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REVIEW PAPER

The Effect of Recycled Steel Fibers from Waste Tires on Concrete Properties

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ABSTRACT: One of the most severe environmental problems in the world is how to dispose of waste tires properly. Many tires are dumped or thrown away worldwide every year, severely threatening the environment. Most waste tires are used as fuel by some industries, but as we know, this type of waste use has a dangerous effect. The use of synthetic fibers, especially industrial steel fibers, which is very common today and requires high raw materials and energy, negatively impacts the environment by emitting CO_2 during manufacturing. Therefore, finding fibers that perform similarly to industrial steel fibers is essential. This article presents a comprehensive overview of the methods of recycling steel fibers from waste tires, the characteristics of recycled fibers, and their application in producing different cement-based composites. The effect of these recycled fibers on fresh concrete properties, including workability and porosity, has been investigated. The effect of these fibers on the concrete's mechanical characteristics, including compressive strength, splitting tensile strength, flexural strength, impact resistance, and durability, is also discussed. According to recent research, using recycled steel fibers to strengthen concrete can be a suitable alternative to industrial steel fibers, which have fewer adverse effects on the environment and reduced recycling costs.

Keywords: Fiber Reinforced Concrete, Fresh Properties, Mechanical Properties, Recycled Steel Fiber, Waste Tire.

1. Introduction

One of the most popular building materials, concrete, due to temperature and relative humidity changes, always has internal micro-cracks that lead to low tensile strength and consequently, brittle failure concrete (Awolusi et al., 2021). Adding natural or synthetic fibers to the concrete mix is one of the most efficient strategies for improving and strengthening the brittle matrix and preventing cracking (Jamshaid and Mishra, 2016). Fibers have been used for a long time as reinforcements for construction materials and composites; according to studies and research, the use of natural and synthetic fibers has shown promising results (Mohajerani et al., 2019); because their use has advantages and significant improvements in the mechanical

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and physical characteristics of the composite material (Ghanbari and Bayat, 2022). Natural fibers (such as straw, coconut, sisal, etc.) are readily available, save energy, and reduce environmental impacts (Mohajerani et al., 2019; Laborel et al., 2016). They are also biodegradable, renewable, and lightweight. Natural fibers can replace synthetic fibers for some applications (Mohajerani et al., 2019); however, natural fibers are less durable and degrade over time in alkaline environments (Saha et al., 2016).

Synthetic fibers can reduce construction costs by substituting traditional reinforcements such as steel mesh and rebars, which are much heavier and require more energy, resources, and time to produce (Yin et al., 2015). Industrial Steel Fibers (ISF) are concrete's most commonly utilized synthetic fibers. Of course, it is essential to note that steel fibers and rebars have distinct but complementary roles in increasing concrete performance. Similar to steel reinforcements, the main feature of steel fibers is their high tensile capacity (Yin et al., 2015). Steel fibers have been extensively studied in concrete applications; hence, they are commonly used to enhance the mechanical characteristics of concrete. Steel fibers help improve concrete behavior in terms of cracking, shrinkage, ductility, toughness, and energy absorption (Yin et al., 2015).

However, synthetic fibers are manufactured and require raw materials and energy; they are challenging to recycle and show the adverse effects of CO_2 emissions during production (Frazão, 2019). Climate change due to increasing concentrations of greenhouse gas emissions and air pollution is considered one of the most critical challenges for humanity in the current century (De Wilde and Coley, 2012). As mentioned above, the construction sector is also one of the main factors in the phenomena, which significantly impacts global warming and accounts for 39% of the relevant CO_2 emissions in 2017 (Frazão, 2019). In recent years, the scientific community has tried to reduce CO_2 emissions and their adverse environmental effects through several measures focused on the sustainability of materials and the environment based on the minimization and reuse of waste (Onuaguluchi and Banthia, 2018).

In particular, using recycled materials as sustainable constituents of cementitious materials has become a promising environmental and technical solution (Sabzi et al., 2022); one of the waste materials used in construction materials is vehicle tires (Bulei et al., 2018). Research on utilizing these waste tires in construction has recently been carried out. Rubber powder, crumb rubber, steel fibers, nylon fibers, and nylon pellets are just a few of the items that may be extracted from tires (Bulei et al., 2018). Recycled Steel Fibers (RSF) from waste tires can be a suitable replacement for ISF (Awolusi et al., 2021; Bulei et al., 2018).

Briefly, this review article focuses on the following issues:

- Investigating waste tire recycling methods and comparing the properties of RSF according to the recycling method in Section 2.
- Investigating the effect of RSF on fresh concrete properties in Section 3.
- Investigating the effect of RSF on concrete's mechanical characteristics, such as compressive strength, tensile strength, flexural strength, impact, and durability, in Section 4.
- Presenting a general conclusion of the studies conducted and presenting the challenges and studies needed for the future in Section 5.

Such information will help gain up-to-date knowledge of fiber properties and stimulate further research into its practical applications.

2. Methods of Recycling Tires and Characteristics of Recycled Steel Fibers

Waste tires are dumped or disposed of worldwide, severely threatening the environment (Liew and Akbar, 2020). Most waste tires are used as fuel by some industries, but as we know, this type of waste use has a dangerous effect due to the production of greenhouse gases (Liew and Akbar, 2020). On the other hand, the excessive disposal of large waste tires has proven to be a significant environmental concern due to their non-biodegradable nature (especially in developing countries) (Frazão, 2019). Tire recycling methods are divided into branches, mechanical and chemical (Tlemat, 2004). In the mechanical method, the tire is divided into smaller pieces. Shredders and mills do this in several stages (Tlemat, 2004). Each step of this method produces different products used in various industries. Finally, the steel fibers, rubber components, and granules obtained during the shredding process are separated using an electromagnetic technique. Some industries use coarse granules, and others require very soft rubber powder; Shredded Recycled Steel Fiber (SRSF) refers to steel fibers obtained through shredding. Figure 1 summarizes the shredding process to recycle tires (Tlemat et al., 2003).

A technique for crumbling is cryogenic fragmentation which involves shredding tires and cooling them to temperatures below minus 80 degrees Celsius (Tlemat, 2004). After that, the chips are pounded in a hammermill to separate the parts. However, much energy is needed to maintain such low temperatures (Tlemat et al., 2003). In the chemical method, either the tire is burned or pyrolysis (Tlemat, 2004). Tire burning can be replaced by pyrolysis to reduce harmful emissions. In a sealed chamber, the tires are heated without air, producing oil and fuel gases as well as carbon and steel leftovers (Tlemat, 2004). Pyrolysed Recycled Steel Fiber (PRSF) is the name for recovered steel fibers through pyrolysis.

The fibers have varied forms and diameters depending on the main source and recycling procedure. Studies have shown that the shredding method is mainly used to recycle the steel fibers of waste tires, and the fibers are recycled in various diameters and lengths (Liew and Akbar, 2020). The type of tire determines the diameter of the RSF, while the recycling method has a more significant effect on the length of the fibers (Caggiano et al., 2015). RSF obtained by the cryogenic method has no significant rubber particles compared to recycled fibers using the shredding method (Awolusi et al., 2021; Caggiano et al., 2015). In the thermal analysis, longer fibers can be recycled and shortened to the required uniform length, while recycled fibers have small variable lengths using the shredding method (Frazão, 2019). Figure 2 shows the recycled fibers from the thermal and cryogenic methods. Statistical analysis is necessary for a specific group of sample fibers to disperse the fibers' frequency and average size due to the vast range of geometric differences in RSF.

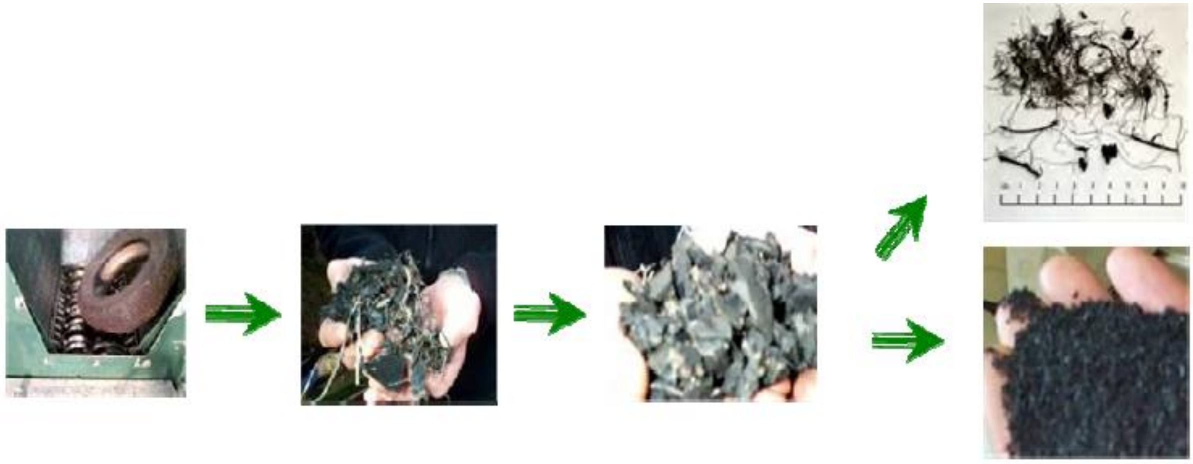


Fig. 1. Shredding process and production of SRSF (Tlemat, 2004)


(a) (b)

Fig. 2. The recycled fibers from: a) The thermal (Tlemat et al., 2003); and b) Cryogenic (Zamanzadeh et al., 2015) methods

For example, Shi et al. (2020) randomly selected 500 fibers to describe the RSFs' size distribution and manually measured their diameter and length with the help of a micrometer (Figure 3). The histograms of length, diameter, and fiber aspect ratio (length-to-diameter ratio) are displayed in Figure 4. According to research, most fibers have a diameter of less than 0.5 mm, with an average of 0.32 mm. Most fiber lengths fall between 5 and 25 mm, with a length of 14.9 mm on average. One crucial variable is the aspect ratio which could directly correlate with the fresh and hardened properties of the fiber-reinforced concrete (FRC). Most samples of RSF have aspect ratios between 20 and 70, and the average for the studied samples is 55.

3. Fresh Properties of Concrete with Recycled Steel Fibers

3.1. Workability (Slump)

Workability is one of the significant limitations of FRC for better performance of hardened concrete (Liew and Akbar, 2020). The kind and volume of RSF significantly impact the workability of concrete, which is the main criterion. Although the slump test is regarded as a standard test for quantifying the performance of a concrete mix, the slump test, in the opinion of many experts, needs to provide more details about the quantitative measurement of FRC performance. However, it is acceptable as a quality control technique to achieve uniformity in the performance of different concrete categories (Liew and Akbar, 2020). The workability and homogeneity of the freshly mixed concrete are both impacted by the high proportion of RSF (Awolusi et al., 2021). The aspect ratio and geometric properties of the fibers, in addition to the volume content of the fibers, significantly impact the workability and homogeneity of freshly mixed concrete with steel fibers (Alsaif et al., 2018b). The workability of fiber reinforcements depends mainly on achieving homogeneous dispersion of fibers in the concrete matrix. According to the obtained results, the geometry of RSF has a similar effect on the uniform distribution of fibers and the workability of concrete compared to ISF (Alsaif et al., 2018b). Numerous studies have found that fibers reduce the workability of concrete.

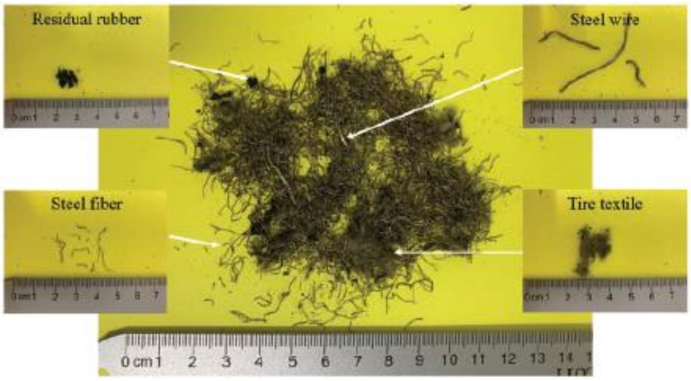
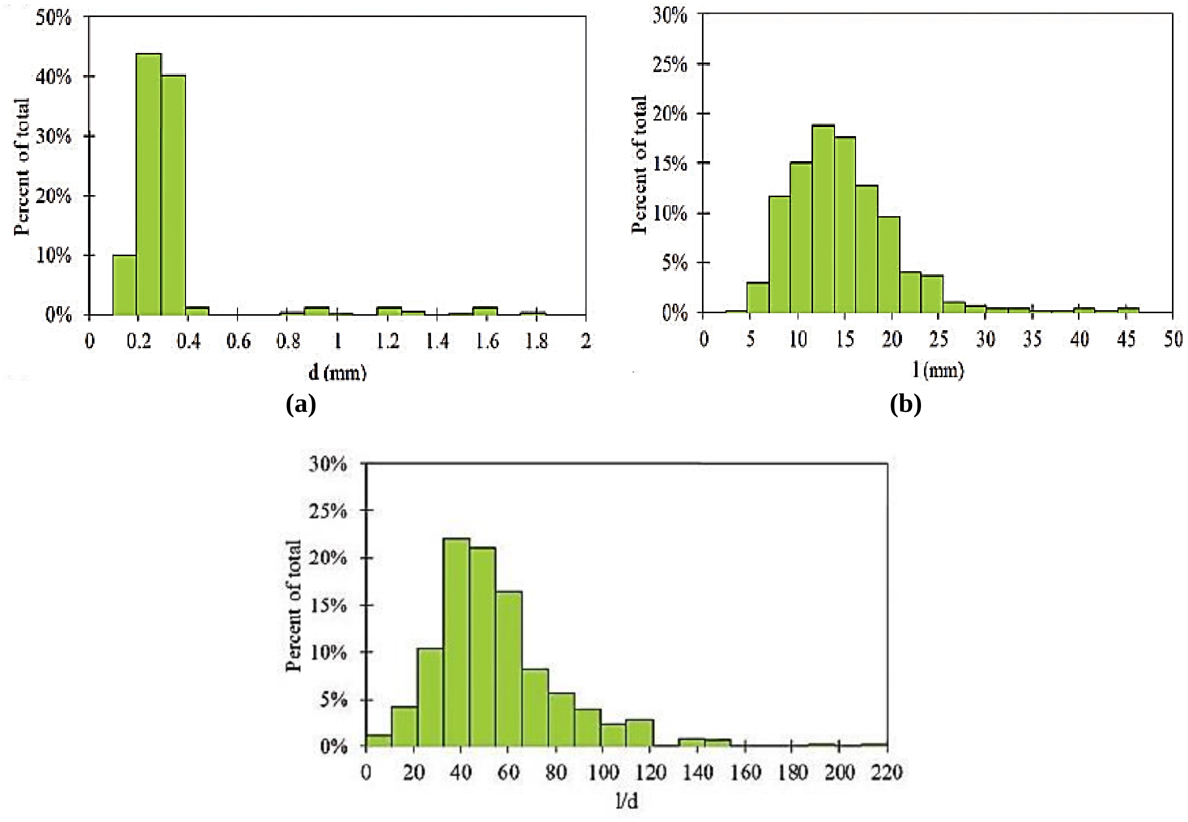


Fig. 3. Scrap tire recycled steel fiber (Shi et al., 2020)



(a) **(b)**

(c)

Fig. 4. Recycled steel fiber dimensions: a) Diameter, b) Length; and c) Aspect ratio (Shi et al., 2020)

Wafa (1990) observed that FRC slump values decrease from 0 to 2% with increasing fiber content. Rossli and Ibrahim (2012) investigated the effect of RSF from waste tires in the concrete mix. With increasing fiber content, the freshly mixed concrete's workability declined. In a study by Sengul (2016), the results showed that for fibers with a fixed length of 50 mm, increasing the fiber content from 10 to 40 kg/m^3 reduces the slump from 10 to 0 cm. In addition, the findings indicated that increasing the aspect ratio of the fibers (smaller fiber diameter) reduced the slump. Bedewi (2009) examined the influence of length (20, 40, and 60 mm) and volume (0%, 0.5%, 1%, and 1.5%) of recycled fibers on concrete slump values. In general, the findings showed that the slump decreases significantly with the increase in the length and volume of fibers. So that the specimen was reinforced with fibers 60 mm long, and a volume percentage of 1.5% had 0 slumps. A summary of the slump results of various studies is shown in Table 1.

3.2. Porosity

Workability in FRC can be attained by adding more water to the mix, but this additional water can lead to more pore volume inside the concrete matrix (Liew and Akbar, 2020). In addition, rubber on recycled fiber surfaces may prevent appropriate interaction with the surrounding cement matrix, which increases porosity and thus reduces mechanical performance (Yang et al., 2019). The porosity and homogeneity of RSF in concrete can be determined using Ultrasonic Pulse Velocity (UPV) testing (Yang et al., 2019; Mastali et al., 2018a). Steel fibers make it difficult to compact concrete in its fresh state, which leads to a decrease in workability; thus, the concrete becomes more porous, which is demonstrated by a reduction in UPV (Mehdipour et al., 2020; Mastali et al., 2018a). Results from UPV showed that by including a 2% volume of RSF, UPV is reduced by 3% to 7% (Liew and Akbar, 2020; Abdul Awal et al., 2015). In a study on self-consolidation concrete, the findings indicated that by using a combination of RSF and ISF, increasing the volume percentage of ISF led to an increase in UPV. (Mastali et al., 2018a). The findings reflect that the lowest and highest UPV reduction in specimens containing 1% ISF and 0.5% RSF, and 0.5% ISF and 1% RSF, compared to the UPV in the control mixture, was obtained about 3% and 12%, respectively.

The studies conducted on microstructure and UPV investigation for recycled fibers are generally limited. Most of the available information is related to industrial fibers. Figure 5 shows some studies' UPV results for specimens reinforced with RSF and ISF. The numbers written in front of each of the abbreviations indicate the volume percentage of the fibers. Where REF stands for Reference concrete, ISF stands for Industrial steel fiber reinforced concrete, RSF stands for Recycled steel fiber reinforced concrete, and PP stands for Polypropylene fiber reinforced concrete. In general, the abbreviations used are mentioned in the captions of all figures.

Table 1. Results of slump values obtained from using RSF

Reference	RSF Content	Diameter (mm)	Length (mm)	Concrete class	W/C	Slump (mm)
Rossli and Ibrahim (2012)	0%	0.2-1.139	20-99	C40	0.53	55
	0.2%					60
	0.4%					30
	0.6%					10
	0.8%					30
	1%					10
Sengul (2016)	0 kg/m^3	-	-	C60	0.5	14
	10 kg/m^3	0.6	50			10
	20 kg/m^3					4
Bedewi (2009)	0%	-	-	C25	0.53	79
	0.5%	0.89	20			64
	1%					56
	1.5%					47
	0.5%	0.89	40			38
	1%					11
	1.5%					6
	0.5%	0.89	60			31
	1%					5
	1.5%					0

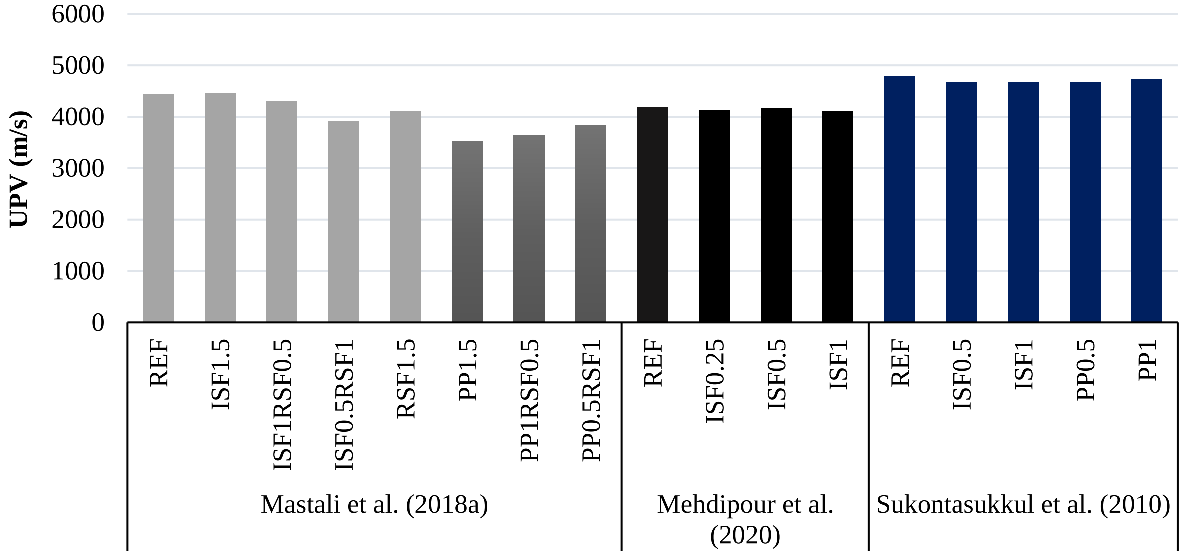
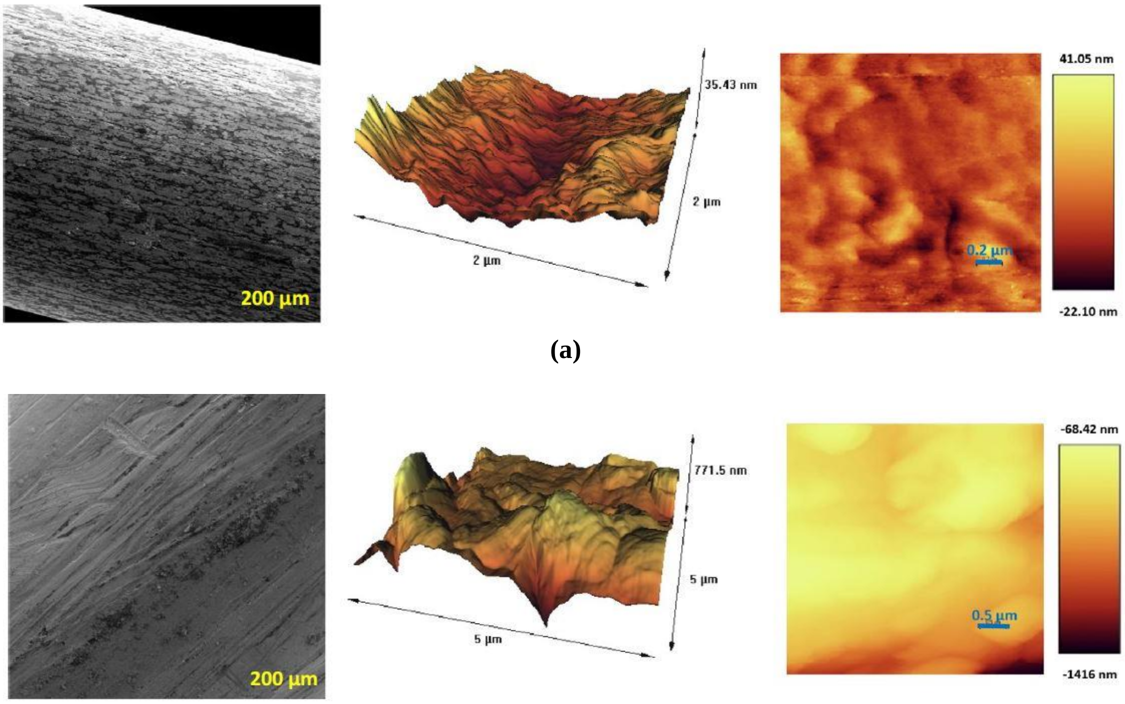


Fig. 5. UPV results for specimens reinforced with fibers (REF: Reference concrete, ISF: Industrial steel fiber reinforced concrete, RSF: Recycled steel fiber reinforced concrete, PP: Polypropylene fiber reinforced concrete)

4. Mechanical Properties of Hardened Concrete with Recycled Steel Fibers

4.1. Compressive Strength

The presence of RSF can positively affect the compressive strength of concrete. However, if a large volume of fibers is used, excess water to solve workability problems can damage the concrete's compressive strength due to increased porosity (Awolusi et al., 2021; Liew and Akbar, 2020). Concrete failure can be delayed using RSF because these fibers cause ductile failure. Fiber content dramatically impacts the response of concrete to compressive loads (Liew and Akbar, 2020). According to the study, despite the minimal amount of fibers present, there was no discernible increase in the compressive strength of concrete. (Yang et al., 2019). It can be assumed that in a small volume content of RSF, the compressive strength of concrete depends mainly on the structure of the internal matrix. Mastali et al. (2018a) examined the impact of hybrid fibers in self-consolidating concrete, which had various fibers (including ISF, RSF, and PP) and different volumes content. In this research, an average length of more than 50 mm and a diameter of 0.15 ± 0.05 mm was measured for RSF. As a result of the fibers' ability to prevent crack propagation, the findings demonstrated that mixtures containing fibers have compressive strengths that are higher than those of the reference mixture. The increase in compressive strength was measured by almost 60% (80 MPa) in the reinforced mixture with 1.5% ISF and about 40% (70 MPa) with 1.5% RSF. The compressive strength increased by around 50% in the specimen with 1% ISF and 0.5% RSF. Mastali et al. (2018b) investigated the topography and morphology of recycled and industrial fiber surfaces, which showed that recycled fibers contain deeper grooves and a rougher surface. The interaction between the fibers and matrix may be enhanced by these deeper grooves and improve the bonding properties at the interface. Due to the ability of fibers to limit crack development and bridging cracks, mixes containing fibers have greater compressive strength than the reference mixture. Figure 6 shows the morphology and topography of recycled and industrial fiber surfaces.



(a)

(b)

Fig. 6. SEM and AFM images of the fiber surfaces: a) Industrial steel fibers; and b) Recycled steel fibers (Mastali et al. 2018b)

According to the reference mixture, Caggiano et al. (2017) showed that RSF with variable lengths and diameters increase compressive strength between 5% and 10%. The existence of fibers has a minor impact on the final compressive strength of FRC. To a certain extent, additional fibers (or rising aspect ratios) can increase the compressive strength of concrete, which is mainly determined by the quality of the cementitious matrix and the aggregates. Dehghanpour and Yılmaz (2018) also show that for fibers with a fixed length of 25 mm, concrete's compressive strength is improved by increasing the fiber content from 0% to 2%. While increasing the content by more than 2% harms compressive strength. This is because large voids formed between the fibers during compaction due to increased RSF in the mortar mixture. Bedewi (2009) examined how the volumetric fraction and fiber length affected the compressive strength of concrete reinforced with steel fibers obtained from used tires. The volumetric content was varied at 0%, 0.5%, 1%, and 1.5%, while the fiber length was varied at 20 mm, 40 mm, and 60 mm. Figure 7 briefly shows Bedewi's (2009) results regarding the effect of recycled fibers with volume percentage and lengths on the compressive strength of concrete with different strength values. The results have shown that the compressive strength increases with the volume percentage of fibers. Increasing the length of fibers up to 40 mm has also improved the compressive strength, but using fibers with a length of 60 mm has decreased strength. Based on the findings, it was found that 1.5% volumetric content with a fiber length of 40 mm provided the highest compressive strength. Details of previous studies for maximum compressive strength are presented in Table 2.

Concrete's compressive strength is also greatly influenced by the surface morphology, amount of rubber attached to the RSF, and fiber shape. Some research has suggested that the existence of rubber adhered to the steel fibers' surface harms the compressive strength of concrete (Rossli and Ibrahim, 2012). Rubber particles' hydrophobicity and insufficient bonding with the surrounding cement matrix negatively impact the concrete's performance (Figure 8) (Yang et al., 2019).

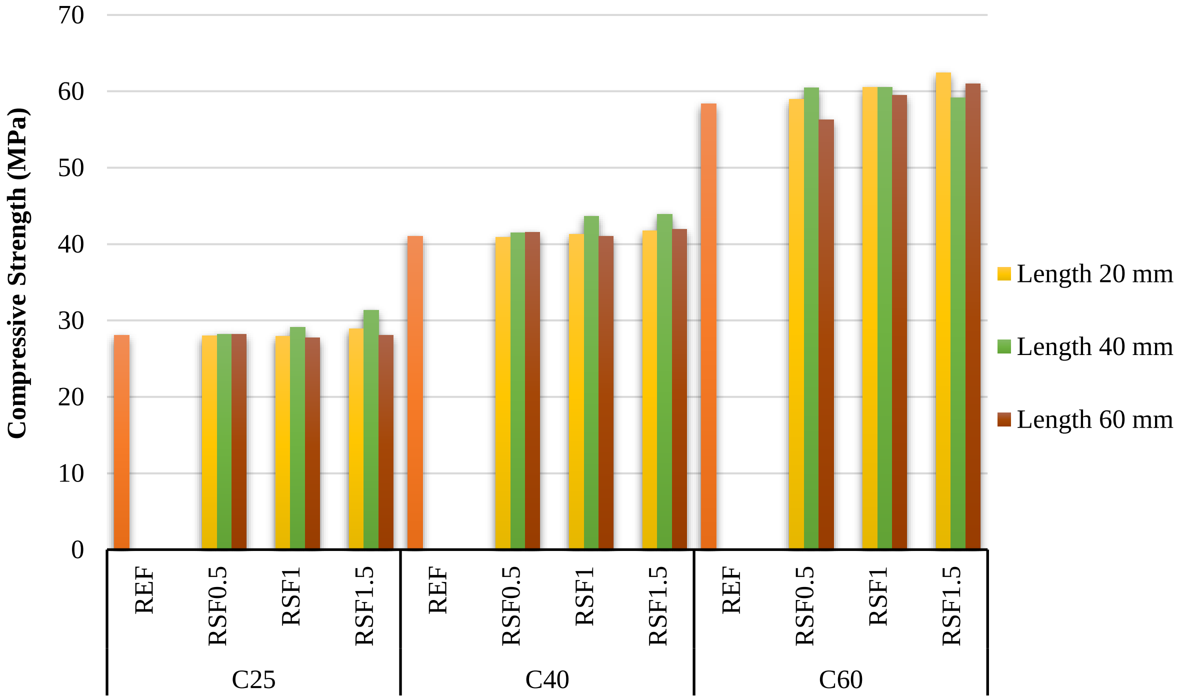


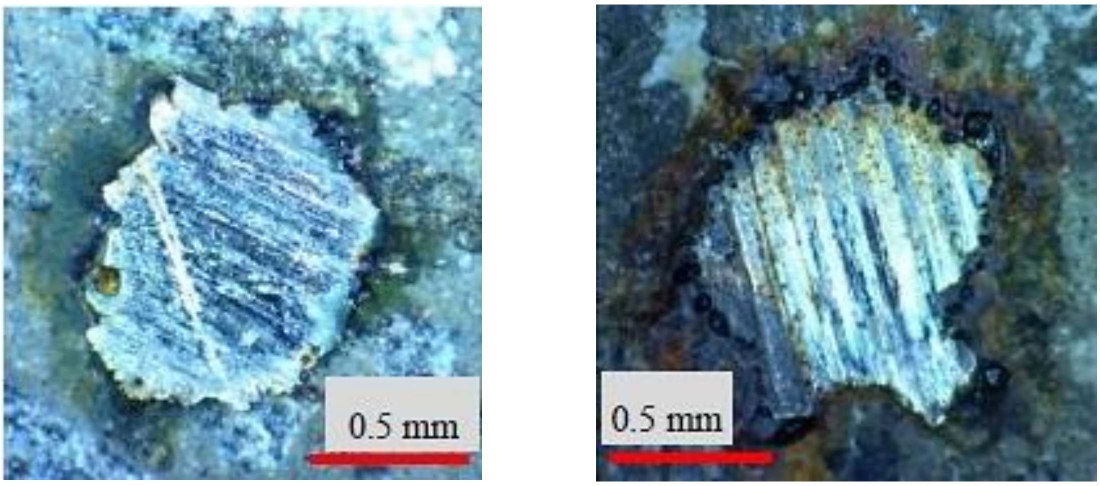
Fig. 7. Effect of length and volume percentage of recycled fibers on compressive strength of concrete (REF: Reference concrete, RSF: Recycled steel fiber reinforced concrete, C: Concrete class)

Table 2. Results of compressive strength obtained from using RSF

Reference	**RSF Content**	**Diameter (mm)**	**Length (mm)**	**W/C**	**CS of PC[1] (MPa)**	**CS of FRC (MPa)**
Mastali et al. (2018a)	1.5%	0.15	Over 50	0.76	50	70
Caggiano et al. (2017)	0.75%	0.11-0.44	6-74	0.49	22	24
Dehghanpour and Yılmaz (2018)	1%	0.26	25	0.5	57.16	62.74
	1.5%					66.62
	2%					70.5
	2.5%					64.55
Bedewi (2009)-C40[2]	0.5%	0.89	20	0.42	41.03	40.92
	1%					41.32
	1.5%					41.78
	0.5%	0.89	40	0.42		41.51
	1%					43.66
	1.5%					43.94
	0.5%	0.89	60	0.42		41.58
	1%					41.06
	1.5%					41.97

[1] CS- Compressive Strength. PC-Plain Concrete

[2] C40- Concrete class



(a) (b)

Fig. 8. Observations of the interface zones between fiber and concrete matrix by an optical microscope: a) RSF without rubber; and b) RSF with rubber (Yang et al., 2019)

The findings revealed a decline in compressive strength from 135.5 to 130.2 MPa; in contrast, the samples' compressive strength was raised from 135.5 to 141.3 MPa by using RSF without rubber on the surface (Yang et al., 2019). In the study by Frazão (2019), the results obtained from the stress-strain curve show that the compressive strength and elastic modulus increase with the age of the specimens. However, RSF-reinforced specimens' compressive strength is lower compared to the reference specimen. Meanwhile, the elastic modulus of specimens reinforced with recycled fibers is higher than the control specimen. According to Figure 9, the fiber-reinforced specimens' ultimate strain is greater than the control specimen, indicating the specimens' better ductility and performance. RSFRC stands for Recycled steel fiber reinforced concrete. The number written with a percentage sign in front of it indicates the percentage of fibers, and the second number after the dash indicates the casting number of the specimen. Six castings were performed in this study. Figure 10 briefly compares the impact of RSF and ISF on the compressive strength of concrete in different studies. The numbers written in front of each of the abbreviations indicate the volume percentage of the fibers.

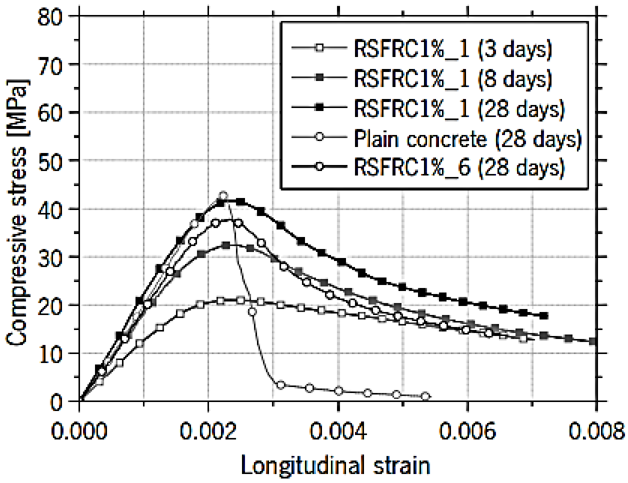


Fig. 9. Average compressive stress-longitudinal strain curve (Frazão, 2019)

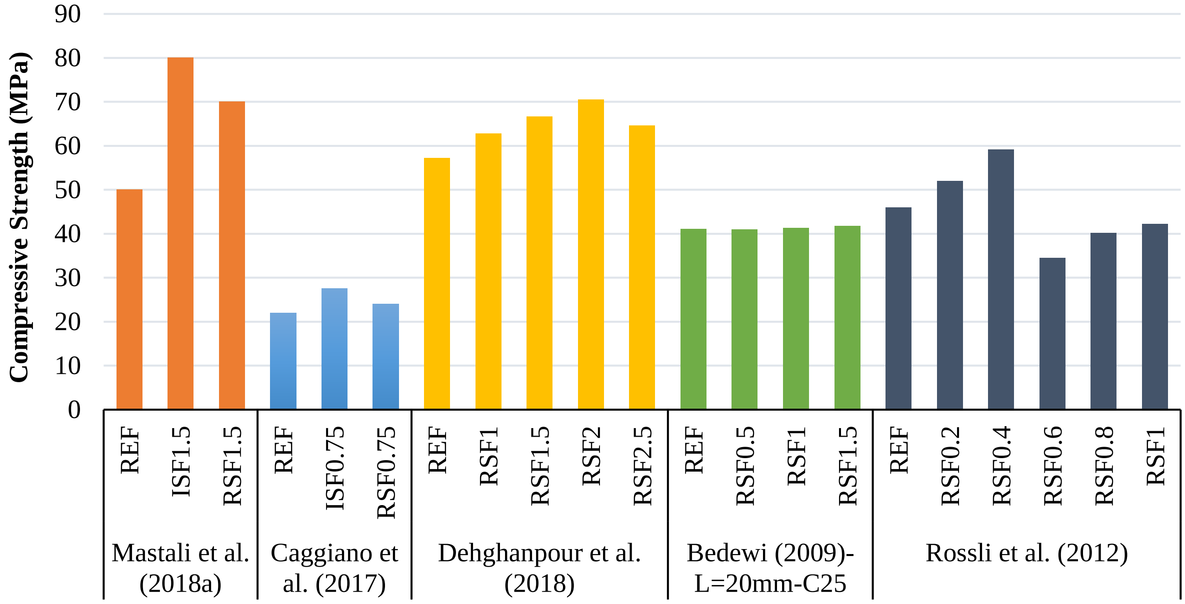


Fig. 10. Compressive strength results for specimens reinforced with recycled and industrial fibers (REF: Reference concrete, ISF: Industrial steel fiber reinforced concrete, RSF: Recycled steel fiber reinforced concrete, C: Concrete class)

4.2. Splitting Tensile Strength

Various studies have reported contradictory results on using RSF from tires on the tensile strength of concrete (Caggiano et al., 2015). Some studies have reported that rubber particles bonded to RSF reduce concrete's splitting tensile strength. Compared to the surrounding dense cement matrix, the rubber's softness leads to elastic imbalance and acts as cavities that provide little load resistance (Liew and Akbar, 2020). Sengul (2016) studied the effect of RSF from tires with different aspect ratios on the splitting tensile strength of concrete. Using RSF did not result in a noticeable increase in tensile strength. However, some studies have shown the opposite result.

Mastali et al. (2018a) examined the impact of hybrid fibers containing RSF longer than 50 mm on the splitting tensile strength of self-consolidating concrete. The findings show that fibers have a positive impact on splitting tensile strength. Like compressive strength, fiber bridging and an increase in splitting tensile strength were caused by the high potential of fibers to stop further crack propagation. Comparing the specimen reinforced with RSF to the plain mixture, a tensile strength increase of roughly 25% was observed. Interestingly, using recycled and industrial steel fibers together provided beneficial results. As previously indicated, ISF were shown to be the most effective at bridging action, followed by RSF. Therefore, in the mixture supplemented with 1% ISF and 0.5% RSF, the most remarkable improvement in splitting tensile strength for the hybrid RSF and ISF was 27%.

Yang et al. (2019) investigated the effect of RSF from tires with and without rubbers attached to the surface on the splitting tensile strength of Ultra-High Performance Concrete (UHPC). In this study, the fiber length was 40 mm, and the fiber diameter was 1 mm. The results showed that the fibers with and without rubber attached to the surface increased the splitting tensile strength by 50% and 40%, respectively, in comparison to the reference specimen. The lower impact of non-rubber steel fibers attached to the surface may be due to the carbon black on the surface of these fibers. Compared to concrete that contained ISF with a tensile strength similar to that of RSF, a study found that the carbon black on the surface of RSF reduced the flexural strength of concrete by around 15% (Yang et al., 2019; Tlemat, 2004). Further study is required to determine how carbon black affects the mechanical characteristics and pore microstructure of UHPC. Rossli and Ibrahim (2012) investigated the effect of volume content (0%, 0.2%, 0.4%, 0.6%, 0.8%, 1%) and the length of randomly distributed fibers ranging from 20 mm to 99 mm on splitting tensile strength. The findings indicate that the splitting tensile strength is optimum at 1% volume content. Table 3 shows the results for splitting tensile strength using RSF.

4.3. Flexural Strength

FRC's post-peak behavior is influenced by the volume, type, and quality of the fibers used in the mixture (Awolusi et al., 2021). RSF can bridge cracks and stop cracking to enhance the post-cracking behavior of concrete. Regarding energy absorption and residual resistance after cracking brought on by flexural loading, RSF can perform similarly to ISF (Aiello et al., 2009). Mastali et al. (2018a) examined the impact of hybrid fibers containing recycled fibers longer than 50 mm on the flexural strength of self-consolidating concrete. For this purpose, the three-point bending test evaluated prismatic beams with dimensions of 420 × 80 × 60 mm^3. The findings indicated that the type of fiber impacts the flexural strength, ductility, flexural stiffness, post-peak residual strength, and ultimate deflection corresponding to the maximum load. The flexural and post-peak residual strengths increased by increasing the fiber mechanical anchorage while the flexural stiffness was reduced. Figure 11 shows that plain, fiber-free concrete has no resistance to energy absorption and crack expansion after maximum load and suddenly fails due to bending load. Conversely, concrete with 1.5% ISF demonstrates better post-cracking performance by preventing crack development. When steel fibers are recycled, some of them are damaged. The loose particles attached to the surface reduce the peak energy response in the energy absorption compared to the ISF with a smooth surface (Mastali et al., 2018a). The insufficient response of RSF can also be related to their irregular geometry (Martinelli et al., 2015). According to the findings, when compared to ordinary self-consolidating concrete, the flexural strengths of mixtures improved in reinforced self-consolidating concrete independent of the fiber combination. Additionally, the hybrid combination of ISF and RSF showed the highest flexural strength among the mixtures reinforced with hybrid fibers (about 35%).

Caggiano et al. (2017) studied the impact of RSF on the flexural behavior of prismatic beams with dimensions of 600 × 150 × 150 mm^3. Prism-shaped specimens were notched in the middle for a depth of around 45 mm prior to the four-point bending tests. As a result of the initial crack's growth, the plain concrete exhibits brittle failure. However, the ISF mix exhibits a post-cracking response (under bending loads) that is distinguished by a notable increase in toughness. The analysis emphasizes the effects of entirely substituting RSF with an equivalent amount of ISF. The results in ductility indices highlight that RSF slightly reduce the FRC toughness. The presence of RSF moves the post-cracking behavior from hardening to plastic (with values varying from 0.9 to 1.1 in every instance where RSF were used).

Dehghanpour and Yilmaz (2018) investigated the effect of recycled fibers on the flexural behavior of prismatic beams with dimensions of 160 × 40 × 40 mm^3. Mortar specimens reinforced with RSF showed higher flexural strength than specimens without fibers. Additionally, the specimens reinforced with 2.0% and 2.5% RSF exhibited the best maximum flexural strength value among the results of the flexural tests. As shown in Figure 12, there was no observable change between specimens reinforced with 1.0% RSF and unreinforced specimens. While the specimens containing 1.5%, 2.0%, and 2.5% RSF compared to the unreinforced specimen, the area under the curves increased by 10, 13, and 18 times, respectively.

Bedewi (2009) examined the impact of volume content and fiber length on the flexural strength of concrete reinforced with RSF. Fiber lengths of 20 mm, 40 mm, and 60 mm and volumes of 0, 0.5%, 1%, and 1.5% were considered. The results obtained in each volume content showed that the maximum fiber length (60 mm) was observed for the maximum flexural strength. Table 4 summarises the results of various research' examinations of flexural strength.

Table 3. Results of splitting tensile strength obtained from using RSF

Reference	RSF Content	Diameter (mm)	Length (mm)	W/C	TS of PC* (MPa)	TS of FRC (MPa)
Sengul (2016)	10 kg/m^3	0.6	50	0.5	6.7	6
Mastali et al. (2018a)	1.5%	0.15	Over 50	0.76	3.5	4.3
Yang et al. (2019)	30 kg/m^3	1	40	0.18	6.91	11.8
Rossli and Ibrahim (2012)	0.2%	0.2-1.39	20-99	0.53	3.88	3.39
	0.4%					3.98
	0.6%					3.90
	0.8%					3.50
	1%					4.44
Onuaguluchi and Banthia (2018)	0.35%	0.2-0.3	15	0.5	3.35	3.98
	0.5%					3.91

*TS- Tensile Strength. PC-Plain Concrete

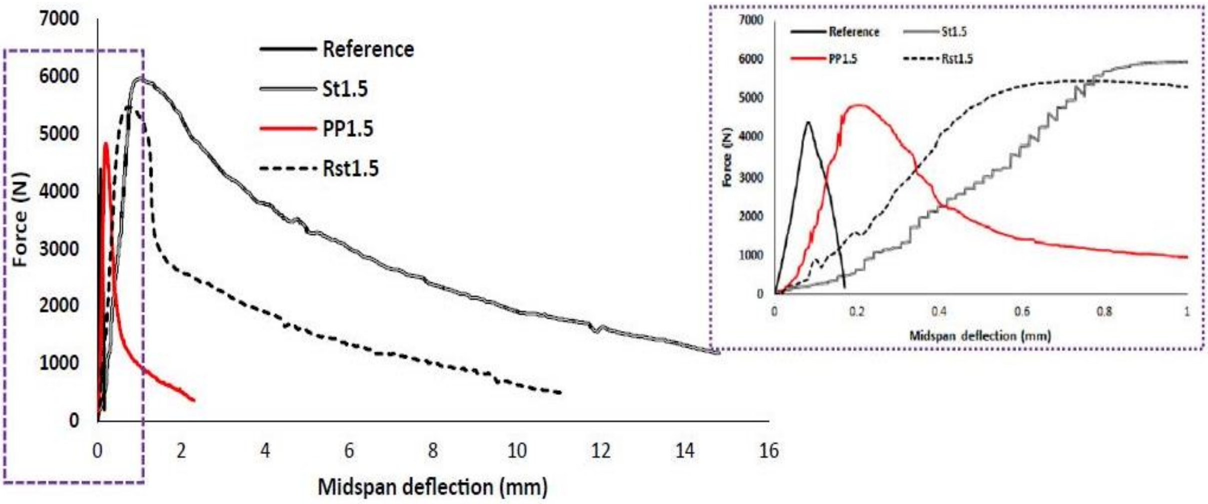


Fig. 11. Force-deflection responses of specimens reinforced with mono-fiber (Mastali et al., 2018a)

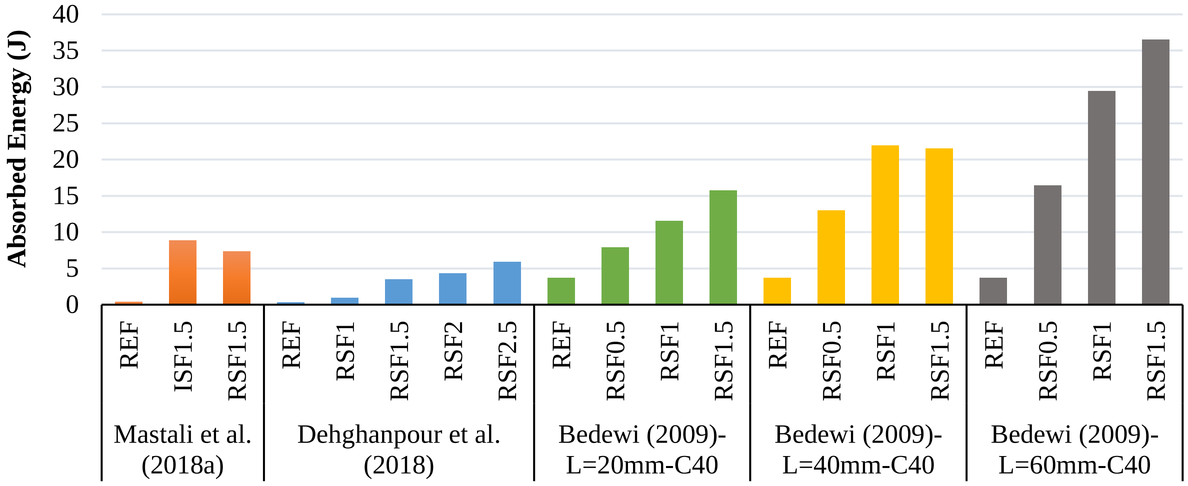


Fig. 12. Amounts of absorbed energy presented in different studies (REF: Reference concrete, ISF: Industrial steel fiber reinforced concrete, RSF: Recycled steel fiber reinforced concrete, L: Fiber length, C: Concrete class)

Table 4. Results of flexural strength obtained from using RSF

Reference	RSF Content	Diameter (mm)	Length (mm)	W/C	FS of PC* (MPa)	FS of FRC (MPa)
Mastali et al. (2018a)	1.5%	0.15	Over 50	0.76	5	6.5
Caggiano et al. (2017)	0.75%	0.11-0.44	6-74	0.49	3	3.68
Dehghanpour and Yilmaz (2018)	1%	0.26	25	0.5	5.21	6.83
	1.5%					7.34
	2%					8.09
	2.5%					8.19
Bedewi (2009)	0.5%	0.89	20	0.53	6.18	6.84
	1%					7.17
	1.5%					8.07
	0.5%	0.89	40	0.53		6.96
	1%					7.89
	1.5%					8.64
	0.5%	0.89	60	0.53		8.19
	1%					10.08
	1.5%					13.71

*FS- Flexural Strength. PC-Plain Concrete

4.4. Impact Resistance

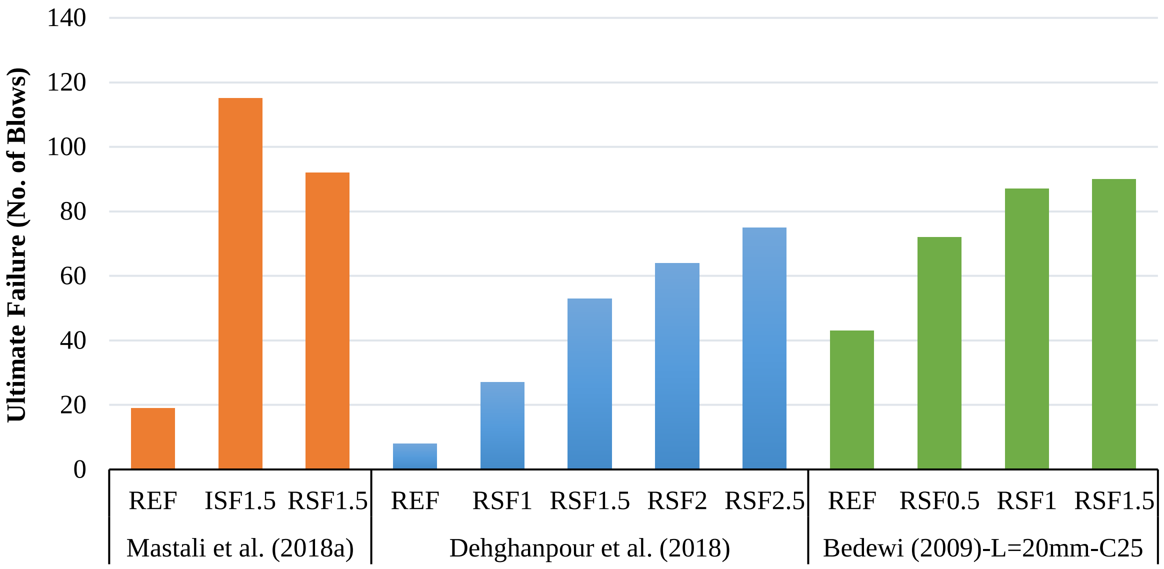
One of FRC's distinctive features is its impact resistance. It has generally been observed that fibers increase fracture energy and maximum load under the impact (Ndayambaje, 2018; Soufeiani et al., 2016; Mastali and Dalvand, 2016). Following the ACI Committee's recommendations, impact resistance should be quantified for repeated blows that the test specimen receives. (ACI Committee, 1996). The number of blows needed to produce the initially visible cracks is considered the first impact resistance. In contrast, the number of blows determines the final resistance that causes the test specimen to fail. Steel fibres' presence positively affects impact resistance because it improves the fracture energy, maximum load, abrasion resistance, and impact resistance. Mastali et al. (2018a) investigated the effect of hybrid fibers containing recycled fibers longer than 50 mm on the impact resistance in self-consolidating concrete. The findings demonstrated that adding fibers enhanced impact resistance due to fiber bridging action regardless of the fiber combination. Also, increasing mechanical anchorage of fibers resulted in a more notable enhancement in impact resistance. Accordingly, the reinforced specimens with 1.5% ISF were found to have the highest impact resistance of discs, with first crack and ultimate crack resistance of 73 and 115 blows, respectively. The first and ultimate cracks increased by more than 4 and 6 times as much as the plain concrete disc. Maximum impact resistance for hybrid fibers was observed as 67 and 101 blows for the first and ultimate crack, respectively; the cementitious disk contributed 1% ISF and 0.5% RSF. Figure 13a shows the number of blows required for ultimate failure in different studies.

Dehghanpour and Yılmaz (2018) investigated the effect of RSF on the impact resistance of concrete. The findings demonstrated that the increased RSF volume fraction improved the ultimate energy values up to the ultimate failure of the RSF-reinforced mortar specimen slabs at 40 mm thickness. For instance, although the slabs without RSF required 30.96 Joules of energy to collapse, the specimens with 2.5% RSF incorporated required an average of 313.80 joules of energy to fail. With the increased RSF volume, a more effective composite material is obtained against stresses due to forming more bridges in the matrix. Energy absorption increases with increasing failure duration (Yahaghi et al., 2016). Impact resistance depends on the length and volume of the fibers in the concrete mix (Mastali et al., 2019). Bedewi (2009) investigated the effect of different lengths of 20 mm, 40 mm, and 60 mm and volumes of 0, 0.5%, 1%, and 1.5% recycled fibers on the impact resistance. The obtained results showed that the number of blows required for the final cracking of the test specimens increases with the fibers' length and volume content. The highest number of impacts was observed in the length of 60 mm and volume of 1.5%, which indicates the highest impact resistance. Figure 13b briefly shows the results of Bedewi's study (2009) regarding the effect of the length and volume percentage of fibers in addition to the concrete strength class.

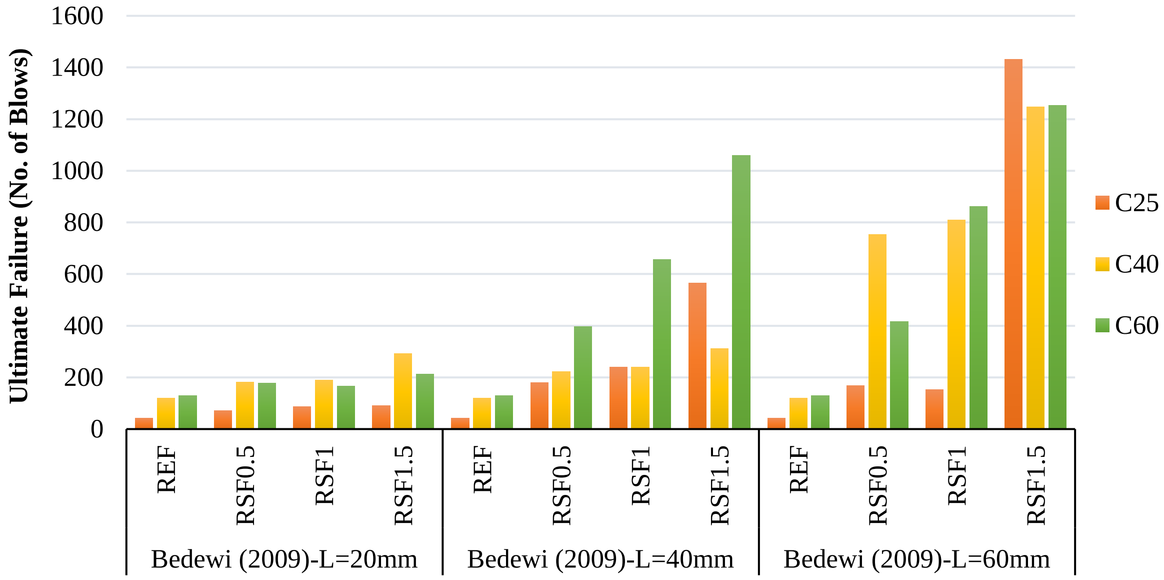
4.5. Durability

The fiber incorporation increases the permeability of the specimens, and this increase in permeability is maintained as the fiber content rises (Ramezani and Esfahani, 2018). Concrete with RSF has improved crack propagation, impact resistance, and shrinkage behavior (Mastali and Dalvand, 2017; Al-Kamyani et al., 2018). Diffusion, capillary transfer, and permeation are the three main modes of corrosive agents entering concrete (Toghroli et al., 2018). Controlling the propagation of crack width reduces the penetration of hazardous chemicals into the concrete structure, thus reducing the concrete's deterioration and structural steel fibers (Caldentey et al., 2016). Only surface fiber damage in the corrosive medium was seen by restricting the crack thickness to 0.3 mm (Graeff et al., 2009). Corrosion significantly affects the interaction of fibers and cement matrix (Frazão et al., 2016). Electrochemical results showed that for RSF in a 3.5% NaCl solution, the probability of corrosion was 90%, and RSF were more vulnerable to corrosion than ISF (Balouch et al., 2010). The corrosion resistance of RSF is not seriously affected by the presence of rubber on the surface of the fibers. It has a negligible effect on concrete reinforced with RSF in terms of corrosion resistance (Frazão et al., 2019). The results showed that combining ISF and RSF increases the durability of concrete (Alsaif et al., 2018a).

In the study conducted by Bjegovic et al. (2012), the effect of steel fibers, textile fibers, and rubber crumb (as an aggregate substitute) recycled from waste tires in freeze-thaw cycles was investigated. The results showed that the presence of by-products from the mechanical recycling of waste tires complies with all criteria and can meet the criteria of water permeability and wear resistance. In a study by Graeff et al. (2009), the effect of RSF and ISF with wet-dry methods to accelerate corrosion was investigated. The findings revealed that when the specimens were exposed to 5 months of continuous wet-dry cycles, the corrosion of the fibers was visible only on the outside. Both types of fibers showed limited signs of corrosion. This study's compressive and flexural results showed that specimens with 2% industrial fibers have the same performance as specimens with 6% recycled fibers.



(a)



(b)

Fig. 13. The number of blows required for ultimate failure: a) Compare different studies; and b) Bedewi's study (2009) regarding the effect of the length and volume percentage of fibers (REF: Reference concrete, ISF: Industrial steel fiber reinforced concrete, RSF: Recycled steel fiber reinforced concrete, L: Fiber length, C: Concrete class)

5. Conclusions

Studies have extensively identified the possibility of reusing waste tire debris as a source of RSF to achieve a sustainable environment and an alternative to ISF. RSF have different lengths, diameters, and tensile strengths depending on the recycling method. As a result, a significant range in the characteristics of fresh and hardened concrete that contained tire waste-derived RSF was noted. Studies show that RSF can provide comparable mechanical properties to ISF if added under optimal conditions. It needs to be determined how RSF may affect compressive strength.

More research is required to comprehend better how the matrix interacts with the fibers and behaves under compressive pressures. Better resistance against structural loads is provided by using hybrid fibers consisting of RSF and ISF. Concrete reinforced with RSF can provide desirable results under bending loads compared to

ISF. Therefore, improving concrete's mechanical characteristics by using RSF in the construction industry can be economical and environmentally friendly.

Based on the available studies, some current challenges and the studies needed for the future are mentioned below:

- RSF from waste tires have rubber attached to the surface and textiles. Therefore, it is essential to investigate the interaction and bonding of fibers with the concrete matrix. In studies, the microstructure of concrete has rarely been investigated, and mostly the surface morphology of fibers has been investigated. Therefore, more studies are needed to understand better the fibers' interaction with the matrix and its behavior under mechanical loads.
- The behavior of these fibers at high temperatures has yet to be studied. Concrete spalling behavior has been investigated only in one case study. Therefore, investigating the effect of these fibers at high temperatures on concrete's mechanical properties is a critical challenge for future work.
- The studies conducted on the effect of these fibers and rubber and textiles on concrete durability issues are also limited and still need more work and study.

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