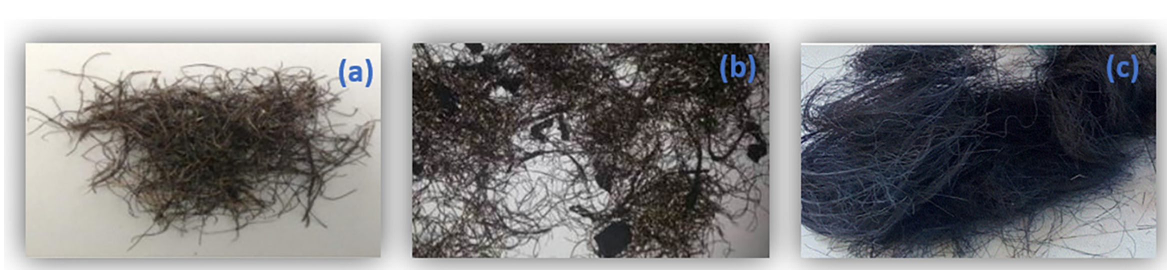

Fig. 5. Recycled Steel Fibers using different recycling techniques (a) Cryogenic Technique, (b) Shredding Technique, (c) Pyrolysis Technique [50,72,91].

significantly influenced by the type and content of recycled steel fibers [34,50,52]. Although slump test, recognized as a standard check to quantify the workability of a concrete mix but according to many researchers slump test do not provide enough information about quantitative analysis of workability of fiber reinforced concrete, but can be accepted as a quality control procedure to gain uniformity in workability of various batches of concrete [98,136].

Higher concentration of recycled steel fibers not only adversely affect the workability but also the influence the homogeneity of fresh concrete mix. To overcome this problem, Dehn et. al. suggested 0.26% volume fraction of recycled steel fiber as highest concentration [137]. On the other hand, planetary vertical concrete mixer was found to be a technological solution to uniform dispersion of recycled steel fibers without any adverse effect on workability even at a higher concentration up to 0.46% by volume [74,131,138]. In addition to fiber concentration, aspect ratio and geometrical characteristics of fibers significantly influences on the workability and homogeneity of fresh concrete mixture with steel fibers [8,74,139]. Additionally, it was noted that geometry of recycled steel fibers has similar influence on uniform fiber dispersion and workability of concrete as in the case of industrial steel fibers [86].

The tendency of steel fibers to interlock at the time of mixing was identified as another potential problem for the decrease in workability of recycled steel fiber concrete and was termed as "balling" in literature. Inconsistency in size and shape of recycled steel fibers was identified as one of the major reason for balling effect in fresh concrete [50,140]. Increase in superplasticizer quantity, mixing procedure, and reduction in both aspect ratio and content of recycled steel fiber can address the problems related to workability and balling effect in recycled steel fiber concrete. To avoid balling effect, some of the recommendations were made i.e. incremental addition of recycled steel fiber during mixing [85], scattering of recycled steel fibers after wet mixing of all ingredients into forced action mixer [83], aspect ratio of steel fibers should be limited to 200 [21], volume fraction to 0.5% [94] and 30 kg/m^3 of recycled steel fibers [96]. However, due to higher workability and flowability of self-compacting concrete, limit of steel fiber content was increased from 30 kg/m^3 to 60 kg/m^3 without any undesirable balling effect [79,99,141]. The planetary vertical mixer [131] and addition of superplasticizer [28,102,142] effectively enhance the workability and recycled steel fiber dispersion in fresh concrete.

4.2. Porosity

In fiber reinforced concrete, workability can be achieved by using additional water content, but this could result in a larger volume of pores inside the concrete matrix. Similarly, any additional material, i.e. rubber, attached to recycled steel surface can cause improper bondage with the surrounding cementitious matrix, which increase the porosity hence decreasing the mechanical performance. Ultrasonic pulse velocity (UPV) test can provide insight into the porosity and uniformity of recycled steel fibers in concrete. Steel fibers decrease the workability which results in improper compaction of the concrete in fresh state; hence porosity of concrete increases which can be depicted by a decrease in UPV [143]. Increase in porosity was observed in recycled steel fiber reinforced concrete, and UPV results revealed that by adding the 2% volume fraction of recycled steel fibers decreases the UPV by 3–7% [144]. Silica Nano-powder was found to be effective in decreasing the porosity of recycled steel fiber concrete, and it was concluded that due to small size, Nano-silica act as filler and resulted in significant decrease in porosity [78]. A recent study revealed that ultrasonic pulse velocity (UPV) of concrete reinforced with recycled steel fiber decreases by 10% while in the same study UPV was reduced by 15% when both industrial and recycled steel fibers were used as hybrid reinforcement. This was attributed to the difficulty in compaction of concrete in the presence of hybrid industrial and recycled steel fibers [17].

4.3. Bulk density

In 2013, Bjegovic et al. conducted the series experiments to study the synergistic effect of industrial and recycled steel fiber with total quantity as 30Kg/m3 on the fresh properties of concrete. It was observed that the fresh density of concrete was increased from 2.4756 Kg/m^3 to 2.4894 Kg/m^3 with a total increment of only 0.56% when industrial steel was entirely replaced by recycled steel. Similarly, [50,76,78,94] reported an increase in bulk density of concrete by adding recycled steel fibers and it was attributed to the higher specific gravity of steel fibers. It appears that small fraction of steel fibers independent of their nature, i.e., industrial or recycled, had no significant influence on the density of concrete [52,58,89]. Conversely, a slight decrease in fresh density was witnessed when 0.46% by volume of recycled steel fiber was added into the concrete but this change (−0.9%) was relatively insignificant [98]. So, it can be concluded that after a certain threshold limit, the inclusion of recycled steel fiber imparts an adverse effect on density [88,98].

4.4. Volumetric stability

Volumetric stability or shrinkage response of cement composites to the environmental conditions, due to excessive moisture evaporation cause surface cracks [145,146]. Shrinkage occurs mainly into two stages; early age shrinkage resulting from evaporation of surface moisture and utilization of matrix water during chemical reaction of cement in the plastic state named as autogenous shrinkage while physical shrinkage occurs at later stages, slow and long-term process. Cracks occurred due to shrinkage in concrete also have prime importance. If distress due shrinkage is ignored than load capacity of steel fiber reinforced concrete pavements can be overestimated as double, which shows the importance of shrinkage during the design of steel fiber reinforced concrete pavements [147]. Although, addition of recycled steel fibers does not provide any significant resistance against moisture loss, but it increases the crack arrest capability. While, additional water to achieve workability, and higher air content of recycled steel fiber reinforced cement composites can exhibit insignificant increase in shrinkage [148].

Similarly, Calcium aluminate cement exhibited much higher autogenous shrinkage (2690 and 2532 $\mu\varepsilon$ at 60 days) due to its smaller particle size and measured as 71% and 64% of their total shrinkage with and without recycled fibers. A linear relation was confirmed between moisture loss percent and shrinkage [148]. A similar phenomenon was observed by [101], but increase in shrinkage was insignificant by the additional charge of recycled steel fibers. Proper curing of the recycled steel fiber reinforced concrete at early ages or use of internal curing agents can provide better resistance against shrinkage. Similarly, uniformly distributed recycled steel fibers can provide restraint against matrix movement due to loss of water or matrix evolution; hence, self-compacting concrete can provide better resistance against shrinkage arrest was be observed in [34,149].

5. Mechanical properties of hardened cementitious composites

5.1. Compressive strength

Incorporation of recycled steel fibers can be slightly beneficial for compressive strength of concrete but if large fiber volume is desired, additional water to overcome the issues related to workability can be detrimental to the compressive stress resistance of concrete due to increase in porosity [131]. Similarly, addition of recycled steel fibers results in ductile failure and can delay the collapse of concrete. It was observed that due to inclusion of the high density recycled steel fibers by a fraction of 5%, dry density of the concrete mix increases which ultimately helped in increasing the compressive strength by 59% [78]. A positive synergistic effect was observed between industrial and recycled steel fibers at fiber fraction of 1% and 0.5% respectively, better crack arrest and anchorage capability resulted in increased compressive strength by 50% [150]. On contrary to this, hybrid inclusion of recycled and industrial steel fibers to concrete resulted in poor workability [52] and increased porosity [130] which ultimately resulted in decrease in compressive strength.

Issues related to the dispersion of recycled steel fibers into concrete were addressed by [131]. It was found that by using the same type and content of recycled steel fibers and conventional concrete mixer do not provide homogenously dispersed steel fibers, so the maximum potential of steel fibers cannot be utilized. Results indicated that by using 0.26% of recycled steel fibers eventuated in 12% increase in compressive strength when conventional concrete mixer was used but on the other hand application of planetary concrete mixer give more dispersed fiber structure in concrete and compressive strength was increased by 20% even at lower content (0.23%) of recycled steel fiber. Use of planetary vertical mixer allowed homogenous and well-dispersed steel fibers, and fiber content was also increased to 0.46% by volume [131].

Fiber content significantly influence the behavior of concrete against compressive stresses. No significant development was witnessed in the compressive strength of concrete at small fiber fraction [151]. The study revealed that by adding a mixture of industrial and recycled steel fibers up to a maximum fraction of 0.5%, no significant strength improvement was observed, and compressive strength was just improved from 36.69 MPa to 37.37 MPa. It can be inferred that at small fraction of recycled steel fibers compressive strength of concrete mainly depends on the internal matrix structure of concrete rather than steel fibers [82,152]. Addition of silica fume not only provide denser cement matrix but also increase friction between fiber surface and surrounding matrix which ultimately provide efficient way to enhance the compressive strength and ductility of recycled steel fiber concrete [153,154].

Similarly, after threshold value further increasing the fiber content negatively affect the cement matrix structure which ultimately results in drop in compressive strength of concrete. The study was conducted by using different fiber content of recycled steel fibers up to a maximum value of 0.75% by volume. Results depicted that there was an improvement in compressive strength by 5% when fiber content was limited to 0.5% but adverse effect of fiber inclusion was observed when recycled steel fibers were added at 0.75% by volume which resulted in poor dispersion of fibers and caused non-homogenous cement matrix, This discontinuity in matrix structure ultimately resulted in 8% lower compressive strength [80]. Similarly, 3% of recycled steel cords by mass were suggested as optimum dosage for better compressive strength of roller compacted concrete [155]. At the fiber dosage of 0.46% by volume, decrease in compressive strength was noted (from 33.61 MPa to 31.60 MPa) and it was concluded that random dispersion of recycled steel fibers in the concrete mix could result in fiber bundles which resulted a slight drop in compressive strength [98]. In another study, optimum fraction for hybrid inclusion of industrial and recycled steel fiber was suggested. It was found that by using a blend of 30% of industrial and 70% recycled steel fibers up to combine content of 1%, compressive strength was increased by 5–10% but when fiber content was further increased to 1.25%, this high fiber content resulted in loss of compressive strength by 5% [89].

The shape of the fiber, surface morphology and amount of rubber attached to the steel fibers recycled from waste tires also have a substantial effect on the compressive strength of concrete. By the inclusion of 0.46% of irregular and random recycled steel fibers provided better resistance against crack propagation and a 25% increase in compressive strength was observed [74]. While presence of rubber attached to the surface of steel fibers negatively affect the compressive strength of concrete. Hydrophobic nature of rubber particles and weak bondage with surrounding cement matrix results in an undesirable effect on concrete performance [34,142]. Results revealed that the value of compressive strength was deceased from 135.5 MPa to 130.2 MPa while on the other hand recycled steel fibers without any rubber attached to surface resulted in an increase in compressive strength from 135.5 MPa to 141.3 MPa (4.3%). Frictional stress provided by corrugated surface and geometry of recycled steel fibers provide better mechanical anchorage that results in an increase in compressive strength [142,156]. Similarly, recycled steel fibers provide crack bridging and lateral crack arrest that results in an increase in compressive strength of concrete [96,101,138,157]. Summary of results for compressive strength of concrete due to the inclusion of recycled steel fibers is provided in Table 2.

5.2. Tensile splitting strength

In the past years, detail research has been carried out to examine the mechanical properties of recycled steel fiber concrete [144,158–162]. Study revealed that the addition of 0.75% by volume of waste steel fiber and industrial steel fiber to concrete, tensile splitting strength can be enhanced by 28% and 26.33% respectively as compared to plain concrete. Brittle failure of plain concrete was shifted to ductile with some small crack along loading direction across the length of the concrete sample [76,80]. Variable fiber length and diameter seems to provide an extra interlocking mechanism as 50% increment in tensile strength was observed by the addition of 0.75% by volume of recycled steel fibers to pavement mixture [163].

Steel fibers less than an adequate fraction badly affect the tensile splitting strength of concrete by introducing irregularities in matrix structure while adding steel fibers equal to the amount of threshold value decrease the porosity and add reinforcing effect to the cement matrix [91,98]. This phenomenon was observed when 0.4% by volume addition of recycled steel fiber resulted in the decrease in tensile splitting strength of concrete. Similarly, a significant decrease in load carrying capacity was observed when the main reinforcement was replaced by recycled steel fibers [164]. While on the other hand 14% increase in tensile splitting strength was noted when recycled steel fibers was increased to 0.6% by volume [91].

In 2018, an attempt was made to optimize the mechanical properties of self-consolidating concrete by adding polypropylene, recycled and industrial steel fibers and their mixture with a total content of 1.5% by volume. Recycled steel fibers increased the tensile splitting strength by 25% as compared to plain concrete. While the maximum rise in tensile splitting strength of hybrid formulation was noted by the mix having 1% of industrial and 0.5% of recycled steel fibers. It was believed that better mechanical anchorage and efficiency in bridging action of industrial and recycled steel fiber enabled the enhanced strength [52,96]. Desirability function analysis revealed that for mono-fiber reinforced concrete, 1.5% recycled fiber concrete was found to be optimum while in case of hybrid formulation 1% of superior industrial steel fibers and 0.5% of recycled steel can provide best mechanical properties [150]. Desirability function analysis results utterly dependent on the

Table 2
Summary of Compressive Strength results due to Inclusion of Recycled Steel Fibers.

Reference	Waste Steel Fiber Content	Strength Indication	Compressive Strength	Remarks
[80]	0–0.75% with 0.25% increment	+ve (at 0.5% of fiber) −ve (at 0.75%)	Increased by 5% at 0.5% Decreased by 8% at 0.75%	Poor dispersion and homogeneity after 0.5%
[89]	Blend of waste and industrial steel fiber up to 1.25% (0, 0.75, 1, 1.25%)	+ve (upto 1% of fiber) −ve (at 1.25% of fiber)	Increase in compressive strength 5–10% while at 1.25% reduction in compressive strength by 5%.	Decrease in compressive strength due to higher fiber content
[82]	Blend of industrial and recycled steel fibers with total 0.5% fiber content	+ve	No significant effect on compressive strength i.e. increased from 36.69 Mpa to 37.37Mpa at 100% recycled steel fibers	Due to small fiber fraction compressive strength was dependent on cement matrix properties.
[78]	Waste steel fibers 0–5% by weight	+ve	Increased by 59% at addition of 5% by weight recycled steel fibers	Increased dry density resulted in compressive strength
[131]	0, 0.13, 0.19 and 0.26% by volume using conventional mixer and 0, 0.23, 0.4 and 0.46% by volume while using planetary mixer	+ve	12% increment at 0.26% using conventional mixer and 20% increment at 0.23% using planetary mixer	Better fiber dispersion using planetary mixer resulted in strength increment
[150]	0–1.5% by volume with increment of 0.5%, recycled and industrial steel fibers and Polypropylene fibers and their mixture	+ve	Almost 50% increase in compressive strength using mix of 1% industrial and 0.5% recycled steel fiber while minimum strength increment of 15% was observed in 0.5% industrial steel and 1% PP fiber blend	Positive synergistic effect between industrial and recycled steel at this ratio and crack arrest and better anchorage resulted in increased strength
[74]	0.46% by volume of recycled steel fiber	+ve	25% increase in compressive strength at 0.46% by volume of recycled steel fiber	Random geometrical irregularities of recycled steel fibers resulted in delaying the crack propagation hence increase compressive strength
[77]	30 and 70 kg/m^3 recycled steel fibers as replacement of gravel limestone aggregates	+ve	54% and 41% increase in compressive strength for 30 kg/m^3 and 70 kg/m^3 of replace of aggregate with recycled steel fiber respectively at 300C	Steel fibers resisted thermal stresses at elevated temperature and reduce the strength degradation, impart smooth rupture and resistance against spalling
[104]	40Kg/m^3 of recycled steel fibers (RSFs), 40Kg/m^3 (RSFs) + 2Kg/m^3 of recycled tire polymer fibers (RPFs) and 40Kg/m^3 of RSFs + 5Kg/m^3 of RPFs	+ve (mono-type fiber) −ve(mixed fibers)	4.5% higher compressive strength with only recycled steel fibers, while in case of combination of steel and polymer fibers compressive strength reduced by 5%	Steel fibers increase ductility by providing lateral restrain thus resulted in increase in compressive strength and strength reduction was attributed to entrapped air during addition of fibers.
[52]	20Kg/m^3 of recycled steel + 20Kg/m^3 manufactured steel fibers	−ve	Compressive strength reduces from 48.1 MPa to 42.5 MPa as compared to control formulation	Because of increase in air content from 1.4% to 2.8%
[102]	45Kg/m^3 of recycled steel fiber (0.57% by volume)	+ve	Improvement in compressive strength was observed	–
[101]	50Kg/m^3 recycled steel fibers (0.25% by volume)	+ve	Compressive strength increased by 22% compared to corresponding plain concrete	Crack bridging capability of fibers resulted in increased strength
[96]	30Kg/m^3 of recycled steel fibers, Hybrid mix of 22.5Kg/m^3 of recycled and 22.5Kg/m^3 of manufactured steel fibers	+ve	10% increase in compressive strength with only recycled steel fiber while 11% increase in compressive strength with hybrid fiber intrusion	Increase in strength was justified by crack arrest capability of steel fibers and recycled steel fibers were found to be more effective
[34]	0.5,0.8,1 and 1.5% by volume of recycled steel fibers	−ve	Compressive strength reduced from 47.72Mpa to 43.25Mpa at 1.5% of fibers	Decrease in strength was attributed to rubber particles attached to surface of fibers which resulted in weaker bong with cement matrix and stress concentration at weak interface
[138]	30Kg/m^3 and 45Kg/m^3 fiber content with blend of recycled steel fiber and recycled tire steel chord	+ve	Compressive strength increased from 46.2 to 49.8 with 30 Kg/m^3 of recycled steel cord and compressive strength increased from 45.8 MPa to 55.7 MPa (+20%) in blend of 22.5 Kg/m^3 of each recycled steel fiber and chord	Lateral crack arrest by fibers increased the compressive strength
[98]	0.46% by volume of recycled steel fiber	−ve	Compressive strength reduces from 33.61 Mpa to 32.60 MPa as compared to control formulation without fibers	Random distribution of recycled steel fiber in concrete mix could result in fiber bundles which resulted in slight loss in compressive strength

factors to be considered. By the addition of only one additional factor, i.e. Global warming potential, volume fraction for the hybrid formulation of industrial and recycled steel fibers inversed from 1% of industrial and 0.5% of recycled steel fibers to 1.35% of recycled and 0.15% of industrial steel fibers [17].

Similar but detail study was conducted by the same research group on the effect of hybrid industrial and recycled steel fiber self-consolidating concrete. SEM analysis revealed that deep grooves at the surface of recycled steel fibers (Fig. 6) improved the bond properties and interaction with the surrounding matrix in comparison to the smooth surface of industrial steel fibers. Results for splitting tensile strength revealed that 22–30% increase in strength was noted regardless of the type and fraction of steel fibers. However, in that study, they concluded that hybrid formulation with 0.15% of industrial and 1.35% of recycled steel fiber having the maximum desirability function value of 0.620 while adding another factor for global warming potential in desirability function analysis [17].

A gradual increase in tensile splitting strength was noted by adding 0–1% of waste steel fibers with an increment of 0.25%, and tensile splitting of concrete was increased by 22.85% at 1% of waste steel fiber inclusion to concrete in the presence of 15% palm oil fuel ash. It was attributed to crack arrest and resistance offered by waste steel fibers towards the development of internal cracks

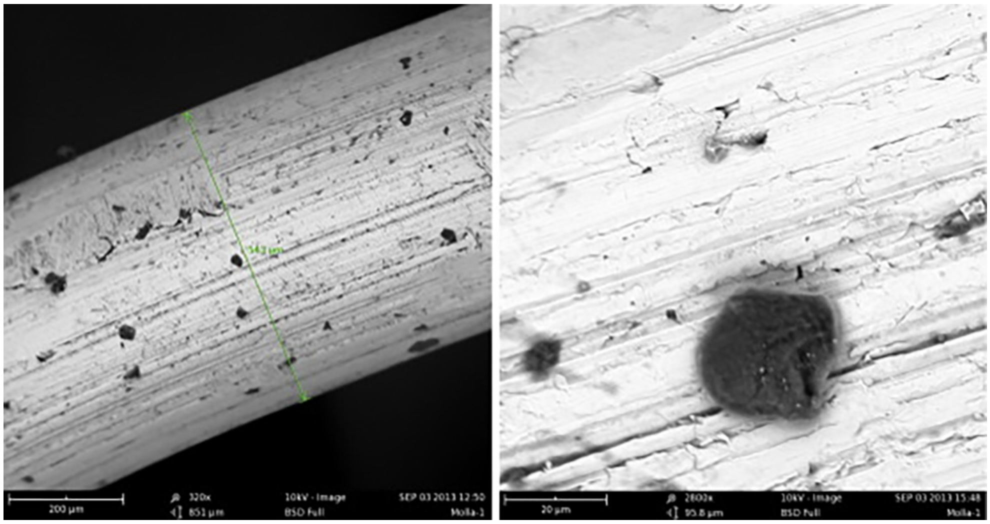

Fig. 6. Scanning Electron Microscopic image for Surface Topology of Recycled Steel Fibers at different magnifications [82].

[90,95,97]. A similar increasing trend was observed for tensile splitting strength of concrete for pavement structures when 0.5% of high specific gravity recycled steel fibers were added [94]. Relatively better results were obtained when 0.5% of recycled steel fibers were added to normal concrete tensile splitting strength was enhanced by 43% in comparison to plain concrete and 9% higher for concrete with 0.25% of industrial steel fibers [101].

Studies on ultra-high-performance concrete revealed that inclusion of recycled steel fibers with rubber particles attached to surface significantly improves the tensile spitting capacity of concrete by 33.48% and 70.77% as compared concrete with and without industrial steel fibers. It was found that high capacity waste steel fibers hindered the crack propagation and resulted in improved tensile splitting capacity of ultra-high-performance concrete [142]. It was further revealed that rubber particles attached to surface of waste steel fiber act synergistically in improving the tensile capacity of concrete and these fibers were free from the damage during the burning process to remove the rubber particles [162] and tensile splitting strength was improved by 13% by adding 1% of recycled steel fibers with 40% of silica fume [153].

However, conflicting results have been reported in various studies regarding the application of recycled steel fibers recovered from tires on tensile splitting strength of concrete [165–169]. Rubber particles attached to recycled steel fibers were reported to negatively affect the tensile splitting strength of concrete. Soft nature of rubber, as compared to surrounding dense cement matrix, which resulted in an elastic imbalance and acted as voids providing negligible resistance against loading [165,167]. Effect of waste steel fibers on the rubberized concrete was studied, and it was observed that flexural strength of concrete without steel fibers was dropped by 50% because of the addition of rubber while the addition of recycled steel fibers helped to regain this strength and drop in strength was recovered to 9.6% [170]. Similar strength gain was observed in recycled aggregate concrete when 3% of recycled steel fibers were added to concrete [171]. Sengul studied the effect of recycled steel fibers recovered from different scrap tires having different aspect ratios on the tensile splitting strength of concrete. No significant improvement in splitting tensile strength by the addition of recycled steel fibers was observed [86]. In addition to this, recycled steel fibers found to be vulnerable to corrosion in high chloride environment that decreases the mechanical strength of fibers hence resulting in a decrease in tensile strength of concrete [172].

5.3. Flexural toughness

Post-peak behavior of fiber-reinforced concrete rely not only on the type and quality of fiber but also the number of fibers into the mixture. A gradual increase in peak load capacity was observed by adding the same type of steel fibers by increasing percentage [80,100]. Recycled steel fibers provide crack bridging and crack arrest capability to improve the post-crack behavior of concrete [83,94,98,106,142]. Recycled steel fibers can provide comparable results to that of industrial steel fibers in terms of energy absorption capacity and residual strength after crack initiation upon flexural loading [131]. Fig. 7 depicts that plain concrete without any fibers do not provide any resistance against crack propagation and energy absorption after the peak load and suddenly fail due to flexural loading. While on the other hand, concrete provided by 0.4% of industrial steel fibers (ISF) shows excellent post-crack behavior by providing resistance against crack propagation.

Similarly, concrete with recycled steel fibers (RSFs) showed better post-peak behavior by absorbing energy after the first crack and provide comparable results with industrial steel fiber concrete. It can be observed that load in RSF (0.23%) suddenly drops after the peak load crack and then provide ductility to the beam. At a lower amount of recycled steel fibers, relatively less residual strength was observed by the samples which

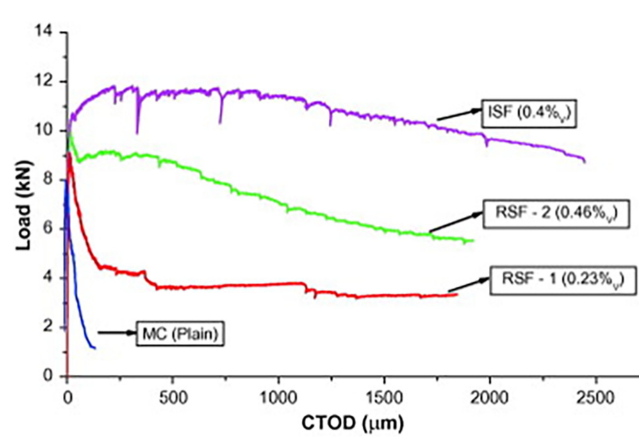

Fig. 7. Post Crack Behavior of Industrial and Recycled steel Fiber Concrete [131].

represent the softening behavior of fiber concrete as presented in [133]. The similar softening phenomenon was also observed at lower fiber content by [81,96,98,138]. On the contrary to this, significant improvement in flexural behavior of recycled steel fiber concrete was observed by [99,173,174]. It was observed that first crack and the ultimate load was enhanced by 60% and 20% respectively by the addition of 60Kg/m^3 of recycled steel fibers. Similarly, flexural stiffness was also improved by 75% at this fiber content [99]. In addition to this, a decrease in crack propagation speed was observed by the addition of recycled steel fibers to the concrete [94]. However, results presented in [86] revealed no significant effect on post-peak behavior of concrete by adding recycled steel fibers. Because of geometry and surface characteristics, recycled steel fibers do not provide effective fiber reinforcement mechanism hence, deflection hardening phase was missing in recycled steel fiber concrete [72]. However, [174] proposed that similar toughness performance can be achieved by adding almost 25–45% of extra recycled steel fibers as in the case of industrial steel fibers. While recycled steel chips (0.6% optimum [175]) found to be better reinforcement against compression and flexural load and enhance the ductility of concrete [176].

During the recycling process, steel fibers get damaged, and loose particles attach to the surface do not provide enough anchorage and ultimately cause a decrease in post-peak response in term of energy absorption as compared to smooth-surfaced industrial steel fibers (Fig. 8) [150]. Inadequate response of recycled steel fibers was attributed to irregular geometry [82]. The better flexural response can be achieved by the hybrid inclusion of hooked end shaped industrial and recycled steel fibers [150]. 15–30% replacement of industrial steel fibers with recycled steel fibers was suggested for a better flexural response [17]. In the study of fiber reinforced concrete aspect ratio of fibers have got prime importance [177]. Higher aspect ratio of recycled steel fibers provides significant improvement in ductility and flexural response [66,89,96,138].

Jafarifar et al. studied the applicability of FE models, i.e., RILEM TC 162-TDF for steel-reinforced normal and roller-compacted concrete, to predict the post-cracking behavior of recycled steel fiber roller-compacted concrete. The analysis demonstrated that these methodologies overestimate the energy absorbing capacity, and it was concluded that this overestimate can go up to 60%. Based on the inverse analysis of laboratory tests and bending test results, a multilinear relationship was proposed to model the tensile behavior of recycled steel fiber reinforced concrete [178]. Similar studies proposed models for the design of recycled steel fiber concrete and found that the new approach is more accurate than RILEM for recycled fiber concrete structure design [107]. Giancarlo et al. analyzed the crack width control capability of recycled steel fibers, and numerical study was done on different structures including simple beam, water-retaining tank wall, a highway overpass and long jointless building using fib Model Code 2010 [179]. It was concluded that the Fib Model Code 2010 could be successfully applied to these structures with some extra effort required for nonlinear sectional analysis for crack width control [180]. Barros and Ferrara et al. also discussed above-mentioned approaches for the design of structural members by recycled fiber reinforced concrete [181] while Caggiano et al. proposed a numerical model for the pullout behavior recycled steel fibers embedded in the cement matrix, based on bond stress at the interface and corresponding displacement [81].

5.4. Response to impact load

Mastali et al. reported an increase in impact resistance with the addition of recycled steel fibers. It was observed that by increasing the recycled steel fiber content, ultimate crack resistance was enhanced while 3 to 4 times better impact resistance at 0.75% of recycled steel fibers was reported [85]. Promising results for impact resistance of lightweight concrete were observed by the addition of 0.75% of waste steel wires, and the ultimate impact resistance was increased by eighteen times [80]. Planner orientation of recycled steel fibers is found to be more effective against impact loading as compared to the 3-dimensional orientation of fibers [7,182]. While improvement in ductile behavior in all direction of soil matrix composite was attributed to the three-dimensional orientation of recycled steel fibers [182].

On the contrary to this, Impact resistance or energy absorption capacity of recycled steel fiber concrete drops with the inclusion of recycled steel fibers as compared to industrial steel fibers [183]. Similarly, as compared to industrial steel fibers, 1.5% of recycled steel fibers reduces the first impact resistance by 15% while 20% decrease in ultimate crack resistance was observed by [17]. Because of high absorbing capacity of rubber, addition of rubber with recycled steel fibers was found to be promising in increasing the impact resistance of concrete [58] while addition of pozzolanic materials, i.e. silica fume and fly-ash also found to be a practical solution to provide additional mechanical interlocking and friction which significantly improve the impact resistance of the recycled steel fiber concrete [153].

6. Durability

Application of recycled steel fibers into the concrete resulted in improvement in shrinkage behavior, impact resistance, and crack propagation [35,99,184–186]. Permeation, diffusion, and capillary transport are the major three transportation mode for ingression of corrosive agents into the concrete. Control on crack width propagation resulted in a decrease in ingression of harmful chemicals into the concrete matrix thus resulted in an overall decrease in deterioration of concrete and constitutive steel fibers. Limiting the crack width to 0.3 mm, the only aesthetic detrimental impact was observed because of the deterioration of surface fibers in the corrosive environment [187–189]. In chloride-rich environment carbon dioxide is found to be susceptible towards the deterioration of steel fibers due to corrosion hence resulting in a decrease in performance of steel fiber concrete [45,105,133,190]. While corrosion was found to significantly affect the fiber and cement matrix interaction. Pretreatment of recycled steel fibers at 350 °C transformed the austenite retained in microstructure to the bainite and eventually increased the hardness of recycled steel fiber. Electrochemical results showed that recycled steel fibers in a solution of 3.5% wt of NaCl solution, corrosion probability was 90% and recycled steel fibers were found to be more vulnerable to corrosion as compared to industrial steel fibers. It can be seen in Fig. 9, reduction in fiber diameter and irregular and rough surface confirms the presence of corrosion product which verifies the deterioration and damage during potentiodynamic polarization test of recycled steel fiber. Presence of rubber at the fiber surface does not significantly affect the corrosion resistance of recycled steel fibers and has a limited effect on the corrosion resistance of recycled steel fiber reinforced concrete [105]. Similarly, after wet and dry cycles of chloride exposure, no significant deterioration in the mechanical performance of recycled steel fiber reinforced concrete was observed [191] and no visual deterioration were observed after accelerated chloride exposure, and embedded steel fibers were found to be free from any severe deterioration under chloride exposure [187]. It was noted that blend of manufactured and recycled steel fibers to concrete enhance the durability of concrete [192].

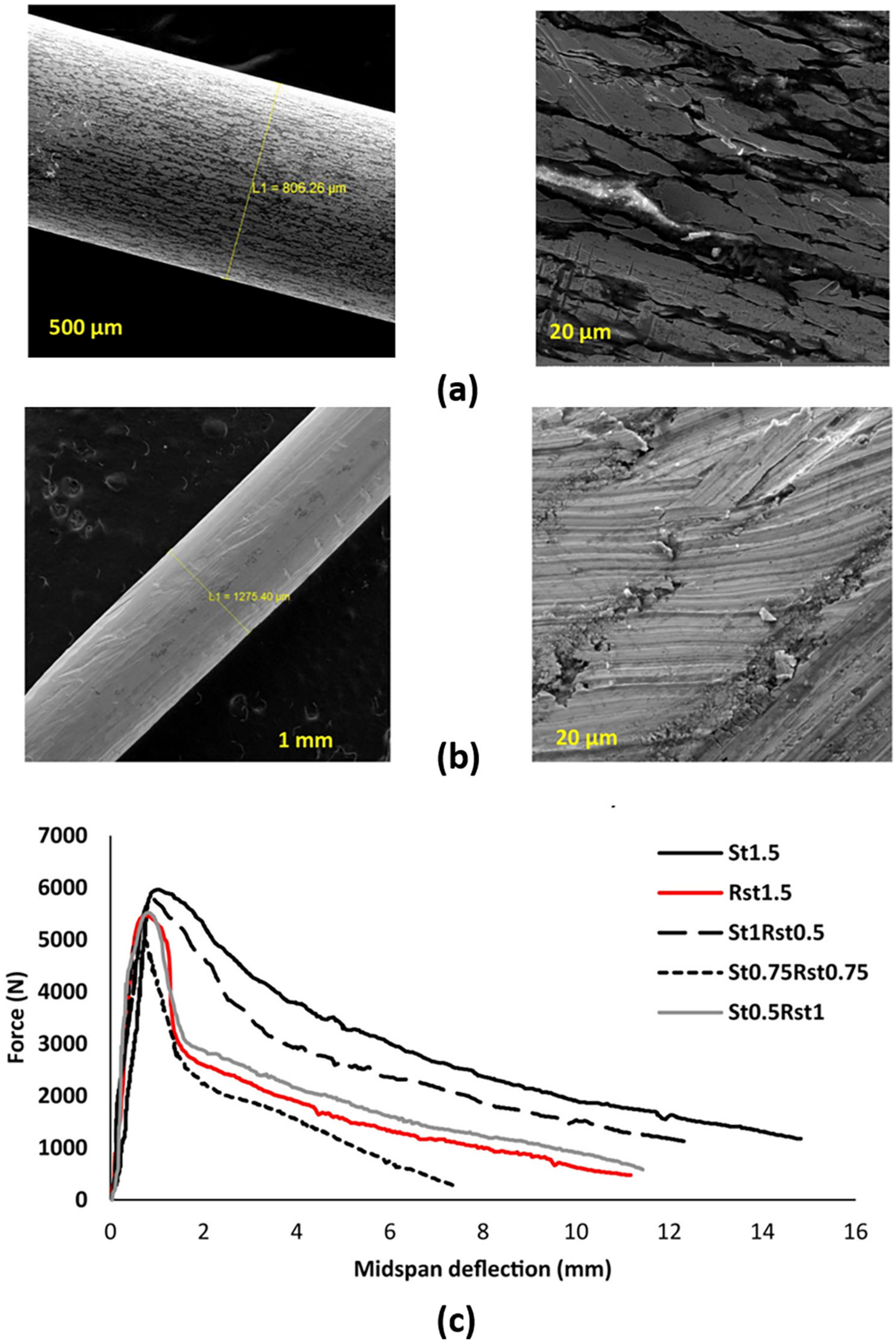

Fig. 8. Surface Morphology of (a) Industrial Steel Fiber (St), (b) Recycled Steel Fibers (Rs) and Flexural Response of Self Compacting Concrete with Hybrid Inclusion of Industrial and Recycled Steel Fibers [150].

Recently, Alsaif et al. studied the freeze-thaw performance of recycled steel fiber reinforced concrete in terms of surface scaling and concrete pop out by following the procedure given in [193]. Less dense rubber particles caused high water uptake [194] and pore connectivity resulting in high surface scaling and mortar coming out due to freeze-thaw cycles. The small size of rubber particles resulted in large pore size and connectivity; hence decrease in compressive strength and increased mass scaling was observed as depicted in Fig. 10. While the presence of steel fibers helped in retaining the flexural strength of concrete [46].

7. Efficiency of recycled steel fiber concrete

To efficiently and effectively utilize the recycled steel fibers in concrete, it is necessary to clarify the influence of geometry and total content of recycled steel fibers to the mechanical properties of resulted concrete. Effect of diameter and length of recycled steel fiber on compressive strength, flexural strength, and tensile strength of fiber reinforced concrete is presented in Fig. 11. Similarly, fiber geometry, optimum content, and the corresponding change in mechanical strength have been tabulated in Table 3.

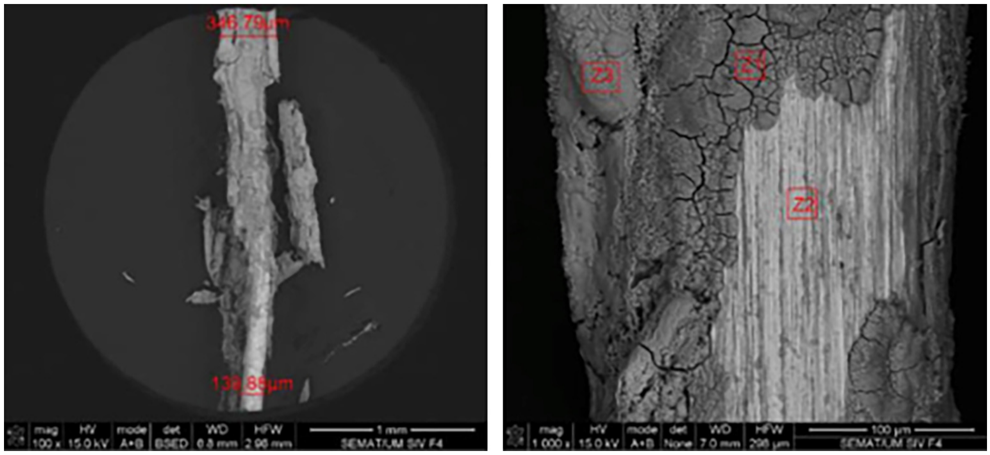

Fig. 9. Recycled Steel Fiber Surface deterioration after potentiodynamic polarization test at different magnifications [105].

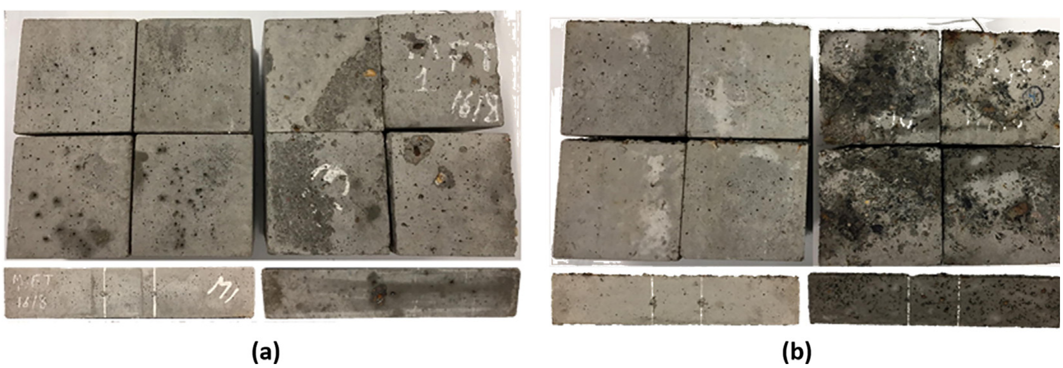

Fig. 10. Surface Appearance of specimens before (left) and after (right) 56 cycles of Freeze-thaw action (a) concrete with only steel fibers, (b) concrete with steel fibers and rubber particles as 30% by volume for fine and coarse aggregates [46].

Based on literature, it is evident that fiber geometry does not greatly influence the compressive strength of concrete and Fig. 11 showed that there is also disagreement in the results presented by different researchers. Mastali et al. reported the 40% increase in compressive strength by using recycled steel fibers of an average diameter of 0.15 mm and length of about 50 mm at 1.5% by volume [17]. Conversely, about 17% decrease in compressive strength was reported when fibers of 0.18 mm diameter and 15 mm length were used. Table 3 gives insight about the effect of the fiber content of recycled steel fiber concrete reported in the literature. According to that, an increase of about 20% in compressive strength was observed at 0.23% by volume of recycled steel fiber concrete, and compressive strength was observed to be enhanced by 40% when 1.5% by volume of recycled steel fibers were used [17,131]. No apparent trend is present in the literature, so it is difficult to fully conclude the effect of diameter and length on the compressive strength of concrete, but it can be partially proposed that fiber diameter range of 0.15–0.26 mm and length of about 25–40 mm were found to be positively influence the compressive strength of recycled steel fiber concrete.

In case of flexural strength, longer fibers were found to be more effective and efficient in increasing the flexural strength of recycled steel fiber concrete. A consistent trend was noted that by increasing the fiber length, flexural strength was observed to be enhanced. Flexural strength was increased by 40% and 68% when 50 mm long recycled steel fibers, having the diameter of 1.2 mm and 0.6 mm, were used respectively [80,86]. Similarly, 40.5% increase in flexural strength was observed when 55 mm long recycled steel fibers of diameter 0.125 mm diameter were used [34]. Fig. 11 revealed that at a constant length of 50 mm, the diameter of recycled steel fibers showed an increasing and decreasing trend for flexural strength. 0.6 mm diameter can be addressed as the optimum diameter for flexural strength enhancement with 0.15 mm and 1.2 mm as lower and upper bound for diameter of recycled steel fibers. One of the researches also revealed the negative effect of recycled steel fibers on flexural strength of concrete when a very small quantity of about 10 kg/m^3 of recycled steel fibers with an equivalent length of 35 mm and 0.2 mm diameter were used [93]. Based on the literature, it can be concluded that 0.6 mm diameter and 50 mm long recycled steel fibers act as an effective reinforcement for concrete against flexural loadings.

Fig. 11 further revealed the effect of fiber geometry on splitting tensile strength of recycled steel fiber concrete. About 45% increase in splitting tensile strength was observed by the inclusion of 20 mm long recycled steel fibers having an average diameter of 0.15 mm [13]. While 10% decrease in tensile strength was observed when using 0.25 mm diameter and 14 mm long steel fibers. Similarly, 21.4% decrease in tensile strength was observed even at higher content of 1% by volume of 16.5 mm long recycled steel fibers. It can be revealed that fiber length has more influence on the tensile strength of concrete. At a same diameter of 0.25 mm, the fiber length of 26.17 mm resulted in an increase of tensile strength by 43% while, on the other hand, an increase of about 23% was observed when the average length of fibers was 25.4 mm [95,101]. While further decreasing the length of fiber to 14 mm, 10% decrease in tensile strength was observed [98]. So, it

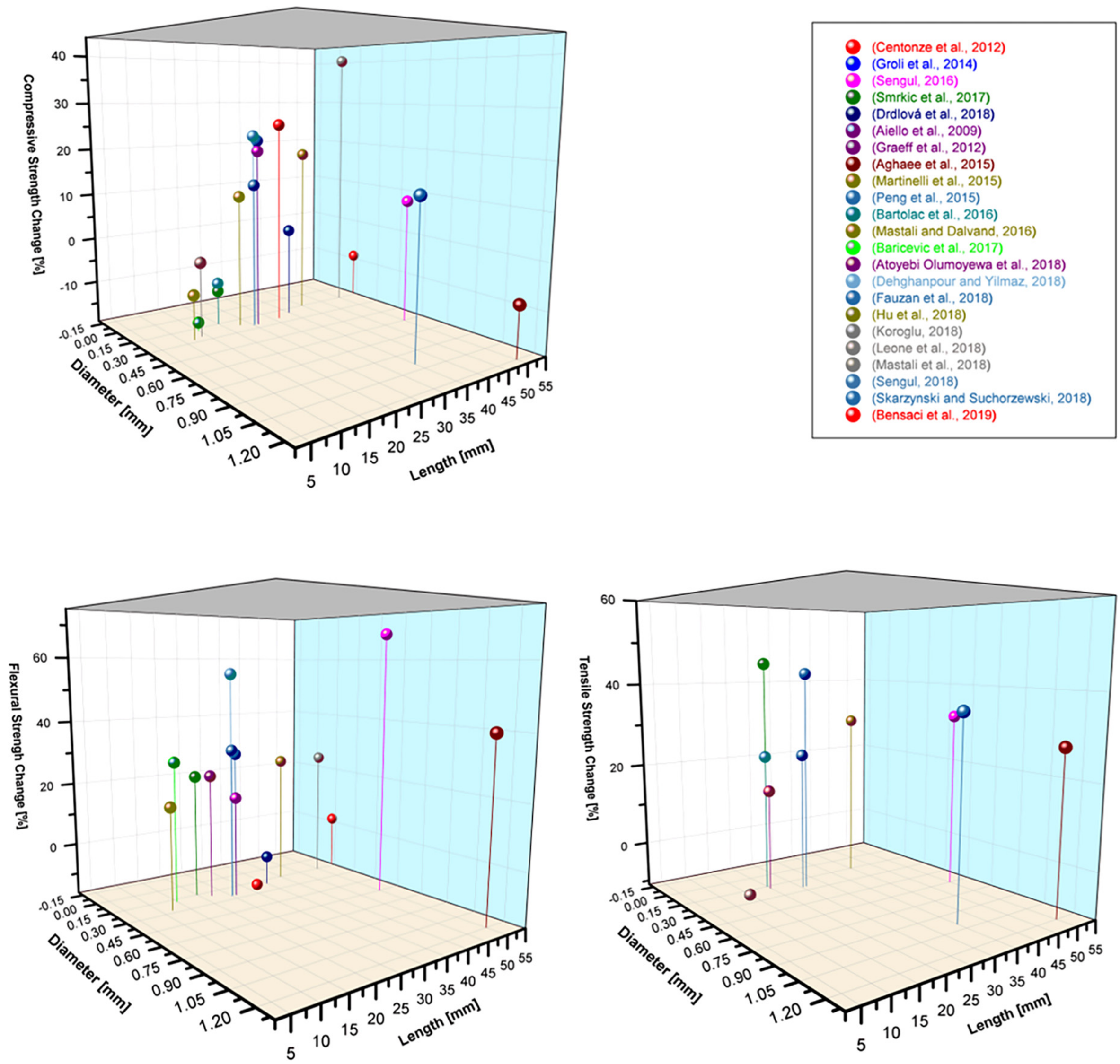

Fig. 11. Effect of recycled steel fiber geometry on mechanical performance of fiber reinforced concrete.

is concluded that at the same diameter, increase in recycled steel fiber length; tensile splitting strength tends to increase and vice versa.

Based on the literature presented in Fig. 11 and Table 3, it is proposed that compressive strength of recycled steel fiber concrete mainly depends on the fiber content while flexural and tensile strengths are significantly influenced by the fiber geometry precisely average length of the recycled steel fibers.

8. Discussion

8.1. Recycled steel fiber reinforced concrete

In fiber-reinforced cementitious systems, workability and flow properties were found to be highly dependent on the fiber content, shape, and geometry of the fibers [86,137]. Due to inconsistent geometry, higher aspect ratio and fiber content, balling effect was found to be prominent in recycled steel fibers reinforced cement systems [163]. Inconsistent geometry of recycled steel fibers is logical due to different types of tires and variable recycling procedures. Consistent geometry of recycled fibers, lower aspect ratio, use of superplasticizers to increase workability and incremental addition of fibers during mixing found to be promising to avoid balling effect and workability of recycled steel fiber reinforced concrete. Also, planetary vertical concrete mixer is proposed to be a technological and practical solution to the uniform dispersion of recycled steel fibers without any adverse effect on workability even at a higher concentration of recycled steel fibers. Moreover, porosity and bulk density are directly affected by the compaction of fiber reinforced concrete in fresh state and rubber attached to the surface of steel fibers recycled from tires. Therefore, specific standard procedures for the recycling of steel fibers from tires are needed, and recycling facilities should be bound to adopt certain consistent procedures to follow and sorting of recycled steel fibers should be done based on diameter and length before their application into the concrete. Based on the literature, fiber diameter range of 0.15–0.26 mm and fiber length of 25–40 mm is proposed as these ranges for diameter and equivalent length were found to be promising in enhancing the different mechanical properties of recycled steel fiber concrete. Better anchorage bond is expected from corrugated and irregular geometry of recycled steel fibers which can provide a better bond with the matrix. In addition to this, special care should be taken to complete removal of rubber

Table 3
Summary of recycled steel fiber geometry, content and corresponding % change in different mechanical properties of recycled steel fiber concrete reported in literature.

Reference	Diameter	Length	Content	Compressive Strength	Flexural Strength	Tensile Strength
[74]	0.24	31.4	0.46	25.45	−15	N/A
[79]	N/A	16.5	1	0	N/A	−21.4
[86]	0.6	50	40*	8.6	67.85	32.3
[13]	0.15	20	20–20	−11.6	22.7	45.16
[93]	0.2	35	10	0.66	−7	N/A
[131]	0.258	26	0.23	19.95	15.87	N/A
[75]	0.2	22	6% by mass	N/A	23.07	N/A
[80]	1.2	50	0.75	−8	40	28
[82]***	0.27	12	0.5	−9.5	15.8	N/A
[83]	1	35	60*	13.9	N/A	35.9
[84]	0.15	20	20–20**	−9.8	N/A	22.4
[85]	0.15	40	0.75	18	25	30
[66]	0.18	15	10–100**	−17.38	28.26	N/A
[91]	0.18	20	0.6	N/A	N/A	14
[92]	0.26	25	2% by weight	23.3	55.27	N/A
[95]	0.25	25.4	1	12.5	31.27	22.85
[138]	0.22	23	30*	10	N/A	N/A
[97]	0.27	60	4	26.7	N/A	78.6
[98]	0.25	13.94	0.46	−3	N/A	−10
[17]	0.15	50	1.5	40	25	N/A
[100]	2	208	4	1.8	N/A	172.8
[101]	0.25	26.17	50*	22.2	30	42.8
[34]	0.125	55	1.5	−9.3	40.5	N/A

*Units = Kg/m^3, ** Industrial and Recycled Steel Fibers in Kg/m^3, *** Strength Changes compared to Industrial steel Fibers, N/A Data not available.

or any other additional material attached to the surface of recycled steel fibers. These procedures can be beneficial, and higher content of fibers can be effectively utilized into to the construction industry which could help us to achieve sustainability goals in cost-effective way.

Volumetric stability and early age shrinkage play an essential role in the durability of concrete structures, cracks developed at the surface are vulnerable to strength decrement and can provide easy access to water and other dangerous chlorides into the cement matrix and resulting in degradation and rusting of steel. Recycled steel fibers were found to be beneficial in providing the volumetric stability, thus enhancing the durability of concrete. Uniform dispersion of recycled steel fibers into the cement matrix and proper curing of RSFRC is desirable to avoid early age shrinkage.

Results for compressive strength of recycled steel fiber reinforced concrete are found to be random in terms of the effect of fibers on compressive strength, fiber content, optimum dosage, and geometry of the fibers. Compressive strength was found to be dependent on the number of fibers rather than the geometry of the fibers. In general, higher content of recycled steel fibers was found to be beneficial in increasing the compressive strength, but variable results are reported in the literature, which needs more attention in future to understand the effect of recycled steel fibers on compressive strength of concrete. Addition of secondary raw materials with recycled steel fibers are found to be beneficial in increasing the compressive strength of concrete because a lower amount of fibers does not provide homogeneity in the matrix and only the cement matrix plays it role under compressive stress.

Relatively consistent results are reported in the literature for the tensile splitting strength of the various concrete by the addition of recycled steel fibers. It is noted that recycled steel fibers can change the failure to ductile, also increase the tensile splitting strength of the concrete. To get better results for tensile behavior of concrete, the inclusion of the threshold dosage of the fibers is necessary. Addition of recycled steel fibers less than the threshold value does not provide enough reinforcing effect while on the other hand, dosage more than threshold value severely affect the dispersion of recycled steel fibers into the concrete which cause porosity and weaker spots in the concrete which ultimately adversely affect the mechanical properties of the concrete. Although the threshold dosage of recycled steel fibers has great importance, but no reliable conclusion can be drawn about the optimum dosage of recycled steel fibers due to variability in results about threshold value of recycled steel fibers. Flexural and tensile strength was found to be influenced by the fiber geometry and it was seen that longer fiber provide a better reinforcing mechanism and results in increased flexural and tensile strength of the concrete. Amount of rubber attached to steel fibers recycled from tires and the heating treatment significantly depends on each other. Low heat during recycling cannot effectively remove the rubber attached to the fibers while overheating can damage the recycled steel fibers. So, care should be taken during heating treatment of steel fibers recycled from waste tires for the removal of rubber particles attached to the surface. Any degradation in fiber mechanical properties ultimately affect the properties of resulted concrete.

Steel fibers recycled from tires can be effectively utilized in concrete to enhance the energy absorption capacity of concrete, due to their crack bridging and lateral crack arrest capability. At relatively low fiber content, concrete shows softening behavior which can be explained by the less effective surface area of the fibers in contact with the surrounding cement matrix that cannot provide effect stress transfer at the interface between fibers and concrete and slippage of fiber cause sudden decrease in load carrying capacity after the first crack appears. So, it is essential to note that not only the quality and but the number of recycled steel fibers also play an important role in the mechanical properties of recycled steel fiber reinforced concrete. In addition to this, the aspect ratio of fibers also plays significant role in the flexural capacity of concrete because this directly relates to dispersion and surface contact area of fibers for effective stress transfer as discussed above.

Impact resistance of the concrete can be enhanced by the addition of recycled steel fibers along with rubber. High absorbing capacity of rubber provides better impact load resistance, and it was noted that fiber orientation in the cement matrix plays a vital role against impact load. It can be further added that 2-dimensional orientation of fibers provide better and effective resistance against lateral cracks upon impact loading as compared to 3-dimensional orientation because fibers along the loading direction are not so effective and do not play substantial role against impact load and lateral crack arrest. Impact resistance can be enhanced by modification of the surface of recycled steel fibers by the inclusion of pozzolanic additive which provides extra interlocking capability and friction at the surface of fibers.

Recycled steel fibers are found to be susceptible to corrosion in chloride rich environment, which results in deterioration and degradation of matrix interaction and ultimately decrease the strength of concrete. It is further noted that recycled steel fibers were found to be more susceptible to corrosion as compared to industrial steel fibers this can be due to longer use of recycled steel fibers as compared to industrial steel fibers. Similarly, rubber particles attached to the surface do not cause any increase in corrosion, which might be due to the blockage effect of rubber against water and other chlorides.

8.2. Current challenges and future trends

Based on literature available on recycled steel fiber reinforced concrete. Some of the current challenges and possible future trends are proposed.

Tire being one of the most abundant waste materials to recover steel fiber but variability in techniques adopted by recycling facilities make it difficult to achieve uniform geometry of the recycled steel fibers, and it is challenging to achieve homogenous concrete mix with uniformly dispersed steel fibers. Some standards should be developed to get the best possible recycled steel fibers to eliminate the issues related to variability in geometries of available recycled steel fibers. Life cycle and environmental impact assessment of various recycling technique should be done to point out the most economical and environmentally friendly technique for the recycling of uniform and best quality steel fibers. Limited data is available on the characteristics and quality of recycled steel fibers. Work can be extended to detail study on the qualitative and quantitative analysis of recycled steel fibers recycled from different sources.

Rubber Particles attached to the surface of recycled steel fibers from tires are found to be the main constraint against better interaction between cement matrix and fiber surface. Detail study is needed to fully understand the interface of recycled steel fiber and the surrounding matrix. Rubber particles attached to recycled steel fibers are found to be susceptible to high temperatures, so fiber interaction should be studied at elevated temperature to understand the behavior of fibers and change in their particular properties within the concrete matrix. Moreover, the spalling mechanism should be considered in detail at elevated temperatures. In addition to this, steel fibers are vulnerable to corrosion, so detail study should be carried out on the durability and corrosion susceptibility of recycled steel fiber reinforced concrete. Literature revealed that no specific guidelines are available for the design of structural members using recycled steel fiber reinforced concrete. Work can be extended to develop design codes by taking variability in quality and possible defects in recycled steel fibers during the recycling.

9. Conclusion

Recent developments in recycled steel fiber reinforced concrete, fresh and hardened properties, and durability has been reviewed. The following concluding remarks are drawn.

1. Recycling of tires, to recover steel fibers, is not only sustainable, environmental, and health-friendly but also provide economical means of energy generation during the production of cement.
2. Rubber particles attached to fiber surface adversely affect the fiber performance. Better recycling procedures and standards are required to recover these fibers with best properties.
3. Planetary vertical mixer, the addition of superplasticizer, uniform geometry of fibers, and limited content and aspect ratio are found to be promising in providing a uniform dispersion of fibers.
4. Secondary raw materials, i.e., silica fume, were found to be useful to address the issues related to high porosity and lower bulk density of recycled steel fiber reinforced concrete.
5. Effect of recycled steel fibers on the compressive strength of various cement-based systems is not clear yet; further study is needed to thoroughly understand the fiber interaction with surround matrix and its behavior under compressive loads.
6. Hybrid inclusion of recycled and industrial steel fibers provide a better mechanism against structural loadings.
7. Recycled steel fiber reinforced concrete can provide comparative results under flexural loading in accordance with industrial steel fibers.

Studies reviewed in this article shows that recycled steel fiber, when added in optimum conditions, can provide comparable mechanical properties as in the case of industrial steel fibers without significantly affecting the workability and other fresh properties. Therefore, the application of recycled steel fibers into construction industry can provide low cost and environmentally friendly alternative to industrial steel fibers with sufficient crack arrest capability and improved mechanical properties. In addition to this, recovering steel fibers by recycling the tire can provide additional stream to utilize end-of-life and waste tires that is more sustainable, can provide economical energy and reduce the possible breeding sites for mosquitoes that spread death-causing diseases like *malaria* and *dengue*.

Declaration of Competing Interest

The authors declare that there were no conflicts of interest regarding the publication of this paper.

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