Environment-friendly recycled steel fibre reinforced concrete

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Environment-Friendliness of Recycled Steel Fibre Reinforced Concrete

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Abstract

Construction wastes have become one of critical issues in lifecycle asset management, slowing down the path towards net zero. Accordingly, the contribution of recycled materials in building design and construction is needed. In such a context, recycled steel fibres (RSF) from waste tires have been considered as an alternative to the industrial steel fibres(ISF). This paper presents a comprehensive and critical review on RSF use relatively to fibre properties, as well as the mechanical properties of RSF reinforced concrete. Both at wet and hardened state comparative analyses between ISF and RSF to improve compressive strength, splitting strength and flexural strength is performed. Moreover, based on the data of global warming potentials and prices, investigates the contribution of RSF towards sustainable development and economy in comparison with ISF.

Keywords: fibre-reinforced concrete; recycle fibres; steel fibres; carbon footprint; eco-friendly concrete

1. Introduction

1.1 Background

Based on research by Mohajerani et al. [1], currently, there are more than billions of tires used for replacement every year in global, and more than half of them are abandoned and are waiting to be disposed. The black pollution which is hard to be biodegrade does not only pose potential risks to the environment, but a threat to the health of human beings who work in the scrap zone [2-5]. However, the main method of assisting waste tires is to landfill after burning, without any treatment [6, 7]. According to the European tire and rubber manufacturers association, the wasted tire can hardly be degraded in landfills without treatment, and the method of disposing of waste tires with burning or landfilling was banned by the European Union (EU) on 16 July 2003 [8-10].

Since, there are some civil engineers in Europe, focusing on the management of wasted tire, and 46% of wasted tire has been materially recycled [11]. According to Roychand et al. [12], there are mainly three types of recycling materials recovered from waste tires, and they are rubber, waste steels and scraps respectively. The rubber from the waste tire is ground into crumb rubber mainly which aims to produce rubberized asphalt pavements [13, 14]. However, if the waste steel is reheated in the factory, the cost and carbon emissions during the recycling will be incredible [15, 16]. Moreover, the resident tensile strength of waste steel keeping in high level, and some researchers are trying to apply its high strength in construction. Due to the previous study of industrial steel fibre (ISF) reinforced concrete, it shows a good improvement of the brittle matrix, especially in terms of toughness and post-cracking behaviours [17-20]. Based on the excellent performance of ISF in concrete, a growing interest towards if recycled steel fibre (RSF) can be a good substitute for ISF has been aroused, one of steel production recovered from the recycling process of waste tire, has similar performance with ISF. This review aims to present the current study of RSF in such mechanical properties as compressive strength, splitting strength and flexural strength, and review the comparison between RSF and ISF with some critical papers.

1.2 Fibre Reinforced Concrete

Owing to its reliable performance, concrete has become a widely used building material [19, 21]. However, the shortcomings of concrete are also clearly: lower tensile strength and brittleness[22-24]. In order to improve the tensile strength and reduce the risks of brittle failure, adding fibres in the concrete mixture is an excellent solution, and ISF is one of the most commonly used fibre materials [5, 25-27]. According to Pająk and Ponikiewski [28], the adding of ISF in concrete is beneficial to controlling the development of the crack and replacing parts of the function of steel bars, which not only increases the shear and tension strength of concrete, but also cut down the construction budgets. The researchers reported that the ISF contributes to building a bridge-effect in the concrete, and ISF carries the work even the crack happened [29-32]. Due to its attractive performance in improving the mechanical properties of concrete, the application of ISF reinforced concrete in construction has been constantly increasing during the last decades [33, 34].

In recently years, there is an increasing trend of interest for the secondary raw materials for their potential benefits in the fields of civil engineering[35, 36]. According to Leone et al.[37], the RSF, coming from the wasted tire, has been used as a substitute for ISF. According to the concrete research, replacing part of ISF with some RSF is a good solution to the disposal of waste tires, and using the RSF can achieve the similar improvements as ISF on concrete [38]. When compared with ISF, using RSF has some advantages, such as the low greenhouse gases emissions and price than ISF [5, 39, 40]. Moreover, the contributes of 1.5% RSF to construction budgets is about 35%, while that of 1.5% ISF is more than 50% [39]. Meanwhile, the contribution of fibre on concrete's carbon emissions varied from 15% (1.5% RSF) to 40% (1.5% ISF)"[39]. Compared with ISF, the RSF is not only contribute to the economic aspects and carbon emission reduction, but have reliable performance in improving the mechanical properties of concrete. Smrkić et al.[41] pointed out that the RSF contributes to the increase of flexural strength of concrete, and there is a synergy between the ISF and RSF. However, there are still some gaps between ISF and RSF in improving the mechanical properties of concrete, and the study of gaps between them has not be explained well.

1.3 Research methodology

This review mainly focuses on the mechanical properties of RSF reinforced concrete, and it collects and analyses relevant literature on different search engines. The bibliometric databases of ScienceDirect, Google Scholar and Web of science are mainly used to collect papers, and there are three key words used during searching: i) recycled steel fibre, ii) fibre reinforced concrete, and iii) mechanical properties. After searching and collecting the most related papers, thirty-six publications have been selected for the data analysis. Fig. 1 describes the strategy of the search process and the final results. According to the collected papers, through analysing the data coming from different countries, authors, journals and research institutes, the benefits of RSF in improving mechanical properties of concrete can be described correctly. Besides, its contribution to concrete performance and sustainable development will also be compared with ISF.

There are four steps in describing the research order.

- Collecting the paper related to RSF concrete, paying attention to the literature review, and determining the analytical method which is used in the analysis process.
- Building forms to summarise the collected information of material properties, fresh concrete properties and harden concrete properties
- Focusing on the RSF content and finding out the potential relationship between the fibre content and other concrete properties.
- Explaining the contribution of RSF to sustainable development.

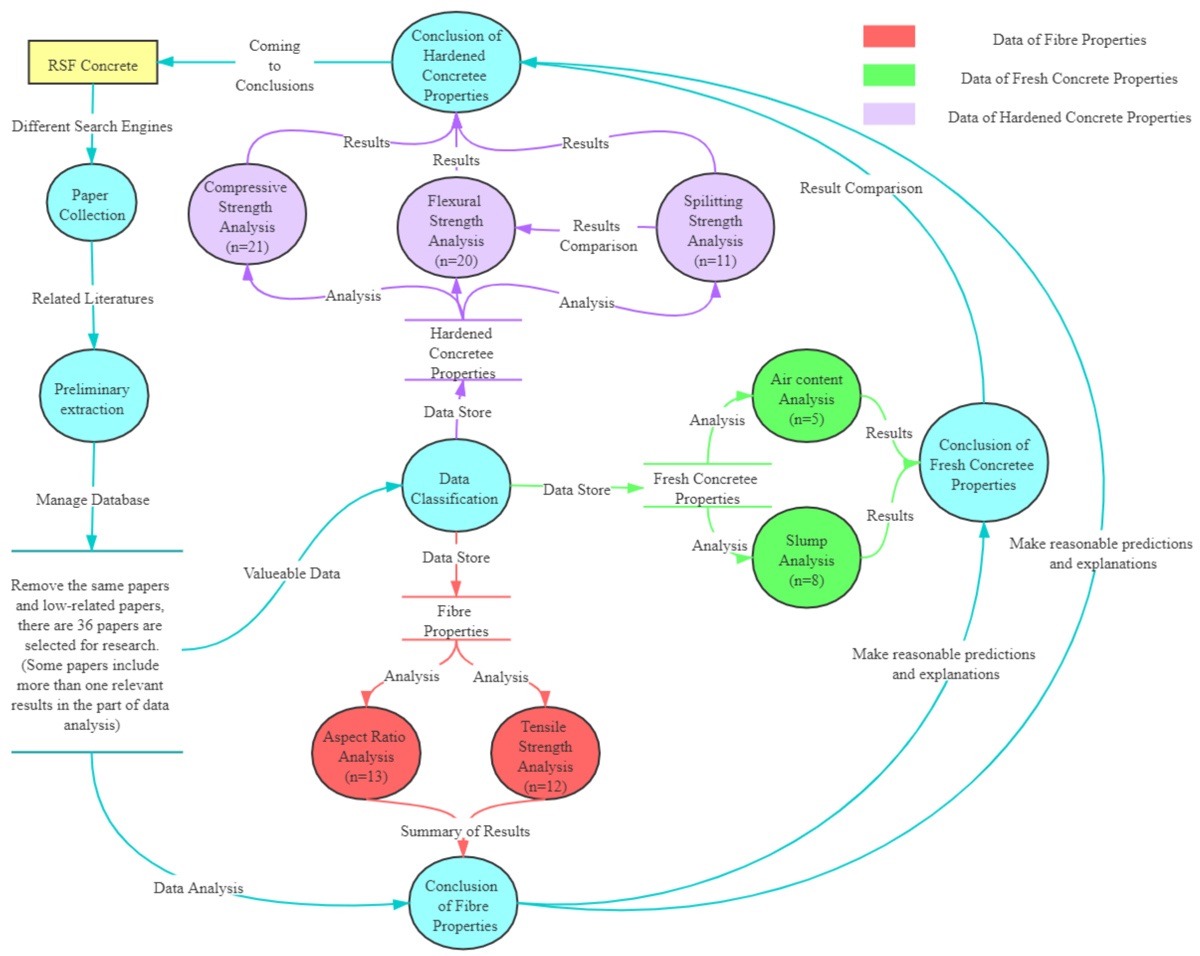


Fig. 1 Strategy of the search process and the data flow diagrams (n is the number of relevant papers)

2. Fibres and their Recyclability

2.1 The characteristics of recycled steel fibre

RSF is not only helpful to improve parts of concrete properties, but also contributes to saving construction budgets and sustainable development. RSF mainly comes from wasted tire, and the methods of recycling are mechanical recycling and thermal technologies [17]. With the aspects of production process and physical properties, this section reviews the literature related to the RSF.

2.2 Production process

The raw material of RSF is waste tires. There are two main methods to produce the RSF from wasted tire: mechanical recycling and thermo-chemical decomposition [42].

The mechanical recycling can be divided into shredding and cryogenic processes [43]. The first step of the shredding process is scrap tire shredded into chips preliminarily, and get a mixture of RSF and rubber particles [44, 45]. After that, RSF and rubber should be separated from magnetic substance. The cryogenic processes are more complex than shredding process. The first step of cryogenic processes is to cool down to a temperature below than -80°C, which can make the rubbers to be crispy [46]. This is because the -80°C is a "glass transition temperature" which makes rubber as crisp as glass and more easily broken [47]. Besides, based on the research by Barros et al. [48], the way of cryogenic processes can easily get finer rubber particles and high-quality steel fibre than the way of shredding process, even with high cost.

The thermal technologies are based on pyrolysis and microwave technology. For the pyrolysis technology, creating an environment that is isolated from the air is the first step [49]. The vacuum environment is mainly filled with the inert gas. After heating with high temperature(above 430°C) and pressure, the RSF and some organic decomposition products from rubbers can be received, such as tire-derived activated carbon, carbon black, boudouard carbon and fuel gas are obtained [50, 51]. There are fuel gases obtained during the decomposition of scrap tires which can support the running of pyrolysis process: therefore the pyrolysis process has limited carbon emission [52, 53]. Microwave treatment occurs in the nitrogen-rich environment without producing unwanted combustion products. Meanwhile, the microwave treatment has high efficiency, which can save more valuable productions [54].

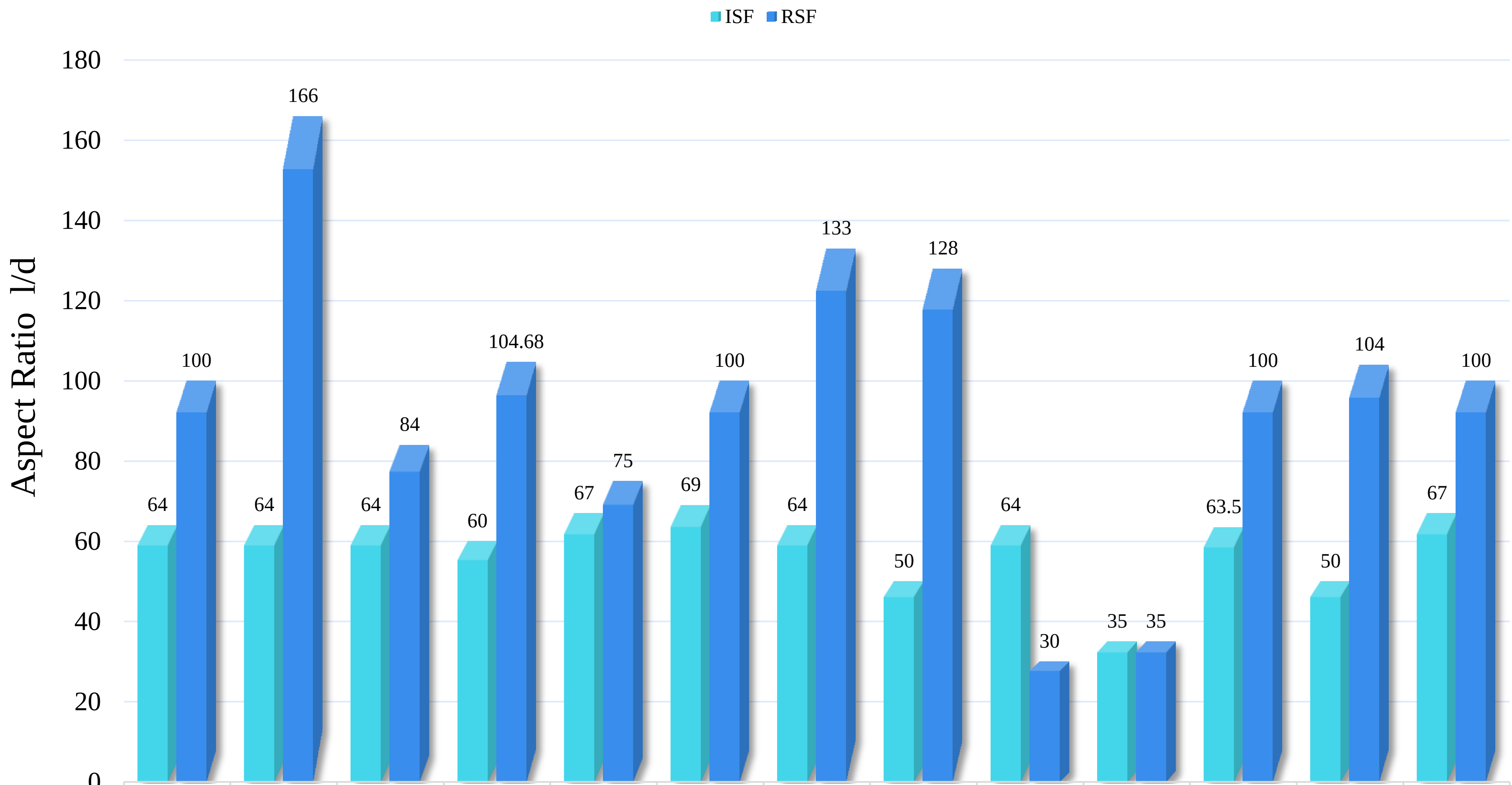
When comparing mechanical recycling and thermal technologies, the most different part is the treatment of rubber instead of the waste steel. The thermal technologies are more likely to get purer RSF, and the RSF which recovered from mechanical recycling will mix with rubber particles. After combustion of the scrap tire, the surface of the steel is covered by ash and combustion by-products rather than rubber particles, which contributes to the high-quality separation and get cleaning steel materials [52, 55]. On as pointed out by Liew and Akbar [5], the benefits of rubber particles are also clearing, and it is beneficial to fill the gap between steel fibre and aggregate and improving the elastic module of concrete [56]. However, the resident rubber (≤1%) can hardly influence the performance of RSF in concrete significate for its limited quality and quantity [57]. In common sense, the effect of rubber particles in mechanical properties of concrete is limited, and most of collected papers used the technology of shredding which is cheap than thermal technologies [37, 39, 41, 48, 58, 59].

2.3 Physical characteristics

Danso et al.[60] stated that fibre contents and the fibre aspect ratio are two essential parameters which can affect the performance of fibre reinforced concrete. The aspect ratio is the ratio of length to equivalent diameter. The aspect ratio of ISF used in concrete is between 50 and 100, and higher aspect ratio will result in the difficulty of concrete compaction [61, 62]. The following section discusses two types of fibre: ISF and RSF. Table 2 summary the physical characteristics between ISF and RSF, and Figure 2 described thirteen papers which compare the aspect ratio between RSF and ISF.

Table 2 Physical characteristics

Author	Tensile Strength (MPa)		Aspect Ratio (l/d)		Manufacture Technique
	ISF	RSF	ISF	RSF	RSF
Baricevic et al. [63]	1100	2000	64	100	Recycling
Bartolac et al. [64]	1200	2850	64	166	Shredding
Hu et al. [65]	1050	2570	69	100	Shredding
Smrkić et al. [41]	1100	2850	64	133	Shredding
Peng et al. [66]	1100	1900	64	30	Shredding
Peng et al. [66]	900	1900	35	35	Shredding
Samarakoon et al. [6]	870	1250	63.5	100	Pyrolysis
Frazão et al. [67]	1100	2570	67	100	Shredding
Graeff et al. [68]	1100	2000	54	15~110	Recycling
Grzymski et al. [69]	-	-	67	75	Shredding
Aiello et al. [70]	1150	1900	-	100.77	Shredding
Tlemat et al. [71]	1150	1250	50	-	Shredding
Caggiano et al. [72]	1200	-	60	104.68	Shredding
Leone et al. [37]	-	-	50	128	Shredding
Skarżyński et al. [56]	-	-	50	104	Shredding
Bjegovic et al. [17, 73]	-	-	64	84	Shredding



	Baricevic et al. [63]	Bartolac et al. [64]	Bjegovic et al. [73]	Caggiano et al. [72]	Grzymski et al. [69]	Hu et al. [65]	Smrkić et al. [41]	Leone et al. [37]	Peng et al. [66]	Peng et al. [66]	Samarakoon et al. [6]	Skarżyński [56]	Frazão et al., [67]
ISF	64	64	64	60	67	69	64	50	64	35	63.5	50	67
RSF	100	166	84	104.68	75	100	133	128	30	35	100	104	100

Fig. 2 Results comparison of aspect ratio between recycled steel fibre and industrial steel fibre concrete

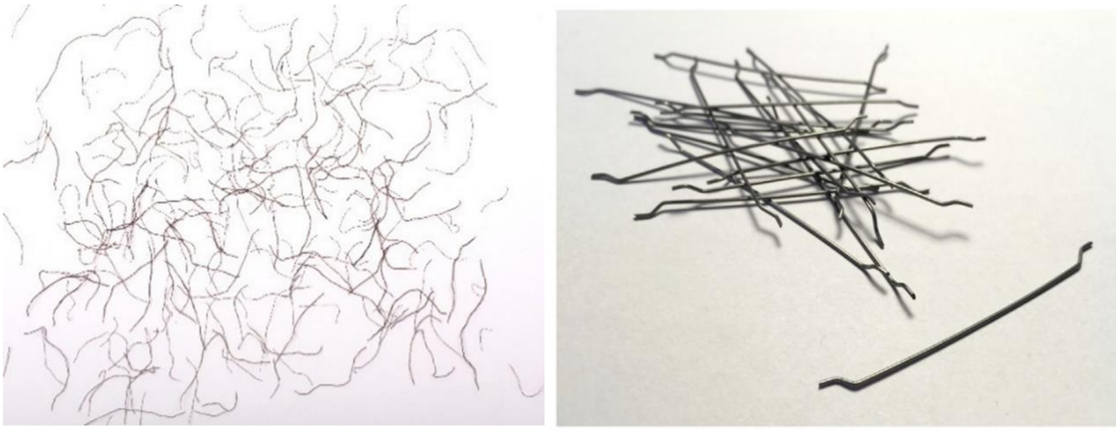
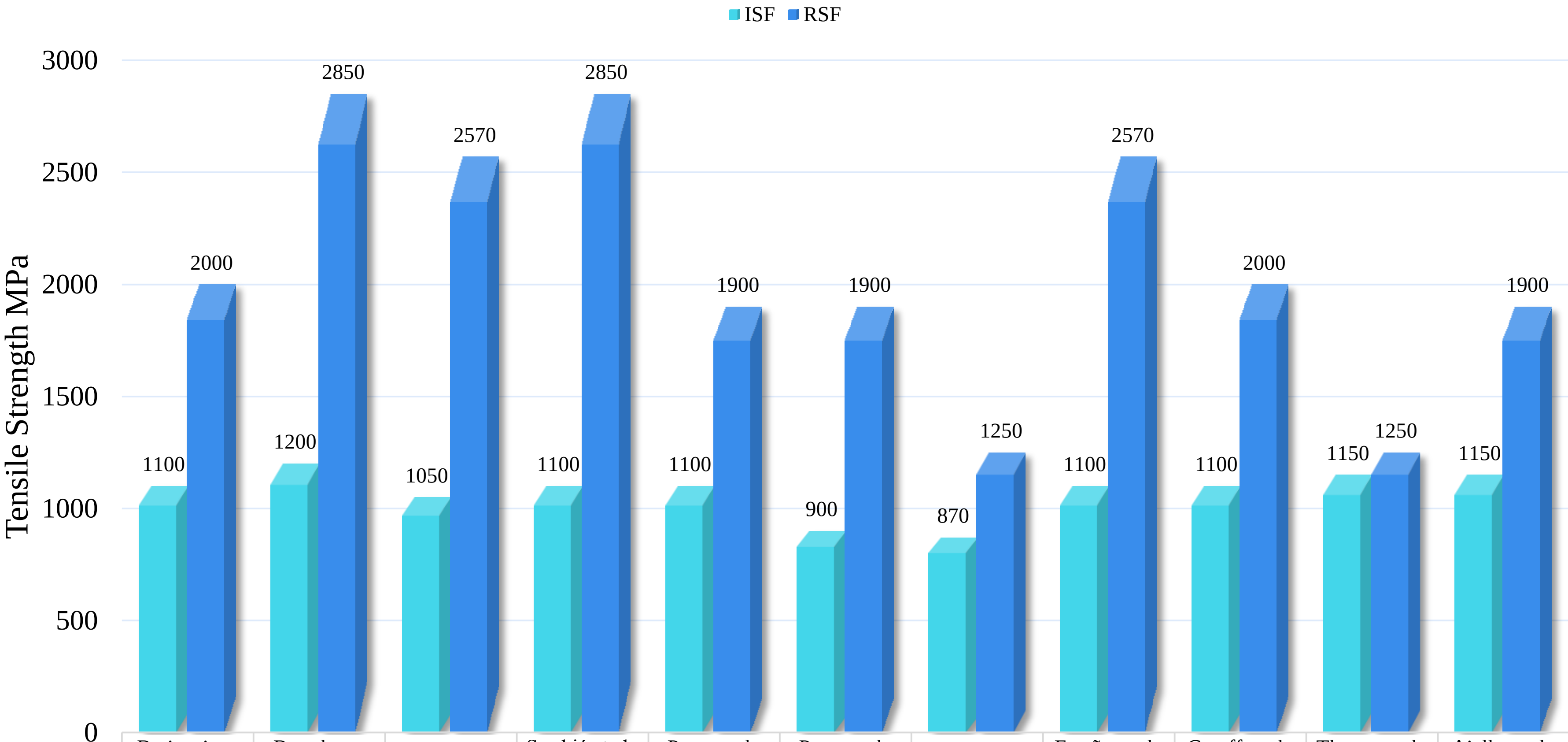


Figure 3 Comparison between RSF and ISF[65, 69]

What can be observed in Figure 3 is that the RSF are more like the micro-fibre which have irregular shapes and lower diameters than ISF, which result in the higher aspect ratio than ISF. According to the Figure 2, the aspect ratio of RSF can reach 133, and the highest aspect ratio of ISF is 69. However, Sudhikumar et al.[74] pointed that the lower aspect ratios of fibre yield higher compressive strength and a higher energy absorptive, which can result in higher flexural strength, toughness indices and impact strength. According to the previous study, the RSF has similar performance with ISF in improving the splitting strength and flexural strength of concrete [6, 56, 65, 66, 73]. Available data represented that good performance of RSF in concrete should related on its high tensile strength [75]. There are twelves papers referring to the tensile strength and manufacturing technique of ISF and RSF as reported in Figure 4.

What stands out in Figure 4 is that the RSF has better tensile strength than ISF, almost twice as much as that of ISF, which lessen the side-effect of higher aspect ratio. The most common recycling method is mechanical shredding. However, Samarakoon et al.[6] treat the RSF with a special method called: pyrolysis. According to Figure 2, there are no signification difference in tensile strength between mechanical and pyrolysis recycling. The explanation for the higher tensile strength of RSF than ISF should related to the different raw material. The RSF is made by the waste wheels which use high strength steel for the car, whereas ISF used less strength raw material because of the budget. The tensile strength of steel wire used in tire is more than 2900 MPa, and parts of steel wire can reach 3300 MPa. [35] However, in order to balance the budgets and fibre strength, the tensile strength of ISF will not higher than 1600 MPa [76].



	Baricevic et al., [63] (mechanical recycling)	Bartolac et al., [64] (mechanical shredding)	Hu et al., [65] (mechanical shredding)	Smrkić et al., [41] (mechanical shredding)	Peng et al., [66] (mechanical shredding)	Peng et al., [66] (mechanical shredding)	Samarakoon et al., [6] (pyrolysis)	Frazão et al., [67] (mechanical shredding)	Graeff et al., [68] (mechanical recycling)	Tlemat et al., [71] (mechanical shredding)	Aiello et al., [70] (mechanical shredding)
ISF	1100	1200	1050	1100	1100	900	870	1100	1100	1150	1150
RSF	2000	2850	2570	2850	1900	1900	1250	2570	2000	1250	1900

Fig. 4 Results comparison of tensile strength between recycled steel fibre and industrial steel fibre concrete

2.4 Final remarks

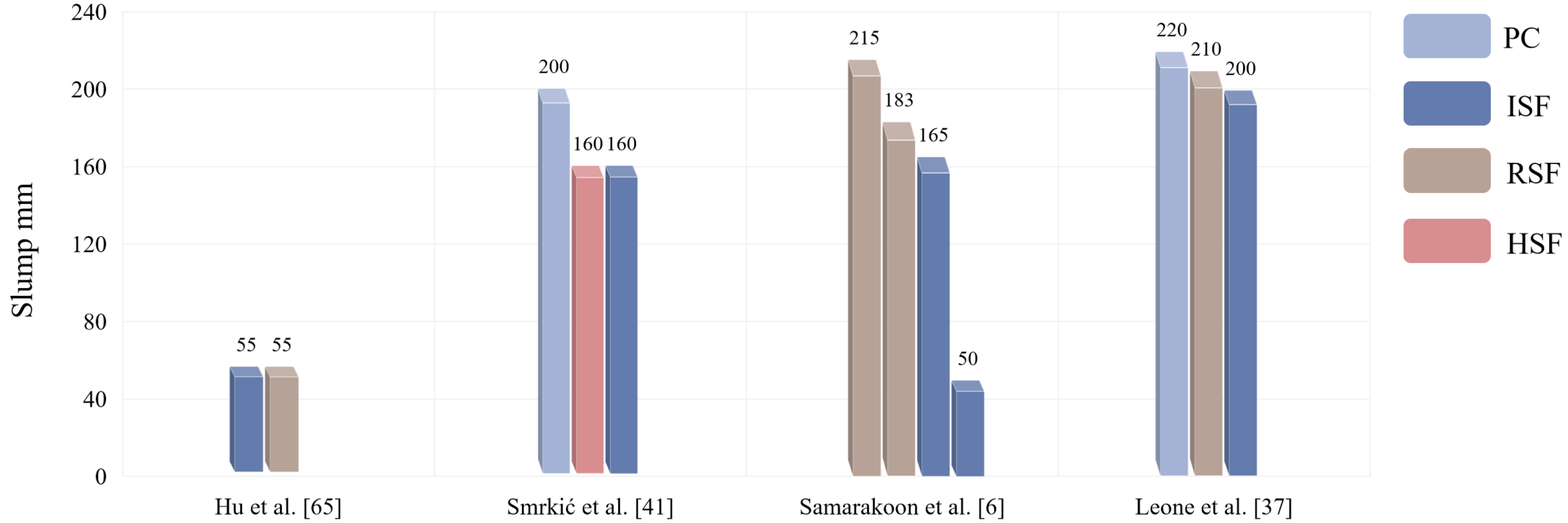
The goals of comparison the between properties of RSF and ISF contribute to giving the reasonable prediction to the performance of concrete with RSF. In common sense, despite the fact that the concrete with the addition of ISF shows good performance in flexural strength and shear strength, the improvement of compressive strength is low than expected. According to the comparison between RSF and ISF, the RSF is expected to improve the flexural strength and shear strength, showing greater potential in improving splitting strength for its high tensile strength especially.

3. Influences of recycled fibres on fresh concrete

According to Figueiredo and Ceccato [77], the addition of ISF reduces the fluidity of material, which means that the workability of concrete shows a decreasing trend with the increasing of ISF. The ISF builds some micro-holes between concrete mix and fibre, resulting in the increase of void content [37]. The following section below presents the properties of fresh concrete with the addition of RSF and ISF, with respect to the slump and air content test.

3.1 Result of Slump Test

The slump test plays an important role in affect the consistency, pumpability, compact-ability, and harshness during concrete mix [78]. Despite the fibre contributes to the improvement of mechanical properties of concrete, the reduction of workability should not be ignored during the process of mixing the fibre concrete [79]. To determine the performance of RSF concrete in the slump test, Figure 5 and 6 describe the relationship between different types of fibre concrete and slump tests. The details for the results of slump are summarized in Appendix Table A-1.



Slump (mm)	ISF (kg/m³)	RSF (kg/m³)	TSF (kg/m³)
55	30	0	30
55	0	30	30

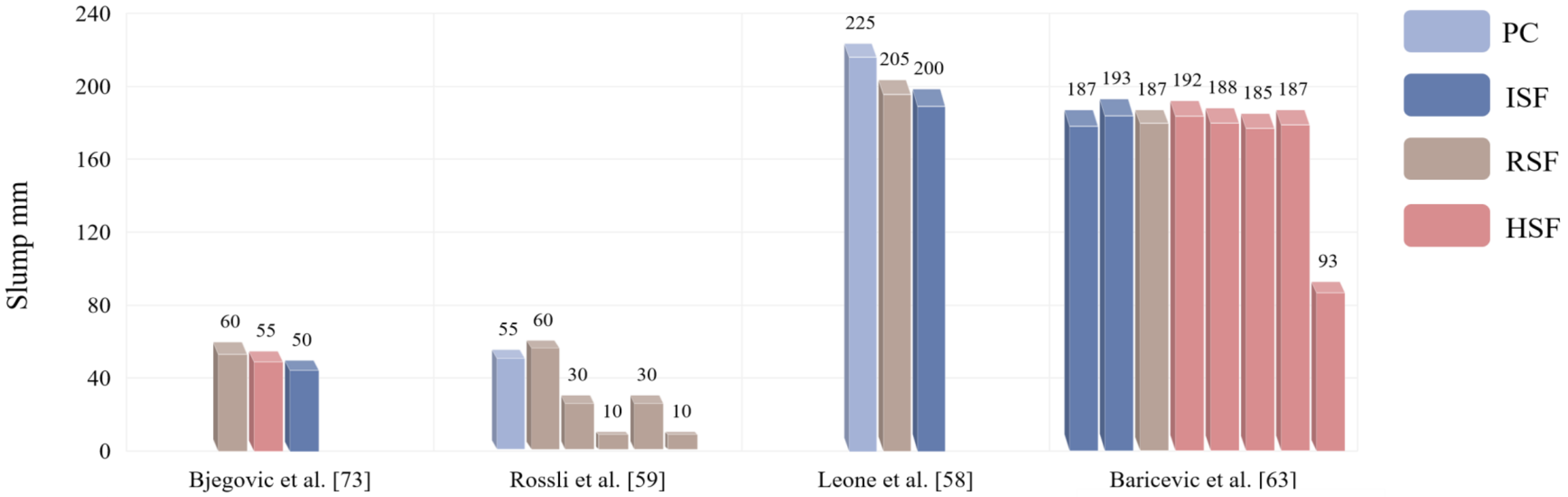
Slump (mm)	ISF (kg/m³)	RSF (kg/m³)	TSF (kg/m³)
200	0	0	0
160	20	20	40
160	40	0	40

Slump (mm)	ISF (kg/m³)	RSF (kg/m³)	TSF (kg/m³)
215	0	15	15
183	0	30	30
165	39	0	39
50	78	0	78

Slump (mm)	ISF (kg/m³)	RSF (kg/m³)	TSF (kg/m³)
220	0	0	0
210	0	35	35
200	36	0	36

*PC is the plain concrete, ISF is the industrial steel fibre concrete, RSF is the recycled steel fibre concrete and HSF is the hybrid steel fibre concrete

Fig. 5 Results comparison of slump test between recycled steel fibre and industrial steel fibre concrete [1]



Slump (mm)	ISF (kg/m³)	RSF (kg/m³)	TSF (kg/m³)
60	0	30	30
55	15	15	30
50	30	0	30

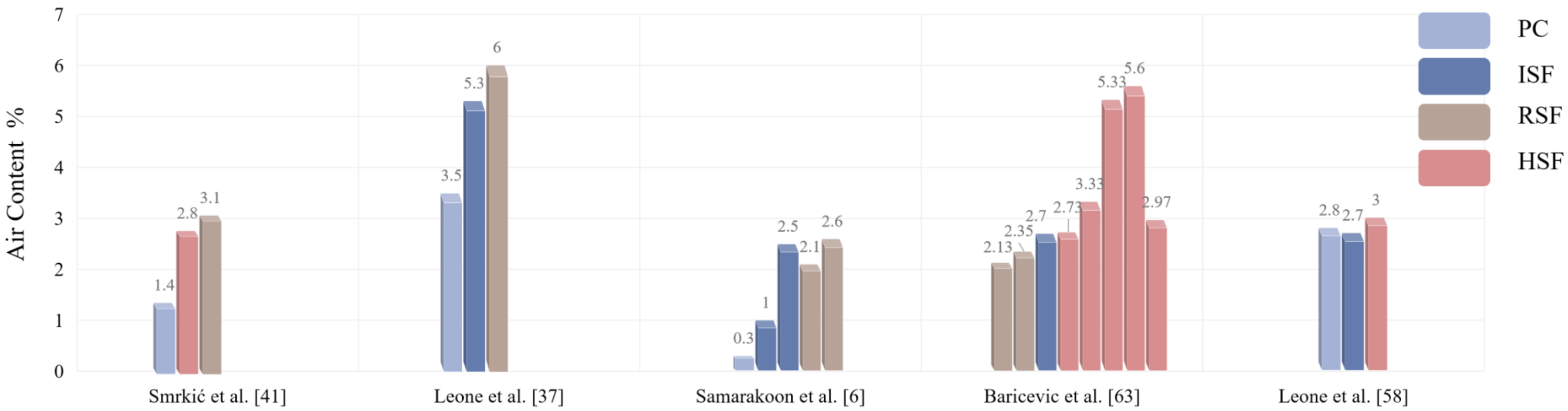
Slump (mm)	ISF (kg/m³)	RSF (kg/m³)	TSF (kg/m³)
55	0	0	0
60	0	9.11	9.11
30	0	18.23	18.23
10	0	27.35	27.35
30	0	35.58	35.58
10	0	36.46	36.46

Slump (mm)	ISF (kg/m³)	RSF (kg/m³)	TSF (kg/m³)
225	0	0	0
205	0	16	16
200	23.45	0	23.45

Slump (mm)	ISF (kg/m³)	RSF (kg/m³)	TSF (kg/m³)
187	20	0	20
193	30	0	30
187	0	30	30
192	10	30	40
188	20	40	60
185	10	50	60
187	10	80	90
93	10	100	110

*PC is the plain concrete, ISF is the industrial steel fibre concrete, RSF is the recycled steel fibre concrete and HSF is the hybrid steel fibre concrete

Fig. 6 Results comparison of slump test slump between recycled steel fibre and industrial steel fibre concrete [2]



Air Contsnt (%)	ISF (kg/m^3)	RSF (kg/m^3)	TSF (kg/m^3)
1.4	0	0	0
2.8	20	20	40
3.1	0	40	40

Air Contsnt (%)	ISF (kg/m^3)	RSF (kg/m^3)	TSF (kg/m^3)
3.5	0	0	0
5.3	35	0	35
6	0	36	36

Air Contsnt (%)	ISF (kg/m^3)	RSF (kg/m^3)	TSF (kg/m^3)
0.3	0	0	0
1	15	0	15
2.5	30	0	30
2.1	0	39	39
2.6	0	78	78

Air Contsnt (%)	ISF (kg/m^3)	RSF (kg/m^3)	TSF (kg/m^3)
2.13	20	0	20
2.35	30	0	30
2.7	0	30	30
2.73	10	30	40
3.33	10	50	60
5.33	10	80	90
5.6	10	100	110
2.97	20	40	60

Air Contsnt (%)	ISF (kg/m^3)	RSF (kg/m^3)	TSF (kg/m^3)
2.8	0	0	0
2.7	16	0	16
3	0	23.45	23.45

*PC is the plain concrete, ISF is the industrial steel fibre concrete, RSF is the recycled steel fibre concrete and HSF is the hybrid steel fibre concrete

Fig. 7 Results comparison of air content test between recycled steel fibre and industrial steel fibre concrete

In all the mixes, it has been observed that the inclusion of RSF and ISF have resulted in a workability decreasing. However, the RSF shows a less workability reduction than ISF in [6, 58, 59, 73]. In the paper of Leone et al. [37], the author increased the dosage of superplasticizer to keep the same slump among ISF, RSF and plain concrete, which is 1.4 kg/m^3 for plain concrete, 1.19 kg/m^3 for concrete with RSF, and 2.07 kg/m^3 for concrete with ISF(see in Appendix Table A-1). Compared with RSF concrete, there are more superplasticizerizer added in ISF concrete, and aims to maintain the same value of slump. Moreover, the shape of most RSF are irregulars and have a higher aspect ratio than ISF which make it difficulty to the process of fusion between fibres. The increasing dosage of admixture indicates that the inclusion of fibres reduces the workability. Results from Figure 5 and 6 show that the use of RSF to replace part of ISF in ISF concrete is beneficial to improving its workability, which called hybrid steel fibre(HSF) concrete. However, the improvement by RSF is limited, and there are no synergistic effects between ISF and RSF in HSF concrete. In the experiments by Rossli and Ibrahim [59], the Authors highlighted that the balling effect of RSF can cause an unusual increase the slump after the RSF content hight than 0.6%. However, the slump increases to 30mm when the fibre dosage reaches 35.58kg/m^3(0.8%). The strange increases is mainly due to the balling effect of fibre. Due to the random shapes of RSF, the potential risks of balling effect will be increased with the addition of fibre. Issues related to the balling effect in concrete could be addressed by the superplasticizer and the smaller size aggregates [80, 81]. Besides, self-compacting concrete could show better cooperation-ship with RSF than normal concrete [82].

3.2 Result of air content test

The air content is an essential parameter that determines the ability of concrete to resist freezing-thawing whether is good or not. Keeping the air content in a reasonable range(≤6%) is beneficial to improve the concrete ability of resist freeze-thaw damage [83]. According Guerini et al. [84], the increase of fibre dosages can lead to a slight increase of air content. The reason should be that consolidation of fibre with the concrete mix becomes more difficult with the addition of fibre, resulting in the increases of voids between fibre and aggregates [43]. There are five papers described the values of air content between the RSF and ISF concrete, shown in Figure 7. The details of the results are shown in Appendix Table A-2.

It can be observed that all results are characterised by an increasing trend when increasing the addition of fibre, indicating a good improvement of air content overall when adding the fibres. According to Figure 7, most Authors argue that the RSF contributes to less improvement of air content than ISF [6, 37, 41, 58]. The reason why RSF increases more air content than ISF is that the Author uses a special type of RSF (unsorted RSF). The fact that the unsorted RSF is more disordered than the normal RSF causes more micro-holes in concrete. According to the experimental result, with the increasing of air content the compressive strength show a decreasing trend, which means that the increased micro-holes have potential risks in the development of micro-cracks, which results in the loss of strength [85, 86]. The results of HSF concrete implies that the addition of RSF in ISF concrete contribute to the increase of air content. Moreover, the volume fraction of total fibres plays a dominant role in air content, and the threshold value is 60kg/m^3 [63].

3.3 Final Remark

The follows conclusion can be drawn.

- With the addition of fibre, the workability shows a decreasing trend. Despite the addition of RSF reduces the slump, the RSF still show less side-effect than ISF on workability reduction.
- Although the addition of ISF and RSF increases the air content when maintaining the total fibre content lower than 60kg/m^3, beyond which too much air is entrapped. Moreover, the RSF show less improvement in air content than ISF, which resulted by its smaller sizes and various shapes.
- The performance of HSF concrete is between RSF and ISF concrete. There is no significant synergistic effect between ISF and RSF on improving fresh concrete properties, and the total fibre content should not higher than 60kg/m^3, in case of “honeycombing” in concrete.

4 Influences of recycled fibres on hardened concrete

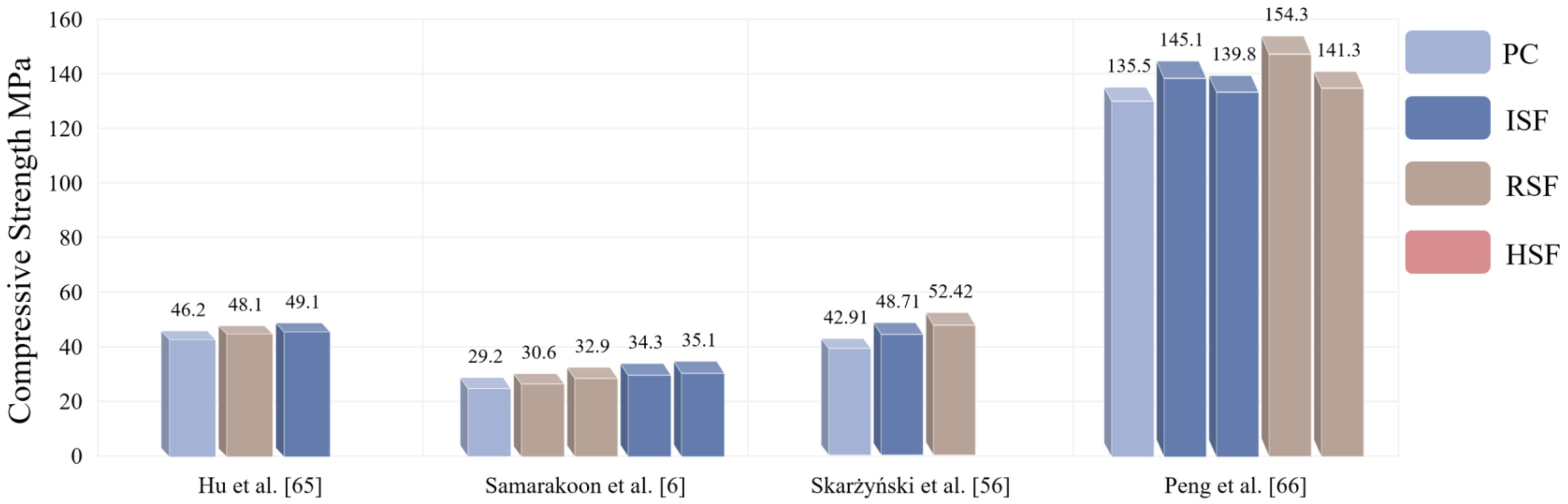
According to the previous study made by Behbahani et al. [87], the ISF has good performance on improving of mechanical properties, especially in flexural strength and splitting strength [26, 88]. This section aims to review the literature related to the mechanical properties of harden concrete with the addition of RSF.

4.1 Compressive strength

Behbahani et al. [87] used to describe the different content of ISF:

- Less than 1% is the Very low volume fraction of ISF.
- 1% to 2% is the Moderate volume fraction of ISF.
- Higher than 2% is the High volume fraction of ISF.

In general, effect of fibres to improve the compressive strength is insignificant. According to Wu et al.[89], the addition of ISF slightly increased its contribution to the compressive strength. Moreover, Song et al.[90] described that the compressive strength of ISF concrete has an increasing trend at very low volume fraction of ISF [91]. The strange increase should relate to the tough and ductile provided by ISF, which helps to the sightly improvement in compressive strength [92-94]. From Figure 8 to Figure 10, the improvement of compressive strength as the addition of fibre content is shown. All data points are collected from the included papers and are sorted by authors, and the details shown in Table A-3 in Appendix A.



Strength (MPa)	ISF (kg/m^3)	RSF (kg/m^3)	TSF (kg/m^3)
46.2	0	0	0
48.1	0	30	30
49.1	30	0	30

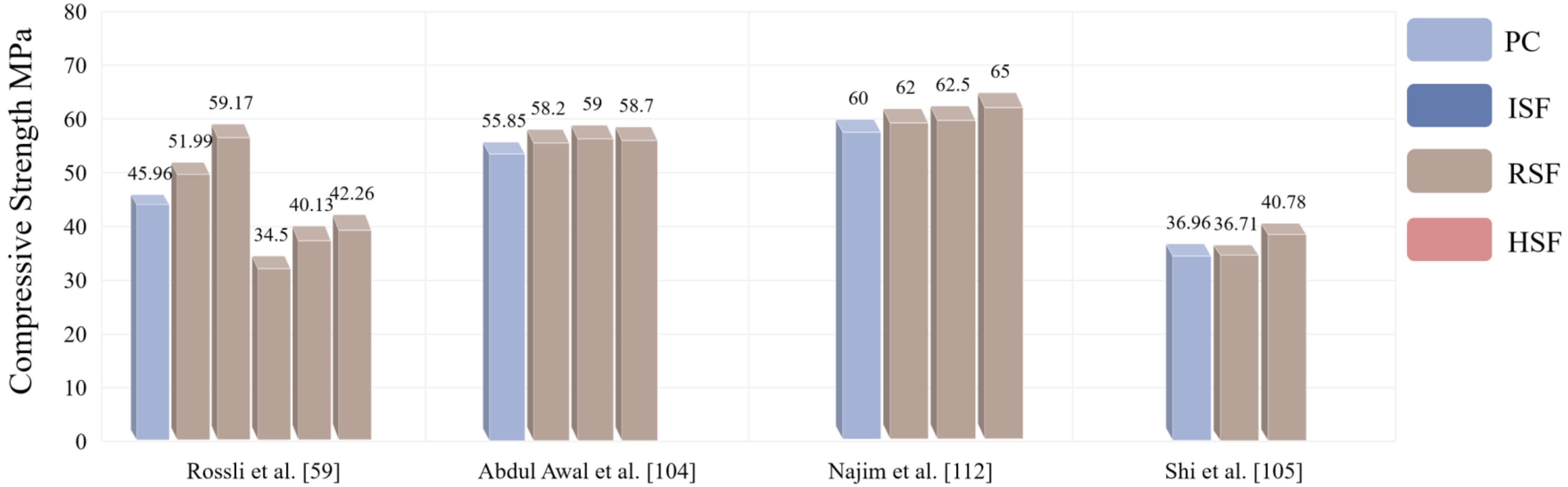
Strength (MPa)	ISF (kg/m^3)	RSF (kg/m^3)	TSF (%)
29.2	0	0	0
30.6	0	15	0.5%
32.9	0	30	1%
34.3	39	0	0.5%
35.1	78	0	1%

Strength (MPa)	ISF (kg/m^3)	RSF (kg/m^3)	TSF (%^{3})
42.91	0	0	0
48.71	25	0	0.25%
52.42	0	50	0.5%

Strength (MPa)	ISF (kg/m^3)	RSF (kg/m^3)	TSF (kg/m^3)
135.5	0	0	0
145.1	60	0	60
139.8	60	0	60
154.3	0	60	60
141.3	0	60	60

*PC is the plain concrete, ISF is the industrial steel fibre concrete, RSF is the recycled steel fibre concrete and HSF is the hybrid steel fibre concrete

Fig. 8 Compressive strength comparison between recycled steel fibre and steel fibre concrete [1]



Strength (MPa)	ISF (kg/m³)	RSF (kg/m³)	TSF (%)
45.96	0	0	0
51.99	0	9.11	0.2%
59.17	0	18.23	0.4%
34.5	0	27.35	0.6%
40.13	0	36.46	0.8%
42.26	0	35.58	1%

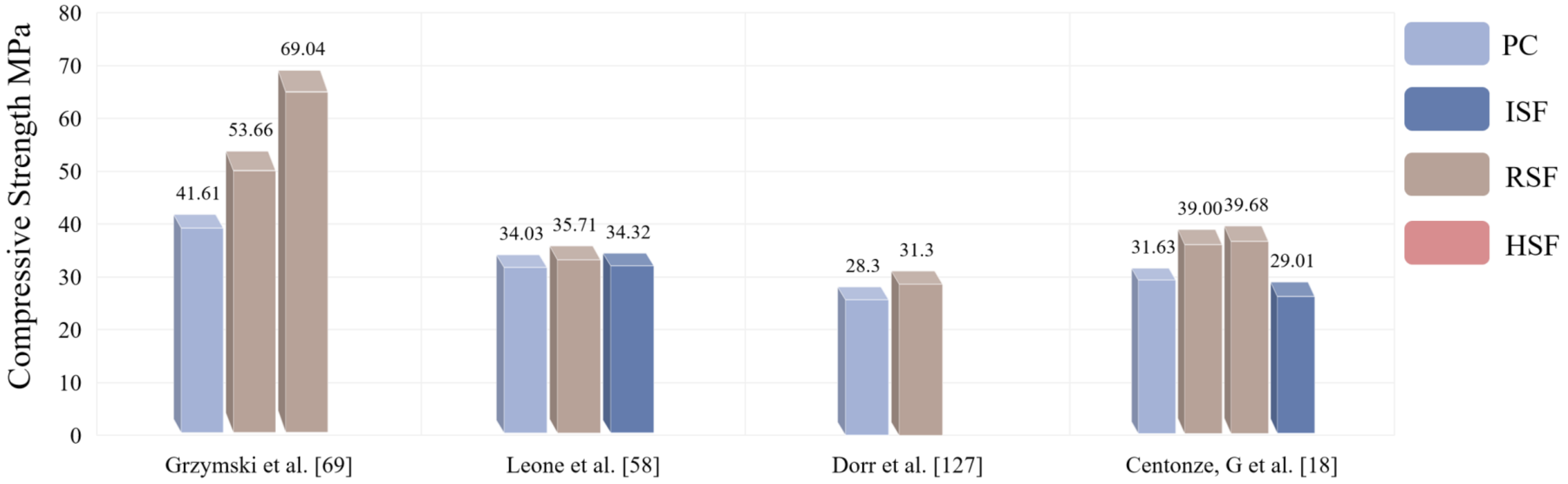
Strength (MPa)	ISF (kg/m³)	RSF (kg/m³)	TSF (%)
55.85	0	0	0
58.2	0	25	1%
59	0	37.5	1.5%
58.7	0	50	2%

Strength (MPa)	ISF (kg/m³)	RSF (kg/m³)	TSF (%)
60	0	0	0
62	0	30	0.4%
62.5	0	45	0.6%
65	0	60	0.8%

Strength (MPa)	ISF (kg/m³)	RSF (kg/m³)	TSF (%)
36.96	0	0	0
36.71	0	79	1%
40.78	0	157	2%

*PC is the plain concrete, ISF is the industrial steel fibre concrete, RSF is the recycled steel fibre concrete and HSF is the hybrid steel fibre concrete

Fig. 9 Compressive strength comparison between recycled steel fibre and steel fibre concrete [2]



Strength (MPa)	ISF (kg/m³)	RSF (kg/m³)	TSF (kg/m³)
41.61	0	0	0
53.66	25	0	25
69.04	0	25	25

Strength (MPa)	ISF (kg/m³)	RSF (kg/m³)	TSF (%)
34.03	0	0	0
35.71	0	16	0.30%
34.32	23.45	0	0.30%

Strength (MPa)	ISF (kg/m³)	RSF (%)	TSF (%)
28.3	0	0	0
31.3	0	0.50%	0.50%

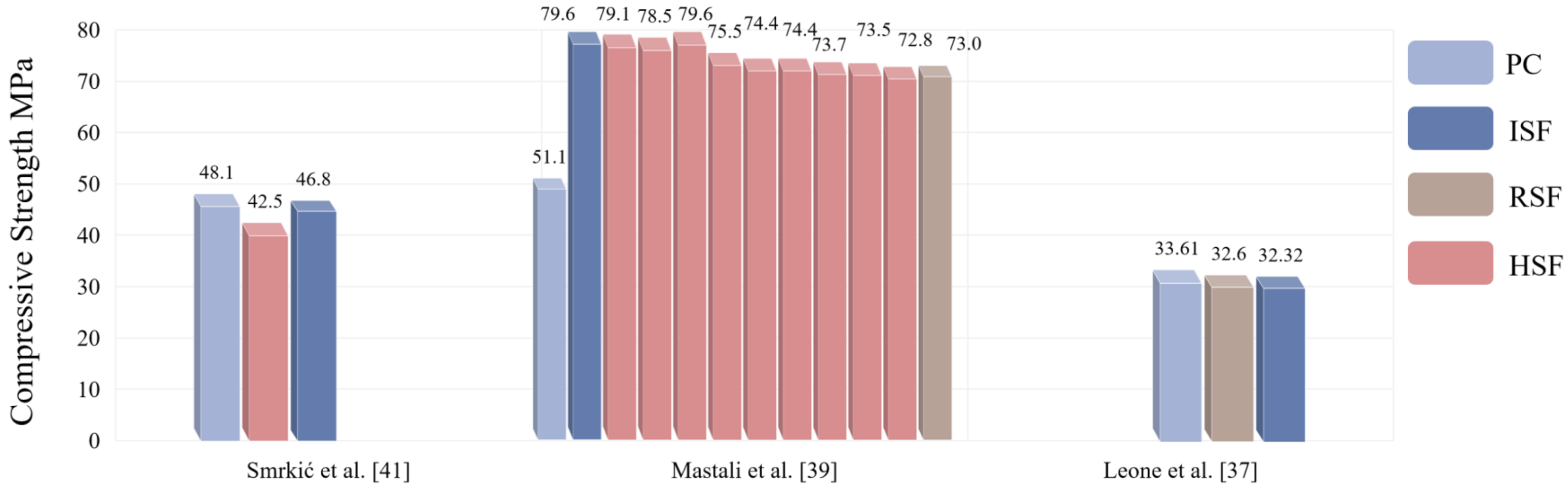
Strength (MPa)	ISF (kg/m³)	RSF (kg/m³)	TSF (%)
31.63	0	0	0
39.00	0	31.75	0.46%
39.68	0	31.75	0.46%
29.01	34.8	0	0.46%

*PC is the plain concrete, ISF is the industrial steel fibre concrete, RSF is the recycled steel fibre concrete and HSF is the hybrid steel fibre concrete

Fig. 10 Compressive strength comparison between recycled steel fibre and steel fibre concrete [3]

It can be seen from Figure 8 to 10 that the experimental results reveals that the inclusion of RSF and ISF fibres in concrete slightly improve the strength capacity, when maintaining the fibre content lower than 1%. However, from the aspect of improving the compressive strength, the RSF has better performance than ISF. A maximum strength gain of approximately 64% was observed after the inclusion of about 25kg/m^3 RSF into the concrete [69]. The slight strength improvement is assumed to be the addition of fibre lending to the decrease of capillary porosity, and low capillary porosity suppresses the development of micro-cracks. However, slight improvement is not playing an important role in improving the mechanical properties of concrete.

The most popular opinion is that the addition of fibre will decrease the compressive strength. According to the results from Figure 8 to 13, the compressive strength of RSF and ISF reinforced concrete higher than plain concrete when fibre content lower than 0.5% mainly. When maintaining the fibre content higher than 1%, most studies reported a strength loss in compressive strength corresponding to an increase of fibre content. The most controversial results focus on the range of fibre content from 0.5% to 1%. Sengul [95] observed that the compressive strength achieves its highest point when the RSF is 1%. However, Rossli and Ibrahim [59] indicated when the RSF content is 0.6% , the compressive strength is the highest. The opposite results mainly resulted by the efficiency of compacting. Rossli and Ibrahim [59] highlighted the balling effect when fibre content higher than 0.6%, and Sengul [95] using siliceous sand and superplasticizer to increasing the cooperation between fibre and concrete mixes.



Strength (MPa)	ISF (kg/m³)	RSF (kg/m³)	TSF (%)
48.1	0	0	0
42.5	20	20	0.50%
46.8	40	0	0.50%

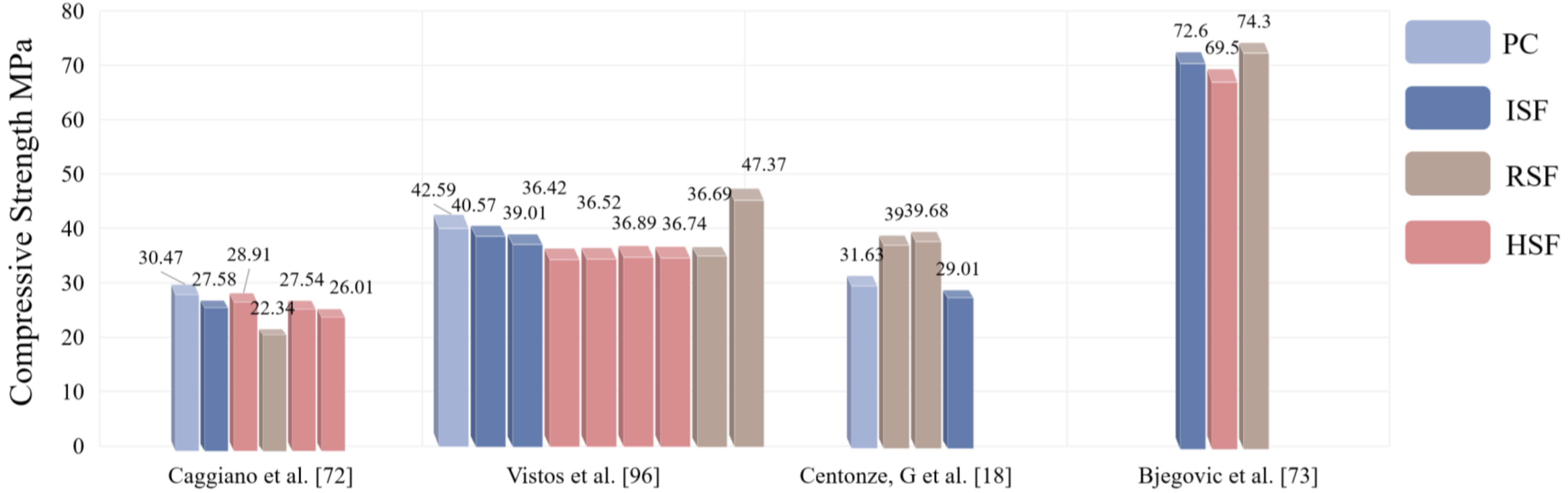
Strength (MPa)	ISF (kg/m³)	RSF (kg/m³)	TSF (%)
51.1	0	0	0
79.6	117	0	1.50%
79.1	105.3	11.7	1.50%
78.5	93.6	23.4	1.50%
79.6	81.9	35.1	1.50%
75.5	70.2	46.8	1.50%

Strength (MPa)	ISF (kg/m³)	RSF (kg/m³)	TSF (%)
74.4	58.5	58.5	1.50%
74.4	46.8	70.2	1.50%
73.7	35.1	81.9	1.50%
73.5	23.4	93.6	1.50%
72.8	11.7	105.3	1.50%
73.0	0	117	1.50%

Strength (MPa)	ISF (kg/m³)	RSF (kg/m³)	TSF (%)
33.61	0	0	0
32.6	0	35	0.46%
32.32	36	0	0.46%

*PC is the plain concrete, ISF is the industrial steel fibre concrete, RSF is the recycled steel fibre concrete and HSF is the hybrid steel fibre concrete

Fig. 11 Compressive strength comparison between recycled steel fibre and steel fibre concrete [4]



Strength (MPa)	ISF (kg/m³)	RSF (kg/m³)	TSF (%)
30.47	0	0	0
27.58	60	0	0.75%
28.91	30	30	0.75%
22.34	0	60	0.75%
27.54	30	50	1.00%
26.01	30	70	1.25%

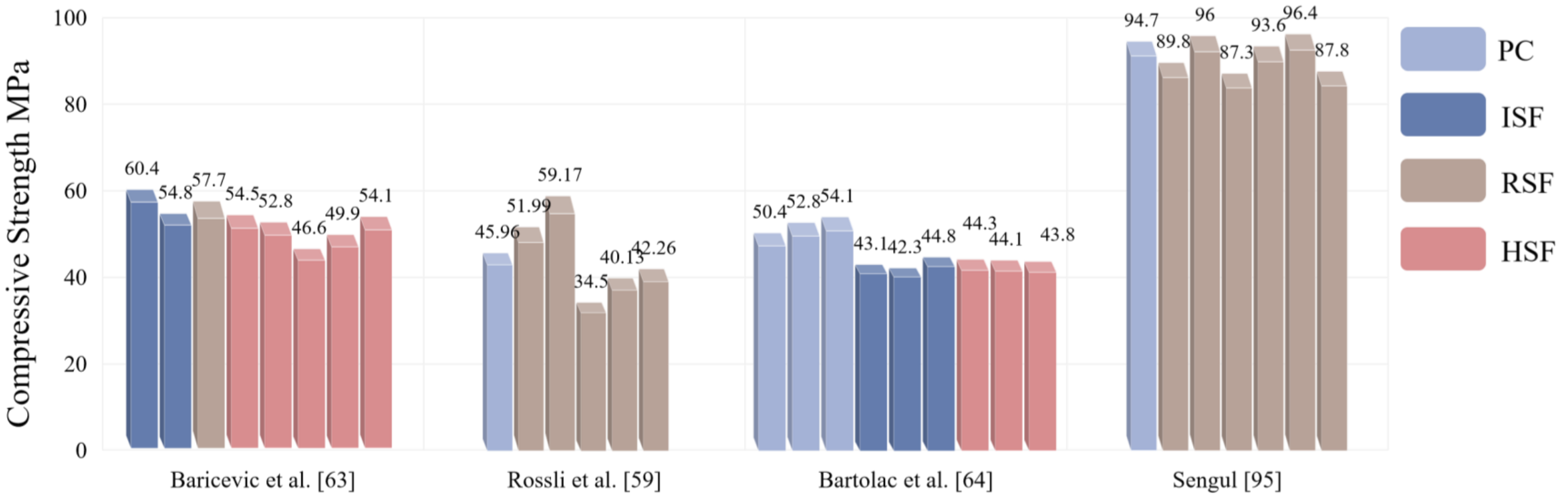
Strength (MPa)	ISF (%)	RSF (%)	TSF (%)
42.59	0	0	0
40.57	100%	0	0.5%
39.01	100%	0	0.5%
36.42	75%	25%	0.5%
36.52	75%	25%	0.5%
36.89	50%	50%	0.5%
36.74	50%	50%	0.5%
36.69	0	100%	0.5%
47.37	0	100%	0.5%

Strength (MPa)	ISF (kg/m³)	RSF (kg/m³)	TSF (%)
31.63	0	0	0
39	0	31.75	0.46%
39.68	0	31.75	0.46%
29.01	34.8	0	0.46%

Strength (MPa)	ISF (kg/m³)	RSF (kg/m³)	TSF (%)
72.6	30	0	0.38%
69.5	15	15	0.38%
74.3	0	30	0.38%

*PC is the plain concrete, ISF is the industrial steel fibre concrete, RSF is the recycled steel fibre concrete and HSF is the hybrid steel fibre concrete

Fig. 12 Compressive strength comparison between recycled steel fibre and steel fibre concrete [5]



Strength (MPa)	ISF (kg/m³)	RSF (kg/m³)	TSF (kg/m³)
60.4	20	0	20
54.8	30	0	30
57.7	0	30	30
54.5	10	30	40
52.8	10	50	60
46.6	10	80	90
49.9	10	100	110
54.1	20	40	60

Strength (MPa)	ISF (kg/m³)	RSF (kg/m³)	TSF (%)
45.96	0	0	0
51.99	0	9.11	0.20%
59.17	0	18.23	0.40%
34.5	0	27.35	0.60%
40.13	0	36.46	0.80%
42.26	0	35.58	1%

Strength (MPa)	ISF (kg/m³)	RSF (kg/m³)	TSF (kg/m³)
50.4	0	0	0
52.8	0	0	0
54.1	0	0	0
43.1	40	0	40
42.3	40	0	40
44.8	40	0	40
44.3	10	45	55
44.1	10	45	55
43.8	10	45	55

Strength (MPa)	ISF (kg/m³)	RSF (%)	TSF (%)
94.7	0	0	0
89.8	0	0.50%	0.50%
96	0	1%	1%
87.3	0	2%	2%
93.6	0	3%	3%
96.4	0	4%	4%

*PC is the plain concrete, ISF is the industrial steel fibre concrete, RSF is the recycled steel fibre concrete and HSF is the hybrid steel fibre concrete

Fig. 13 Compressive strength comparison between recycled steel fibre and steel fibre concrete [6]

Moreover, according to Mastali et al.[39] and Vistos et al.[96], the performance of HSF in compressive strength was studies while keeping the same total fibre content(TSF): with the increase content of RSF, the compressive strength steadily decreases [39, 96]. Moreover, 100% RSF concrete seems to show better performance than 100% ISF concrete in terms of improving compressive strength. The efficiency of concrete compacting shows a decreasing trend with the addition of RSF in ISF concrete. Moreover, there is no significant synergistic effect of ISF and RSF on improving compressive strength. The size of voids between fibres and concrete mix is becoming more disordered with the addition of different types of fibres, which can hardly be solved by conventional compacting. However, the side effect of the addition of fibre in compressive strength is limited, which not higher than ±30% than plain concrete mostly. To identify the improvement with the addition of RSF with respect to plain concrete, Figure 14 built based on the data from Figure 8 to 13.

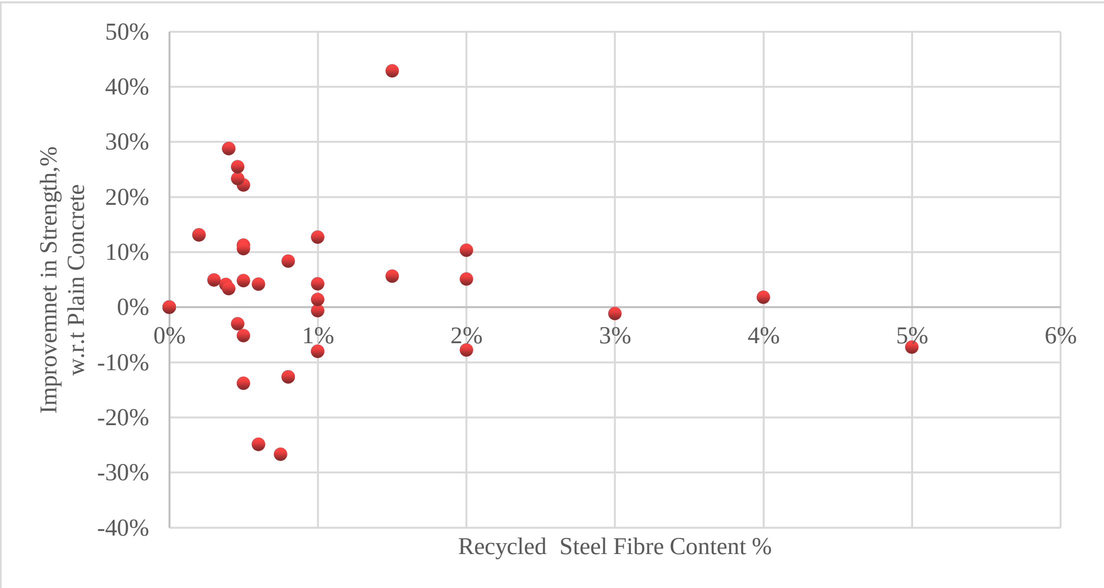


Fig. 14 Strength improvement with respect to plain concrete

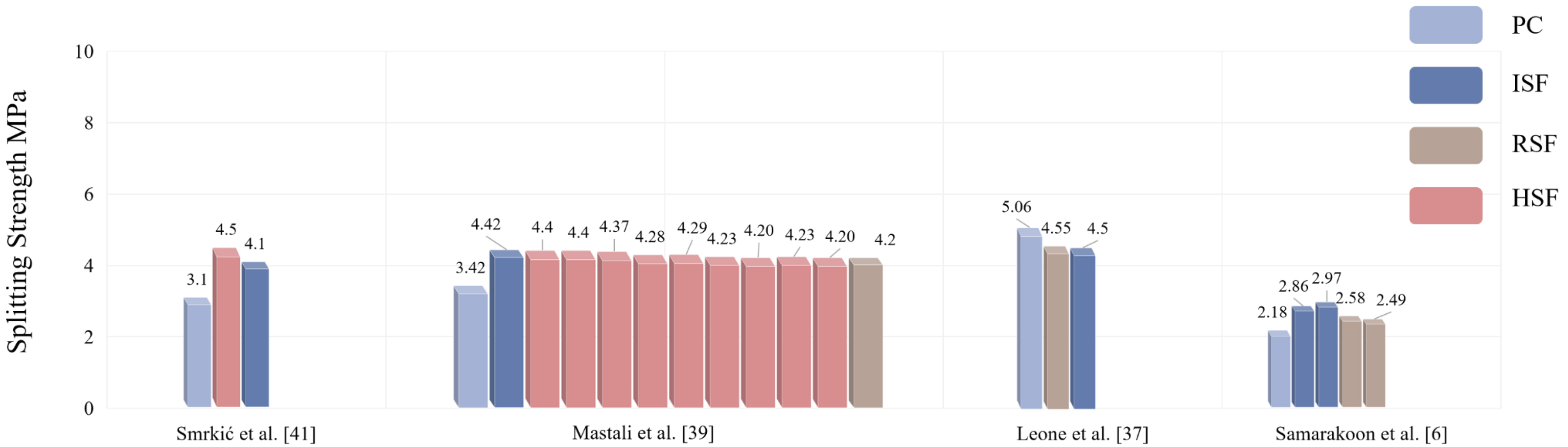
According to Figure 14, in most cases, compared with plain concrete, RSF contributes to the improvement of compressive strength of less than 1% by volume mostly. Besides, all data whose RSF is less than 0.5% achieved an increase in compression ratio. In general, the impact of RSF on compressive strength is limited. Compared with plain concrete, the increase or decrease of RSF concrete on the compressive strength is mostly no more than 30%. In most cases, with the increase in fibre content, the relative compressive strength of ISF and SRF almost linearly increase when controlling the fibre under a low volume, and the rate of strength increasing is limited. Opposite to the low volume of fibre concrete, if the fibre content is controlled higher than moderate volume (1% to 2%), the improvement will show a slightly dropping trend with the addition of RSF.

The reasonable explanation should focus on the size of the void between the fibre and aggregates. When the fibre content is low, the filler effect of fibre contributes to locking the internal structure. However, as explained in the part of air content, the air content shows an increasing trend with the addition of fibre. The main issue is that the gap between different parameters of concrete mix becomes larger with the addition of fibre, which will lead to the development of micro-cracks with the increase of strength.

Moreover, the ISF shows better performance than RSF in increasing air content, which also gets an explanation on the RSF playing a better performance in improving compressive strength and causes less damage beyond the optimum level. For the high-volume fibre (higher than 2%), the advanced concrete compacting technology is beneficial to decrease the loss of compressive strength, such as self-compacting concrete and high efficiency superplasticizerizers [28, 97, 98].

4.2 Splitting strength

According to Larsen and Thorstensen [99], the capacity of tensile loads for concrete is close to zero, in that case, adding fibre plays an important role in increasing the tensile strength of concrete. For cementitious material, tensile strength contributed to the generation and propagation of micro-cracks, and the aim of adding fibres is to sustain structural integrity towards tensile load after first cracking [89, 100, 101]. The splitting strength is a convenient method to determine the tensile strength of concrete [102]. Denneman et al. [103] illustrated that the splitting strength was beneficial to predicting the flexural strength of concrete, and the ISF contributes to the improvement of splitting strength. Figure 15 and 16 (details are shown in Table A-4 in Appendix), describe the relationship between splitting strength and different types of concretes.



Strength (MPa)	ISF (kg/m³)	RSF (kg/m³)	TSF (kg/m³)
3.1	0	0	0
4.5	20	20	40
4.1	40	0	40

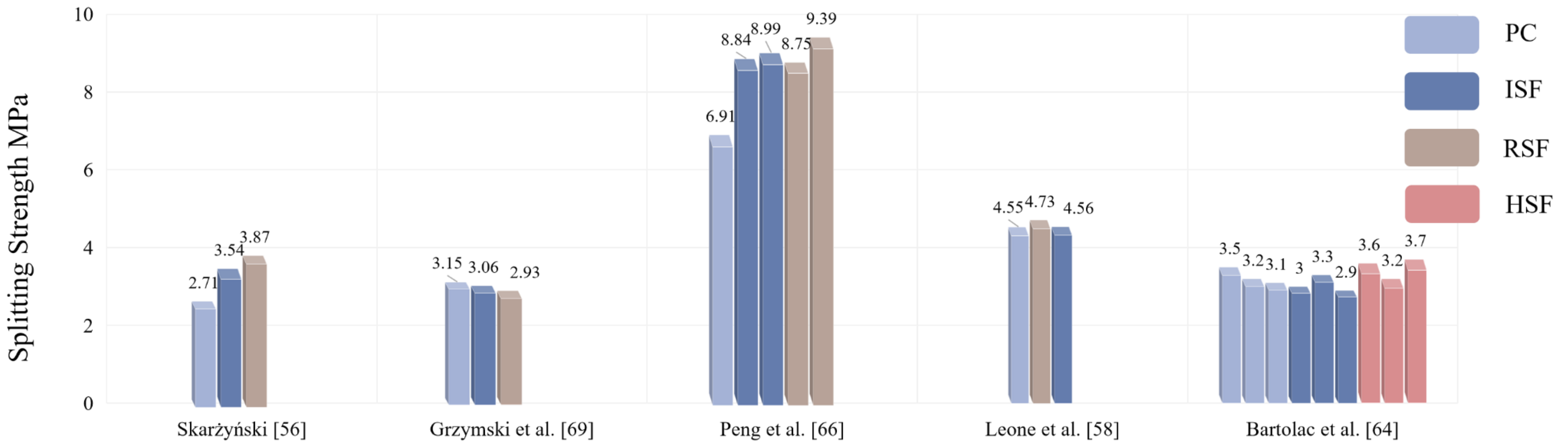
Strength (MPa)	ISF (kg/m³)	RSF (kg/m³)	TSF (%)	Strength (MPa)	ISF (kg/m³)	RSF (kg/m³)	TSF (%)
3.42	0	0	0	4.29	58.5	58.5	1.5%
4.42	117	0	1.5%	4.23	46.8	70.2	1.5%
4.4	105.3	11.7	1.5%	4.20	35.1	81.9	1.5%
4.4	93.6	23.4	1.5%	4.23	23.4	93.6	1.5%
4.37	81.9	35.1	1.5%	4.20	11.7	105.3	1.5%
4.28	70.2	46.8	1.5%	4.2	0	117	1.5%

Strength (MPa)	ISF (kg/m³)	RSF (kg/m³)	TSF (%)
5.06	0	0	0
4.55	0	35	0.46%
4.5	36	0	0.46%

Strength (MPa)	ISF (kg/m³)	RSF (kg/m³)	TSF (%)
2.18	0	0	0
2.86	39	0	0.50%
2.97	78	0	1%
2.58	0	15	0.50%
2.49	0	30	1%

*PC is the plain concrete, ISF is the industrial steel fibre concrete, RSF is the recycled steel fibre concrete and HSF is the hybrid steel fibre concrete

Fig. 15 Splitting strength comparison between recycled steel fibre and steel fibre concrete [1]



Strength (MPa)	ISF (kg/m^3)	RSF (kg/m^3)	TSF (%)
2.71	0	0	0
3.54	25	0	0.25%
3.87	0	50	0.50%

Strength (MPa)	ISF (kg/m^3)	RSF (kg/m^3)	TSF (kg/m^3)
3.15	0	0	0
3.06	25	0	25
2.93	0	25	25

Strength (MPa)	ISF (kg/m^3)	RSF (kg/m^3)	TSF (kg/m^3)
6.91	0	0	0
8.84	60	0	60
8.99	60	0	60
8.75	0	60	60
9.39	0	60	60

Strength (MPa)	ISF (kg/m^3)	RSF (kg/m^3)	TSF (%)
4.55	0	0	0
4.73	0	16	0.3%
4.56	23.45	0	0.3%

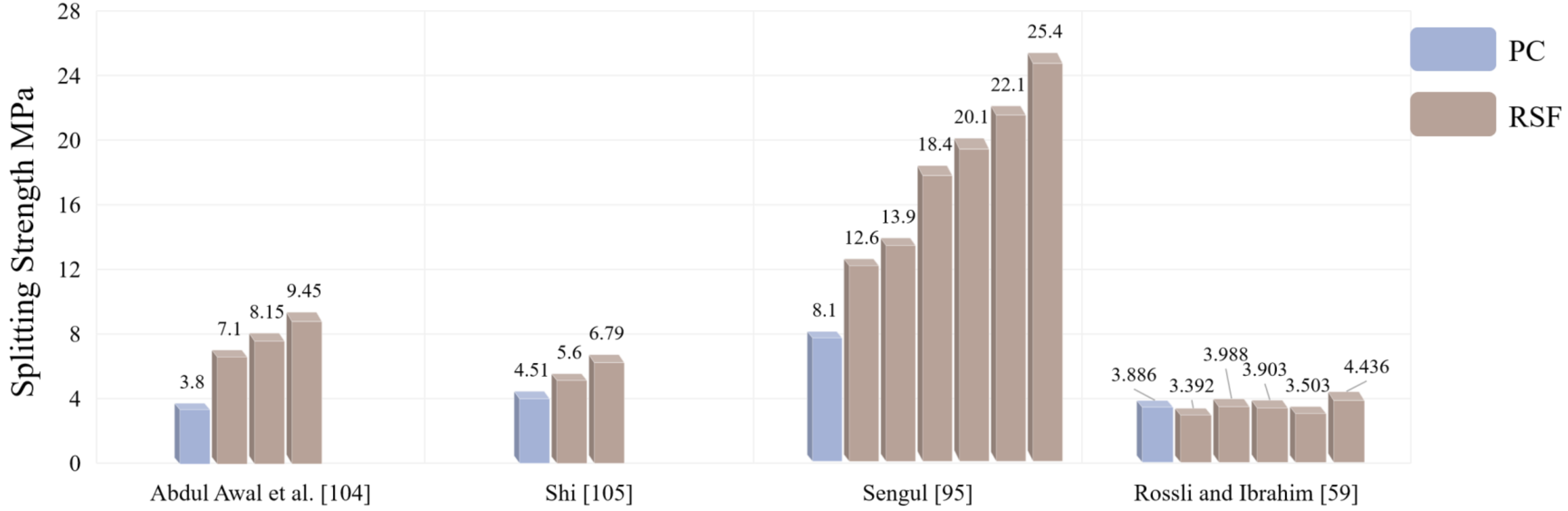
Strength (MPa)	ISF (kg/m^3)	RSF (kg/m^3)	TSF (kg/m^3)
3.5	0	0	0
3.2	0	0	0
3.1	0	0	0
3	40	0	40
3.3	40	0	40
2.9	40	0	40
3.6	10	45	55
3.2	10	45	55
3.7	10	45	55

*PC is the plain concrete, ISF is the industrial steel fibre concrete, RSF is the recycled steel fibre concrete and HSF is the hybrid steel fibre concrete

Fig. 16 Splitting strength comparison between recycled steel fibre and steel fibre concrete [2]

According to Figure 15 and 16, ISF has better performance than RSF concrete in strength improvement with respect to plain concrete, and the maximum splitting strength are provided by the ISF concrete. However, the gap between ISF and RSF in improving splitting strength is limited, and Peng et al. [66] presented that the RSF has higher splitting strength than ISF with fibre dosage at 60 kg/m^3. In addition, qualitative studies made by Leone et al. [37] and Grzymski et al. [69] revealed that the addition of ISF and RSF result in the reduction of splitting strength. The loss of strength may be due to the random distribution of the fibres, which causes the development of cracks with a discontinued way. Moreover, the HSF contributes to improving the splitting strength [39, 41, 64], and HSF leads to more than 45.1% splitting strength enhancement of concrete than plain concrete. However, Mastali et al. [39] said that RSF and ISF have no synergistic effect in improving the splitting strength when maintaining the total fibre content at 1.5%. In the experiment of Mastali et al. [39], the total fibre content(ISF content + RSF content) are kept in 1.5%. And with the increase of RSF content in the total fibre content, there are no significant increasing trend or decreasing trend of splitting strength of concrete. The splitting strength shows a gradual drop with the addition of RSF in ISF concrete, but the strength loss is limited which not higher than 5% than 100% ISF concrete [39]. To identify the splitting strength improvement with the addition of RSF with respect to plain concrete, Figure 17 is built.

Figure 17 mainly compares RSF with the plain concrete. With the addition of RSF, the splitting strength achieves a significant enhancement. Moreover, the maximum improvement of splitting strength reaches 213% when RSF added to 5% [95]. Compared with the splitting strength of plain concrete, when controlling the fibre content at 1%, the increasing range from 13.1% to 86.8%, respectively [59, 95, 104, 105]. The efficiency of improvement seems not to be declined with the increase of fibre dosages. The results address that the RSF incorporated into concrete curbs the development of cracks, and the tensile strength improves with the increase of RSF dosage.



Strength (MPa)	ISF (kg/m³)	RSF (kg/m³)	TSF (%)
3.8	0	0	0
7.1	0	25	1%
8.15	0	37.5	1.50%
9.45	0	50	2%

Strength (MPa)	ISF (kg/m³)	RSF (kg/m³)	TSF (%)
4.51	0	0	0
5.6	0	79	1%
6.79	0	157	2%

Strength (MPa)	ISF (kg/m³)	RSF (%)	TSF (%)
8.1	0	0	0
12.6	0	0.50%	0.50%
13.9	0	1%	1%
18.4	0	2%	2%
20.1	0	3%	3%
22.1	0	4%	4%
25.4	0	5%	5%

Strength (MPa)	ISF (kg/m³)	RSF (kg/m³)	TSF (%)
3.886	0	0	0
3.392	0	9.11	0.20%
3.988	0	18.23	0.40%
3.903	0	27.35	0.60%
3.503	0	35.58	0.80%
4.436	0	36.46	1%

*PC is the plain concrete and RSF is the recycled steel fibre concrete

Fig. 17 Splitting strength comparison of concrete with addition of recycled steel fibre

4.3 Flexural strength

The plain concrete is a brittle material: the addition of fibres aims to change the failure mode of concrete from a brittle to ductile [106, 107]. According to the previous studies, the addition of ISF contributes to the improvement of flexural strength [108, 109]. In addition, Gao and Zhang [110] revealed that if the volume of ISF is higher than 0.5%, the flexural strength will achieve a high improvement. Based on the study of splitting strength, the RSF should show a similar performance with ISF. In this section, the study that related to flexural strength of RSF concrete will be divided into three parts with different types of testing method.

4.3.1 Experiments followed by standard of UNI-11039

The CTOD(Crack Tip Opening Displacement) test is one of the fracture toughness tests which aim to observe the development of cracks prior to failure, and it contributes to the evaluation of the flexural strength of the concrete structure [111]. Table 1 presents the collected data related to RSF and ISF concrete, and Figure 18 and Figure 19 are based on Table 2.

Figure 18 and Figure 19 describe that the first crack strength(f_{lf}) gets a slightly increases with the addition of fibre, and the value of f_{lf} in RSF concrete is higher than that of ISF concrete. Besides, the strength of f_{eq}(0-0.6) shows the similar trend with that of f_{lf}, meaning that the RSF has better bridge-effect than ISF at the beginning of the happening of crack. However, the ISF seems to provide higher post-crack strength of f_{eq}(0.6-3.0) than that of RSF concrete. Moreover, the most likely causes of the different performance between f_{eq}(0-0.6) and f_{eq}(0.6-3.0) with the addition of RSF is that the average length of RSF that has been used is shorter than ISF, which is beneficial for RSF to control the micro-cracks rather than macro-cracks. Toughness (D_0, D_1) is calculated by following equations:

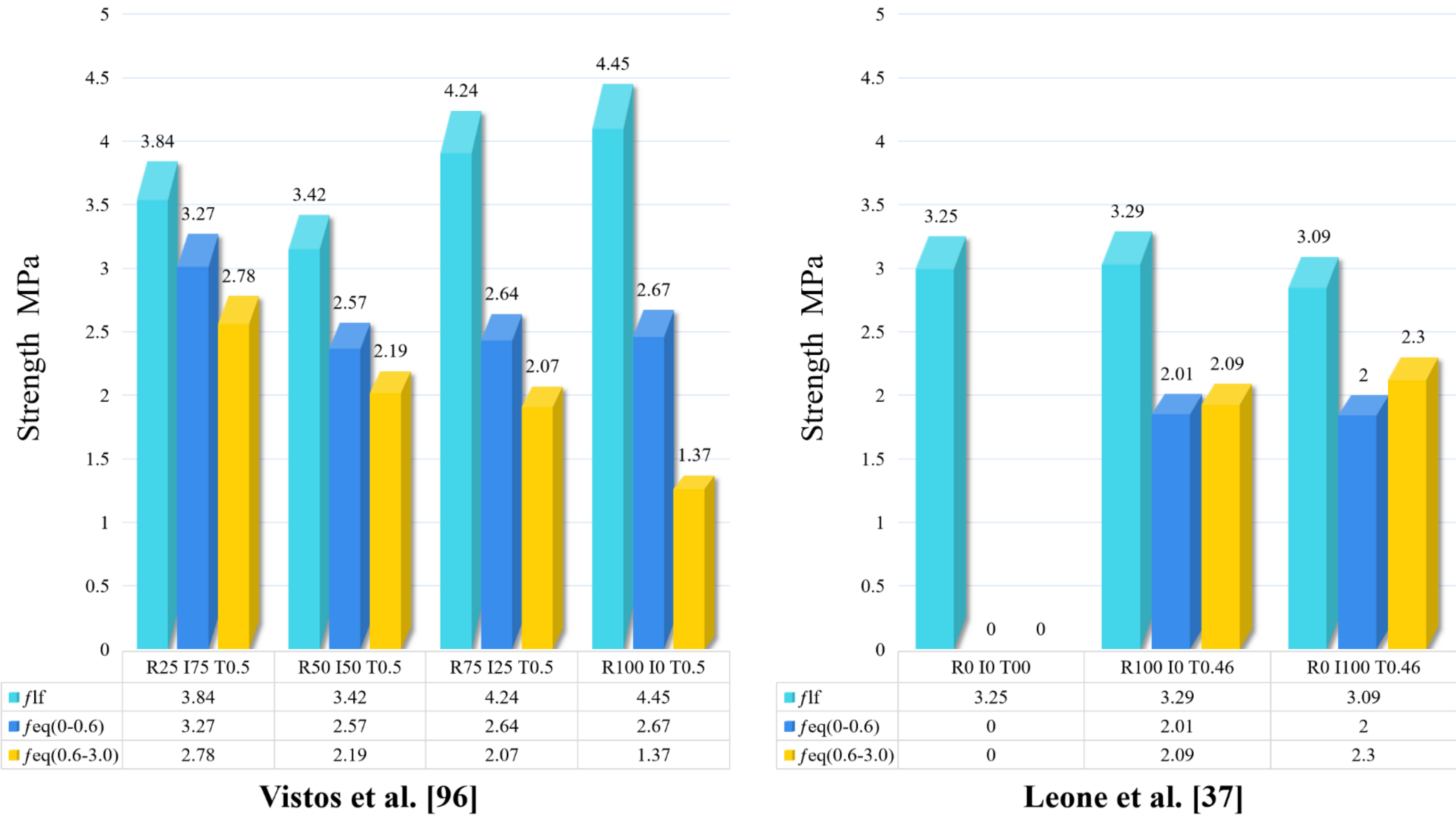
$$\mathrm{D}_0 = f_{\mathrm{eq}}(0-0.6)/f_{\mathrm{lf}} \quad (1)$$

$$\mathrm{D1} = f_{\mathrm{eq}}(0.6-3.0)/f_{\mathrm{eq}}(0-0.6) \quad (2)$$

Table 2 Results of CTOD tests performed according to UNI-11039 standard

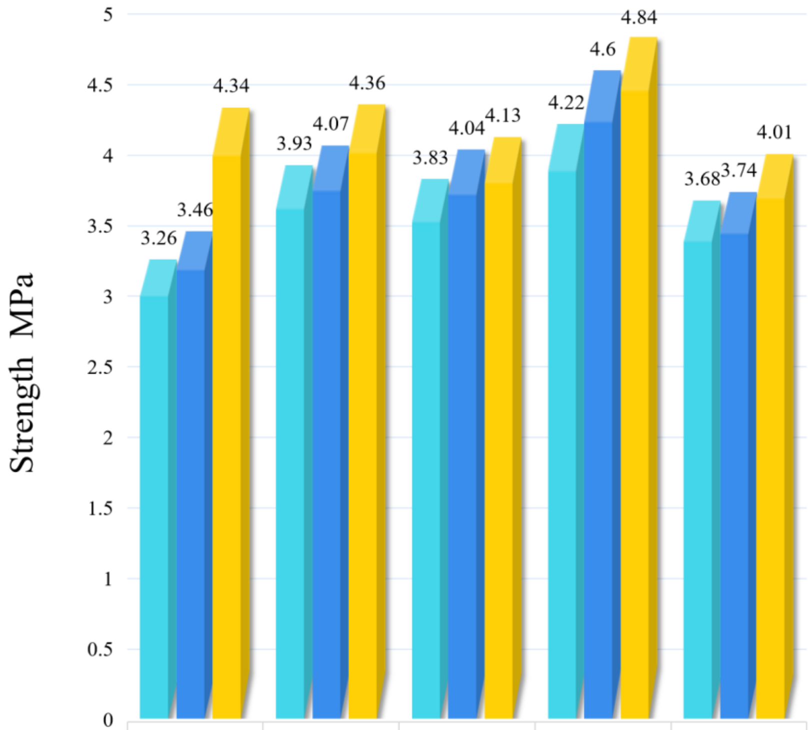
Authors	Year	Fibre Properties: Tensile Strength Mpa RSF	Fibre Properties: Tensile Strength Mpa ISF	Fibre Properties: Aspect Ratio l/d RSF	Fibre Properties: Aspect Ratio l/d ISF	RSF (kg/m^3)	ISF (kg/m^3)	Total (%v)	$CTOD_0$ (mm)	f_{lf} (MPa)	$f_{eq(0-0.6)}$ (MPa)	$f_{eq(0.6-3.0)}$ (MPa)	D_0	D_1
Vistos et al. [96]	2018	-	1200	104.68	60	25%	75%	0.50%	-	3.84	3.27	2.78	0.85	0.84
						50%	50%	0.50%	-	3.42	2.57	2.19	0.75	0.83
						75%	25%	0.50%	-	4.24	2.64	2.07	0.61	0.76
						100%	0	0.50%	14.28	4.45	2.67	1.37	0.6	0.51
Caggiano et al. [72]	2017	-	1200	104.68	60	0	60	0.75%	14.28	3.26	3.46	4.34	1.06	1.24
						30	30	0.75%	14.28	3.93	4.07	4.36	1.02	1.06
						50	30	1%	14.28	3.83	4.04	4.13	1.06	0.99
						70	30	1.25%	14.28	4.22	4.6	4.84	1.08	1.06
						60	0	0.75%	14.28	3.68	3.74	4.01	1.01	1.08
Leone et al. [37]	2018	-	-	58	50	0	0	0	18.85	3.25	-	-	-	-
						35	0	0.46%	18.85	3.29	2.01	2.09	0.6	0.83
						0	36	0.46%	18.85	3.09	2	2.3	0.64	1.34
Leone et al. [58]	2016	-	-	128	50	0	0	0	15.5	3.32	-	-	-	-
						16	0	0.30%	15.5	3.35	2.21	1.92	0.67	0.85
						0	23.45	0.30%	15.5	3.13	2.6	2.25	0.84	0.86

*The unit of RSF and ISF in Vistos et al. [96] is %



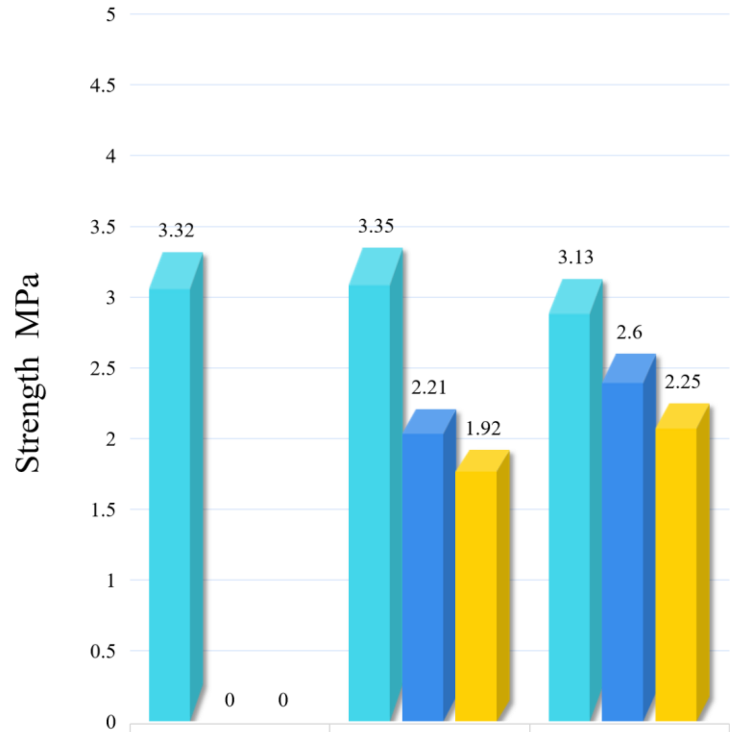
*R is content of recycled steel fibre, and I is the content of industrial steel fibre, and T is the total fibre content in concrete. (Ex. The R0 I100 T0.75 which means the content of RSF is 0% and ISF is 100%, the volume of total fibre content in concrete is 0.75%)

Fig. 18 Post-cracks strength comparison of concrete with addition of recycled steel fibre or industrial steel fibre [1]



	R0 I100 T0.75	R50 I50 T0.75	R62.5 I37.5 T1	R70 I30 T1.25	R100 I0 T0.75
*f*lf	3.26	3.93	3.83	4.22	3.68
*f*eq(0-0.6)	3.46	4.07	4.04	4.6	3.74
*f*eq(0.6-3.0)	4.34	4.36	4.13	4.84	4.01

Caggiano et al. [72]



	R0 I0 T00	R100 I0 T0.3	R0 I100 T0.3
*f*lf	3.32	3.35	3.13
*f*eq(0-0.6)	0	2.21	2.6
*f*eq(0.6-3.0)	0	1.92	2.25

Leone et al. [58]

*R is content of recycled steel fibre, and I is the content of industrial steel fibre, and T is the total fibre content in concrete. (Ex. The R0 I100 T0.75 which means the content of RSF is 0% and ISF is 100%, the volume of total fibre content in concrete is 0.75%)

Fig. 19 Post-cracks strength comparison of concrete with addition of recycled steel fibre or industrial steel fibre [2]

There are three levels of toughness [72]:

- ‘‘softening”, for D_0 and D_1 ranging between 0.5 and 0.9
- ‘‘plastic”, for D_0 and D_1 ranging between 0.9 and 1.1
- ‘‘hardening”, for D_0 and D_1 higher than 1.1.

The results listed in Table 2 indicate that the toughness of concrete which adds the RSF mainly tends to be softening, and ISF mainly tends to be softening and plastic. Moreover, Vistos et al.[96] and Caggiano et al.[72] compared the HSF concrete. Caggiano et al.[72] noted that the HSF contributes to improve flexural strength and shows better performance than ISF and RSF. In contrast to Caggiano et al.[72], Vistos et al.[96] addressed that the performance of HSF is determined by the content of fibre. If the contents of ISF are higher than those of RSF in HSF concrete, the performance of HSF concrete will be more likely to be similar with ISF concrete. In the opinions of Vistos et al.[96], the synergetic effect between ISF and RSF is limited in improving the flexural strength of concrete. The different opinions of HSF should be related to the total content of fibre. If the content of RSF or ISF is kept at a low level (below than 0.5%), the synergetic effect between ISF and RSF will hardly be acquired.

In general, in the early stage of cracking, the RSF is more efficient, and the ISF show better performance in controlling the large cracks. The synergetic effect between ISF and RSF mainly results from the hybridisation of fibres with different geometries. As described in chapter 2.3, the RSF is more like the micro-fibre which has different shapes and aspect ratios than ISF. In that case, the different geometries of fibre contribute to establishing the bridging effect with different lengths of cracks. Moreover, the addition of RSF lead to the structure to be softening, which is beneficial to reduce the risks of brittle damage. Besides, all the results show that the HSF is conductive to the control of both the micro-cracks and macro-cracks, which can be a good choice to balance the strength improvement and economic benefits.

Table 3 Results of flexural strength tests performed according to ASTM C78 standard

Author	**Year**	**Fibre Properties: Tensile Strength Mpa**		**Fibre Properties: Aspect Ratio l/d**		**RSF (kg/m^3)**	**ISF (kg/m^3)**	**Total (kg/m^3) and (%v)**	**f_{ct} (MPa)**	**I_5**	**I_{10}**	**I_{20}**	**$R_{5,10}$**	**$R_{10,20}$**
		RSF	**ISF**	**RSF**	**ISF**									
Bjegovic et al. [73]	2014	-	-	83	63	0	30	30	6.47	3.72	6.46	12.03	54.7	55.7
						15	15	30	6.53	3.41	5.65	9.72	44.8	40.7
						30	0	30	5.74	3.36	5.38	8.67	40.4	32.8
Najim et al. [112]	2018	781.3	-	50	-	0	0	0	9.51	4.15	9.27	20.43	102.4	111.6
						30	0	30	14.21	4.9	10.52	22.91	112.4	124
						45	0	45	15.40	5.1	11.05	24.06	119	130
						60	0	60	16.67	5.24	11.24	24.35	120	131
Mastali et al. [39]	2018	-	1300	111~333	47	0	0	0	6.55	1	1	1	0	0
						0	117	117（1.5%）	8.89	5.53	9.66	15.54	82.57	58.79
						11.7	105.3	117	8.84	6.74	12.94	21.7	124.06	87.6
						23.4	93.6	117	8.74	6.05	10.91	18.47	97.29	75.56
						35.1	81.9	117	8.66	4.9	8.37	13.15	69.45	47.82
						46.7	70.2	117	8.51	4.62	7.56	11.64	58.89	40.75
						58.5	58.5	117	8.41	4.92	7.87	11.59	58.94	37.16
						70.2	46.8	117	8.34	5.06	8.17	12.59	62.23	44.2
						81.9	35.1	117	8.24	5.87	9.71	15.49	76.77	57.86
						93.6	23.4	117	8.21	5.01	7.94	11.91	58.71	39.62
						105.3	11.7	117	8.19	6.24	9.71	15.23	69.32	55.28
						117	0	117	8.2	5.06	7.7	11.62	52.77	39.24

Continue with Table 3

Author	Year	Fibre Properties				RSF (kg/m³)	ISF (kg/m³)	Total (kg/m³) and (%v)	f_{ct} (MPa)	I_5	I_{10}	I_{20}	$R_{5,10}$	$R_{10,20}$
		Tensile Strength Mpa		Aspect Ratio l/d										
		RSF	ISF	RSF	ISF									
Mastali et al.[98]	2017	1200	-	333	-	0	0	0	4.41	1	1	1	0	0
						0.35%	0	0.35%	4.89	4.32	8.17	13.13	77	49.6
						0.70%	0	0.70%	4.98	9.93	28.3	30.94	165.4	127.4
						1.05%	0	1.05%	5.31	5.89	9.68	16.52	75.8	68.4
Tlemat et al. [71]	2003	1250	1150	-	50	1.0%	0	1.0%	10.7	2.58	4.44	8.37	37.2	39.3
						1.5%	0	1.5%	12.7	4.75	8.34	14.46	71.8	61.2
						0	1.5%	1.5%	14.5	5.97	12.2	24.48	124.6	122.8

*The unit of RSF and ISF in Mastali et al. [98] is %

Table 4 Results of CMOD test performed according to EN 14651 standard

Author	**Year**	**Fibre Properties**				**RSF (kg/m^3)**	**ISF (kg/m^3)**	**Total (kg/m^3) and (%v)**	$f_{ct.L}$ **(MPa)**	$f_{R.1}$ **(MPa)**	$f_{R.2}$ **(MPa)**	$f_{R.3}$ **(MPa)**	$f_{R.4}$ **(MPa)**
		Tensile Strength Mpa		**Aspect Ratio l/d**									
		RSF	**ISF**	**RSF**	**ISF**								
Hu et al. [65]	2018	2570	1050	100	69	0	30	30	3.9	4.1	4.2	3.7	3.2
						30	0	30	3.7	3.4	2.7	2.1	1.7
Smrkić et al. [41]	2017	2850	1100	133	64	0	0	0	4.25	0.56	0.15	0	0
						20	20	40	5.00	4.59	4.50	3.94	3.46
						0	40	40	5.57	5.74	5.3	4.78.	4.16
Skarżyński [56]	2018	-	-	104	50	0	0	0	3.59	-	-	-	-
						0	25	0.25%	4.82	2.29	-	-	0.98
						50	0	0.5%	4.67	4.67	-	-	2.45
Bjegovic et al. [73]	2014	-	-	83	63	0	30	30	6.47	-	-	-	-
						15	15	30	6.53	-	-	-	-
						30	0	30	5.74	-	-	-	-
Zamanzadeh et al. [113]	2015	-	-	-	-	45	0	45	4.73	4.16	3.94	3.69	3.43
						60	0	60	5	5.36	5.17	4.86	4.41
						90	0	90	4.56	6.62	6.56	5.9	5.55
						0	45	45	5.14	8.61	8.36	6.83	5.64
						0	60	60	6.62	10.43	7.39	4.8 6	3.4
						0	90	90	5.99	12.37	12	9.71	7.38

Continue with Table 4

Author	**Year**	**Fibre Properties**				**RSF (kg/m^3)**	**ISF (kg/m^3)**	**Total (kg/m^3) and (%v)**	**$f_{ct.L}$ (MPa)**	**$f_{R.1}$ (MPa)**	**$f_{R.2}$ (MPa)**	**$f_{R.3}$ (MPa)**	**$f_{R.4}$ (MPa)**
		Tensile Strength Mpa		**Aspect Ratio l/d**									
		RSF	**ISF**	**RSF**	**ISF**								
Tlemat et al. [114]	2006	1250	1150	-	50	0%	0	0%	3.45	-	-	-	-
						0.50%	0	0.50%	4.26	1.1	-	-	0.8
						1%	0	1%	5.32	3.9	-	-	1.7
						2%	0	2%	6.24	6	-	-	2.5
Baricevic et al. [63]	2017	2000	1100	100	64	0	20	20	4.6	1.47	0.83	0.59	0.44
						0	30	30	5.1	2.54	2.36	1.59	1.09
						30	0	30	4.4	3.55	3.77	3	2.38
						30	10	40	4.9	2.49	1.86	1.24	0.88
						50	10	60	4.9	3.12	2.61	1.94	1.4
						80	10	80	4.4	3.05	2.32	1.81	1.42
						100	10	100	5.9	5.8	4.47	3.32	2.49
						40	20	40	4.7	3.47	3.23	2.41	1.85

*The unit of RSF and ISF in Tlemat et al. [114] is %

4.3.2 Experiments followed by standard of ASTM C78

Table 3 lists the results of experiments based on the standard of ASTM C78. Table 3 describes that the ISF have better performance in increasing the flexural strength of fibre-reinforced concrete than RSF. However, the gaps of improving flexural strength between RSF and ISF reinforced concrete is limited, ranging from 7.7%[39] to 12.4% [71], with a fibre content of 1.5%. Moreover, the addition of RSF contributes to the improving of flexural strength, and it can reach 75.3% maximum improvement than plain concrete [112]. By focusing on the value of toughness indices(I_5-I_{20}), the addition of higher fibre content in reinforcement of plain concrete leads to the increase of toughness indices. Besides, Mastali et al.[39] paid attention to the performance of HSF in flexural strength and revealed that with the (I_5-I_{20}) decrease of the addition of RSF, it reaches the lowest point at 46.7 kg/m^3(40%)RSF with 70.2 kg/m^3 (60%)ISF. The toughness indices show a decreasing trend of about 50% with the increase of RSF content, indicating that the toughness of concrete decreases the post-cracking strength and the ability of concrete for absorbing energy. However, the maximum toughness indices appear at the beginning of adding RSF to ISF concrete, which means that there are still some synergetic effects between ISF and RSF.

The Residual strength factors ($R_{5,10}$; $R_{10,20}$) aim to assess the levels of toughness, the formulas are as follows:

$$R_{5,10} = 20(I_{10} - I_5) \quad (3)$$

$$R_{10,20} = 10(I_{20} - I_{10}) \quad (4)$$

Jeng et al.[115] introduced that the concrete will tend to be softening if the factor value less than 100. According to Table 3, the addition of ISF in HSF concrete cause the residual strength factor decreased slightly. Opposite to ISF, the RSF contributes to making the concrete softer, which shows the same results with CTOD test. Moreover, if keep the same content of RSF and ISF in concrete, the ISF concrete show better performance in energy absorptive and residual flexural strength. Besides, the efficiency of energy absorptive quite low for RSF concrete when maintain the fibre content at low level ($\leq$ 0.5%.). However, the efficiency of energy absorptive show a rapidly increasing trend for the fibre content higher than 0.5% and stay stable after 1%.

4.3.3 Experiments followed by standard of EN 14651

This test method evaluates the tensile behaviours of fibre-reinforced concrete either in terms of areas under the load-deflection curve or by the load bearing capacity at a certain deflection or crack mouth opening displacement (CMOD) obtains by testing a simply supported notched beam under three-point loading [116]. Table 4 describes the results of experiments based on the standard of EN 14651.

The results of limit of proportionality ($f_{ct,L}$) show that the concrete adding RSF can hardly achieve the same tensile strength improving with that of ISF. However, the strength loss of RSF concrete relative to ISF concrete ranges from 3.1%(fibre content at 40kg/m^3 in Skarżyński and Suchorzewski [56]) to 23%(fibre content at 90kg/m^3 in Zamanzadeh et al.[113]). The gaps between ISF and RSF reinforced concrete is limited, and with the increase of RSF content, same strength could be achieved. Besides, Smrkić at al. [41] and Bjegovic et al. [73] conducted experiments on HSF, and the performance of HSF in improving flexural strength is between that of ISF and RSF. Moreover, the residual flexural strength values ($f_{R,1}$-$f_{R,4}$) from Baricevic [63] show that the cooperation between ISF and RSF makes it possible to delay the development of cracks, making the failure process of structure researched in a modest way. However, the concrete of RSF still show less strength support with that of ISF after crack happened, and the gaps of resident strength become bigger with the development of cracks.

4.3.4 Flexural strength only applicable to RSF

Figure 20 ad 21 aims to describe the flexural strength improvement with the addition of RSF with respect to plain concrete. The details shown in Table 6 in Appendix.

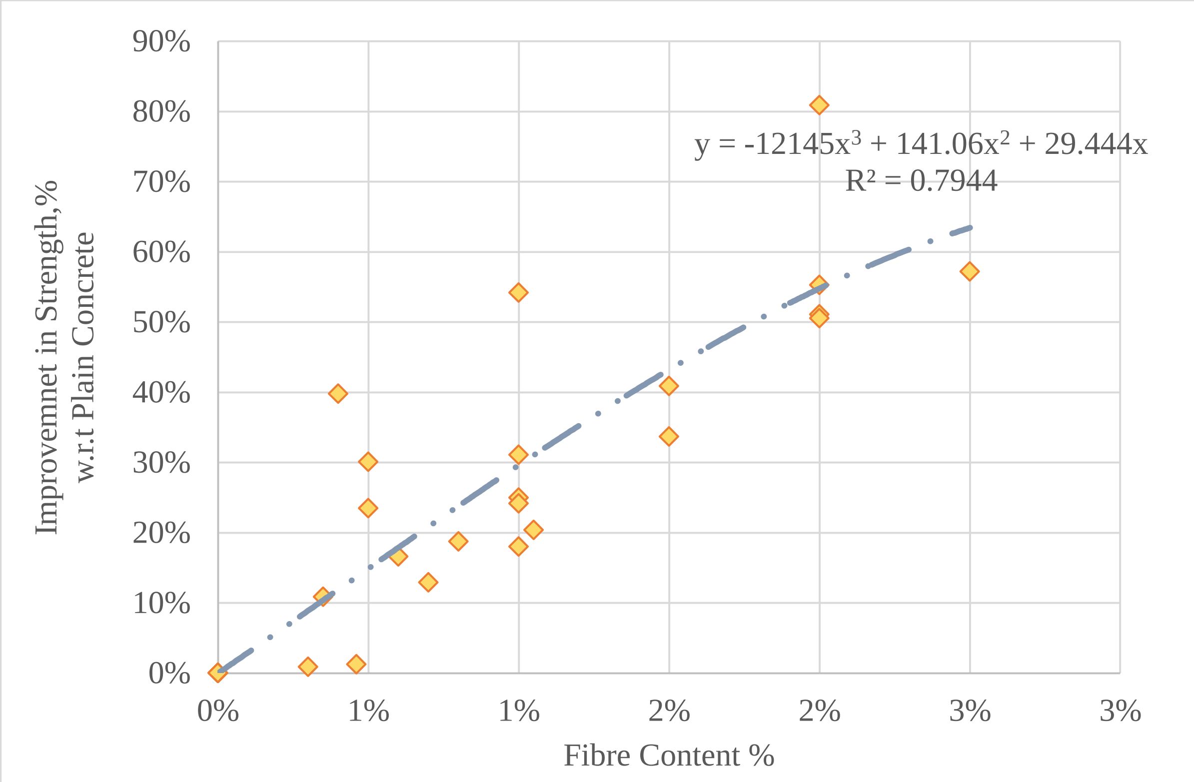


Fig. 20 Effect of RSF to improve the flexural strength

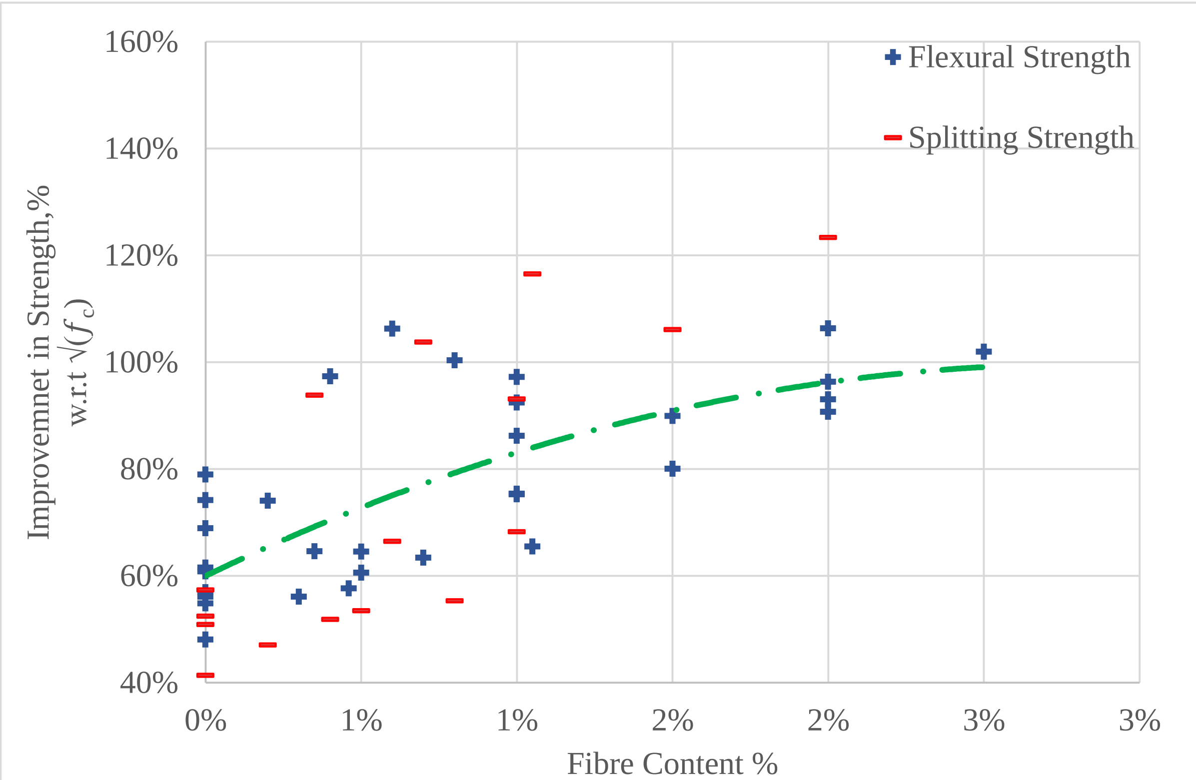


Fig. 21 Strength improvement with respect to compressive strength

According to Figure 20, there is an increasing trend with the addition of RSF, and the R square can reach 0.7945. The efficiency of RSF to improve the flexural strength increase with the fibre content higher than around 0.5% and stay stable after around 1%. When keeping the fibre content at 1%, the most used in practical application, the percentages of strength improvement provided by the addition of RSF are between 18% and 31%.

For plain concrete, there are some standards that described the relationship between compressive strength and flexural strength or splitting strength.

$f_{sp} = 0.56\sqrt{f_c}$ ACI Committee 318 (5)

$f_r = 0.6\sqrt{f_c}$ BS-8110 (6)

According to Equation 5 and 6, the flexural strength and splitting strength show the potential relationship with $\sqrt{f_c}$. Results in Figure 21 show the $f_r/\sqrt{f_c}$ ratio and $f_{sp}/\sqrt{f_c}$ ratio increase with the addition of fibre, which means that the RSF contributes to tensile strength improving. Besides, there are the same increasing trend between $f_r/\sqrt{f_c}$ ratio and $f_{sp}/\sqrt{f_c}$ ratio. However, the increasing trend going to be stable with the RSF content higher than 1%, which means the efficiency of RSF in improving tensile strength reach the highest point around the fibre content at 1%. According to the Table 8 in Appendix, there are two different trend in compressive strength with the addition of RSF [98, 114], but the $f_r/\sqrt{f_c}$ ratio still show the same increasing trend with each other. In that case, the compressive strength loss or increase can hardly influence the efficiency of RSF in improving tensile strength.

4.4 Final Remarks

Based on the previous study, the mechanical properties of RSF concrete can be described well in Table 5.

Table 5 Summary of recycled steel fibre concrete in mechanical properties

<table>
<tr><th>Properties</th><th>Highlight Finding</th><th>Knowledge Gap</th></tr>
<tr><td>Compressive Strength</td><td>The addition of RSF is beneficial to improving the compressive strength, the efficiency of strength improvement decreases sharply after the fibre content reach 0.5%. The strength loss than plain concrete could be happened with the fibre content higher than 0.5%, which mainly due to the poor compacting and balling effect. Moreover, the RSF content higher than 1% will not show improvement in compressive strength</td><td>There are limited studies using different compacting technical to improving the performance of RSF concrete in compressive strength. The future study for compressive strength can focus on the self-compacting concrete with addition of RSF.</td></tr>
<tr><td>Splitting Strength</td><td>In the study of splitting strength compared with plain concrete, the fibre content of 5% RSF can increase the strength by more than 213% maximum. In addition, the efficiency of improvement will not be decreased when maintaining the fibre content at a high level (≥1%).</td><td rowspan="2">According to the performance of RSF in improving the flexural and splitting strength of concrete, the RSF should also be beneficial to improving the shear strength of fibre-reinforced beams. According to previous study, using steel fibre as the transverse reinforcement to replace the stirrup has been widely accented. Besides, there are some semi-empirical formula or empirical formula has been published since late 20th. However, the research of RSF in improving the shear strength of concrete beams is limited.</td></tr>
<tr><td>Flexural Strength</td><td>For the flexural strength, the RSF can increase the flexural strength to 55% than that of plain concrete with a fibre content at 2.5%. Besides, the addition of RSF is beneficial to controlling the micro-cracks, but the strength resistance decreases rapidly with the development of cracks. The efficiency of RSF in improving the strength increase rapidly for the fibre content between 0.5% to</td></tr>
</table>

	1% and stay stable after 1%	The future study should try to describe the contribution of RSF in shear capacity, determine the fibre factor of RSF in shear strength and build semi-empirical formula or empirical formula.
The performance of HSF concrete	There are no synergistic effects in improving the splitting strength and compressive strength with HSF. And the risks of balling effect increased with the addition of different types of fibre. However, there is a synergistic effect happened in improving the flexural strength and resident tensile strength when maintaining the fibre content higher than 1%.	As a result of the comprehensive review, it can be said that the RSF can replace the function of ISF in concrete. However, the research about the dynamic properties of RSF concrete, and the structure application withstand impact still empty. However, the study about HSF concrete is limited, and the contribution of HSF in concrete is also not so clear. Besides, such durability properties of RSF concrete as chloride resistance and freeze-thaw resistance are still empty. In that case, the further work can focus on HSF and durability properties.
Comparing with ISF concrete	When compared with ISF, the RSF shows better performance in compressive strength, but weaker performance in splitting strength and flexural strength. Despite the gaps of splitting strength improvement between RSF and ISF concrete will not be higher than 5%. Besides, the higher tensile strength of fibre can hardly improve tensile strength significantly. This review indicted the result of CMOD and CTOD, and the RSF shows better performance at the beginning of the happening of crack f_{eq}(0-0.6) while ISF shows better	

	performance in controlling longer cracks f_{eq}(0.6-3.0).	

5. Sustainability of recycled fibre reinforced concrete

As the material with huge recycling potential, the waste tire has been paid attention to its potential contribution to the environment and economy. The RSF is a recycled material recovered from waste tires. In order to identify the sources of RSF, the structure of the tire is shown in Figure 22.

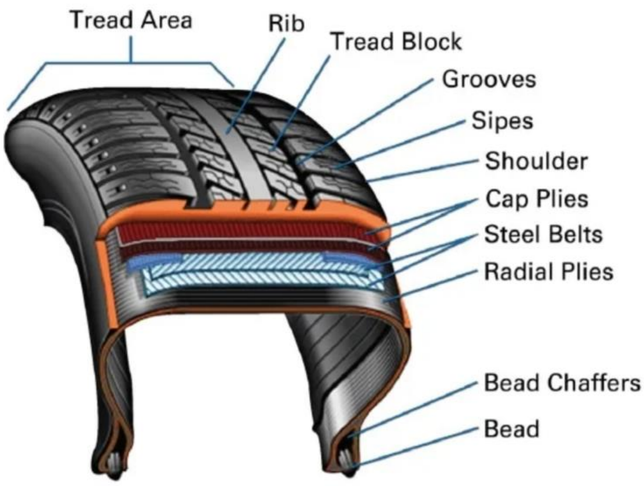


Fig. 22 Structure of tire [117]

Figure 22 reveals that the RSF is mainly recovered from steel belts and bead, both of which are parts of tire and can hardly be separated out from the structure individually [118]. In that case, the process of recycling will cut the tire to small pieces, and then separate the RSF from waste tire [5]. This section aims to discuss the significant findings about RSF's contributions in sustainability, economics, environment, and social value.

5.1 Sustainability

Carbon dioxide (CO_2) footprint is one of the biggest indicators for assessing the environmental impact which influences the growth of sustainable development extensively. There are more than 13% the steel can be recovered from wasted passenger tires, and 25% of the steel from truck tire in European Union has limited carbon emissions during the recycling process [119]. Thus, whether the wasted steel can be recycled in a right way, such as using RSF to replace the ISF in concrete, has practical significance for carbon emission reduction by civil constructions. To identify the contribution of RSF in sustainable development, Table 6 is built to describe the global warming potential (GWP) between RSF and ISF. Besides, due to the limited information about GWP of RSF, two papers that describe the value of GWP during the process of recycling tires have been collected.

Table 6. Global warming potential (GWP) between RSF and ISF

ISF (kg CO_2 eq)		**RSF (kg CO_2 eq)**	
Mastali **[39]**	2.15	Mastali [39]	0.5(RSF)
Isa et al.**[40]**	2.68	Isa et al.[40]	0.083(RSF)
Mehdipour et al.**[120]**	1.6	Piotrowska et al.[121]	-2.116(T)
Yepes et al.**[122]**	2.35	Turner et al.[123]	-1.17±1.047(T)
Mean Value	2.2	Max Value	0.5

Note: Negative values denote net GHG (Greenhouse Gas) emission reductions or carbon storage from a materials management practice; T which means the GHG emission during the recycling process of whole tire.

In common sense, the process of recycling tire is clean, which is beneficial to reducing the carbon emission. The reason for the positive value in Mastali et al.[39] is mainly the transportation, not the recycling process. The mean GWP of ISF is 2.2 kg CO_2 eq, which is almost four times that of maximum value in RSF. Based on the data provided by Samarakoon et al.[6], there are more than 500,000 tonnes of RSF that could be recovered from wasted tire annually in Europe. Thus, if reusing the RSF in concrete to replace the ISF, the maximum GWP saving will be more than 1 billion kg CO_2 eq per year.

5.1 Economics

Except the contribution of RSF in GWP, the low price should also not be ignored. There are three papers comparing the price between ISF and RSF, and the results are shown in Table 7.

Table 7. Price between RSF and ISF

ISF (€/kg)		**RSF (€/kg)**	
Mastali **[39]**	0.8	Mastali [39]	0.5
Neocleous et al.**[124]**	0.7	Neocleous et al.[124]	0.05-0.2

Samarakoon et al.[6]	1.5	Samarakoon et al.[6]	0.15
Mean Value	1.0	Mean Value	0.24

These results indicated that the RSF is cheaper than ISF, which can be more than ten times. The mean price of ISF is almost five times as that of RSF. In common sense, the dosages of ISF generally range from 20 to 50 kg/m^3 [94]. In addition, if the ISF is replaced by RSF, the cost will be saved from 15.2€/m^3 to 38€/m^3.

According to the Table 6 and 7, the results imply that the contribution of using RSF replaces the ISF from the aspect of economy and environment. Moreover, the social contribution of RSF should not be ignored. As mentioned in the part of introduction, the waste tire has huge potential risks on environment [125]. The incineration or burying of waste tires will cause irreversible harm to human health and the water resources [126]. The reuse of waste tires as an environment-friendly material in civil construction promotes the cleanliness of buildings and prolong the service life of the structure. From the detailed study on the mechanical properties of RSF concrete, it is observed that the usage of RSF has enhanced the performance of the fibre reinforced concrete on its mechanical properties. Although the performance of RSF is not superior, or ever weaker than ISF concrete, the RSF can still be a good substitute for ISF for its contribution to economics, environment, carbon emission, and social development.

6. Conclusions

In this paper, a comprehensive review on the mechanical properties of RSF concrete is conducted. The contribution of RSF in fresh or harden concrete properties and sustainable development have been presented, and it is compared with ISF. Based on the extensive review of research data, the following conclusions can be drawn.

- Owing to the need for high-strength steel in the process of making tires, the tensile strength of RSF is almost twice as much as that of ISF, which ensures the good performance of RSF in flexural strength and splitting strength.
- It is evident from the literature that the workability of RSF concrete shows a decreasing trend with the increase of dosages of RSF. In addition, the ISF

provides lower workability than that of the RSF. The side-effect of low workability of RSF concrete could be addressed by adding superplasticizer and using small size-aggregates. The air content of RSF concrete increases with the increasing dosage of fibre. However, due to the fact that RSF has more micro fibres than ISF, the ISF shows better performance in improving the air content than RSF, making it possible to fill the voids in concrete.

- The compressive strength of RSF concrete increases with the increase of fibre content when the fibre content not higher than 0.5%. When the fibre content higher than the 1%, the improvement will be disappeared. Moreover, the strength loss will be happened when the fibre content higher than 0.5%. The issues of strength loss in compressive strength are mainly due to the size of voids between RSF and cement matrix. Better vibrating technology or using self-compacting concrete contributes to reducing the size of voids in concrete and increasing the performance of RSF in compressive strength.
- The RSF shows good performance in improving the splitting strength of concrete, and the efficiency of strength increases will not be decreased with high fibre dosage. The majority of the studies follow a trend that ISF have better strength improving when comparing with RSF, but the gap between ISF and RSF in increasing the splitting strength is limited.
- The effect of RSF on improving the flexural strength of concrete is similar to that of splitting strength. For the performance of post-cracks, at the beginning, the RSF has better performance in controlling the development of cracks, but weaker with the development of cracks. Besides, the ISF shows better performance in controlling the macro-cracks in concrete than that of RSF. The different performance between ISF and RSF is mainly reasoned by the size of the fibre, and the RSF is smaller than ISF, making it possible to control the micro-cracks in concrete than that of ISF. In addition, despite the fact that the ISF provides higher flexural strength than RSF, the gaps for improving the strength of plain concrete is limited, ranging from 7.7% to 12.4%. Besides, the synergy between ISF and RSF mainly happens when the fibre content higher than 1%. To ensure the

efficiency of RSF concrete in mechanical properties, the fibre range should from 0.5% to 1.5%.

- The contribution of RSF to sustainable development should not be ignored. If the distance of transportation is kept in a low range, the value of GWP of RSF will be negative. In addition, the price of RSF is a quarter of that of ISF, which can save a budget of more than 38€/m^3.

Author Contributions: S.K developed the concept; X.Q did the data collection, and data analyzed; X.Q contributed the manuscript; S.K and X.Q reviewed the paper. All authors wrote the paper. All authors have read and agree to the published version of the manuscript.

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Appendix A

Table 1 Results of slumps

Authors	Fibre Content(kg/m^3)			Superplasticizerizer (kg/m^3)	Slump mm	Aspect Ratio	
	Recycled Steel Fibre	Steel Fibre	Total			ISF	RSF
Hu et al. [65]	0	30	30	6.7	55	69	100
	30	0	30	6.7	55		
	0	0	0	6.7	-		
Smrkić et al. [41]	0	0	0	2.22	200	64	133
	20	20	40	2.22	160		
	0	40	0	2.22	160		
Leone et al. [37, 58]	0	0	0	1.4	220	50	128
	35	0	35	1.19	210		
	0	36	36	2.07	200		
Samarakoon et al. [6]	0	0	0	-	-	63.5	100
	15	0	15	-	215		
	30	0	30	-	183		
	0	39	39	-	165		
	0	78	78	-	50		
Bjegovic et al. [73]	0	30	30	2.31	50	64	84
	15	15	30	2.31	55		
	30	0	30	2.31	60		
Baricevic et al. [63]	0	20	20	2.2	187	64	100
	0	30	30	2.2	193		
	30	0	30	2.2	187		
	30	10	40	2.2	192		
	50	10	60	2.2	185		
	80	10	90	2.2	187		
	100	10	110	2.2	93		
	40	20	60	2.2	188		
Leone et al. [58]	0	0	0	2.45	225	50	128
	16	0	16	2.8-3.0	205		
	0	23.45	23.45	1.86	200		
Rossli et al. [59]	0	0	0	0.56	55	-	-
	9.11	0	9.11	0.56	60		
	18.23	0	18.23	0.56	30		
	27.35	0	27.35	0.56	10		
	36.46	0	36.46	0.56	30		
	35.58	0	35.58	0.56	10		

Table 2 Results of air content

Authors	Fibre Content(kg/m^3)			Air Content %	Aspect Ratio	
	Recycled Steel Fibre	Steel Fibre	Total (%v)		ISF	RSF
Smrkić et al. [41]	0	0	0	1.4	64	133
	20	20	40	2.8		
	0	40	40	3.1		
Leone et al. [37]	0	0	0	3.5	50	128
	35	0	35	5.3		
	0	36	36	6		
Samarakoon et al. [6]	0	0	0	0.3	63.5	100
	15	0	15	1		
	30	0	30	2.5		
	0	39	39	2.1		
	0	78	78	2.6		
Baricevic et al. [63]	0	20	20	2.13	64	100
	0	30	30	2.35		
	30	0	30	2.7		
	30	10	40	2.73		
	50	10	60	3.33		
	80	10	90	5.33		
	100	10	110	5.6		
	40	20	60	2.97		
Leone et al. [58]	0	0	0	2.8	50	128
	16	0	0.30%	2.7		
	0	23.45	0.30%	3		

Table 3 Results of compressive strength

Authors	Fibre Content(kg/m^3)			Compressive Strength MPa
	Recycled Steel Fibre	Steel Fibre	Total	
Smrkić et al. [41]	0	0	0	48.1
	20	20	40	42.5
	0	40	40	46.8
Mastali et al. [39]	0	0	0	51.1
	0	117	117(1.5%)	79.6
	11.7	105.3	117(1.5%)	79.1
	23.4	93.6	117(1.5%)	78.5
	35.1	81.9	117(1.5%)	79.6
	46.8	70.2	117(1.5%)	75.5
	58.5	58.5	117(1.5%)	74.4
	70.2	46.8	117(1.5%)	74.4
	81.9	35.1	117(1.5%)	73.7
	93.6	23.4	117(1.5%)	73.5
	105.3	11.7	117(1.5%)	72.8
	117	0	117(1.5%)	73.0
Leone et al. [37]	0	0	0	33.61
	35	0	35(0.46%)	32.6
	0	36	36(0.46%)	32.32
Vistos et al. [96]	0	0	0	42.59
	0%	100%	0.50%	40.57
	0%	100%	0.50%	39.01
	25%	75%	0.50%	36.42
	25%	75%	0.50%	36.52
	50%	50%	0.50%	36.89
	50%	50%	0.50%	36.74
	100%	0	0.50%	36.69
	100%	0	0.50%	47.37
Caggiano et al. [72]	0	0	0	30.47
	0	60	60(0.75%)	27.58
	30	30	60(0.75%)	28.91
	60	0	60(0.75%)	22.34
	50	30	80(1%)	27.54
	70	30	100(1.25%)	26.01
Dorr et al. [127]	0	0	0	28.3
	0.50%	0	0.50%	31.3

Authors	Fibre Content(kg/m^3)			Compressive Strength MPa
	Recycled Steel Fibre	Steel Fibre	Total (%v)	
Centonze, G et al. [17, 18]	0	0	0	31.63
	31.75	0	31.75(0.46%)	39
	31.75	0	31.75(0.46%)	39.68
	0	34.8	34.8(0.46%)	29.01
Bjegovic et al. [73]	0	30	30(0.38%)	72.6
	15	15	30(0.38%)	69.5
	30	0	30(0.38%)	74.3
Baricevic et al. [63]	0	20	20(0.8%)	60.4
	0	30	30(1.25%)	54.8
	30	0	30(1.25%)	57.7
	30	10	40(1.6%)	54.5
	50	10	60(2.4%)	52.8
	80	10	90(3.6%)	46.6
	100	10	110(4.5%)	49.9
	40	20	60(2.4%)	54.1
Rossli et al. [59]	0	0	0	45.96
	9.11	0	0.20%	51.99
	18.23	0	0.40%	59.17
	27.35	0	0.60%	34.5
	36.46	0	0.80%	40.13
	35.58	0	1%	42.26
Bartolac et al. [64]	0	0	0	50.4
	0	0	0	52.8
	0	0	0	54.1
	0	40	40(0.5%)	43.1
	0	40	40(0.5%)	42.3
	0	40	40(0.5%)	44.8
	45	10	55(0.7%)	44.3
	45	10	55(0.7%)	44.1
	45	10	55(0.7%)	43.8
Sengul [95]	0	0	0	94.7
	0.50%	0	0.50%	89.8
	1%	0	1%	96
	2%	0	2%	87.3
	3%	0	3%	93.6
	4%	0	4%	96.4
	5%	0	5%	87.8
Hu et al. [65]	0	0	0	46.2
	30	0	30	48.1
	0	30	30	49.1

Authors	Fibre Content(kg/m^3)			Compressive Strength MPa
	Recycled Steel Fibre	Steel Fibre	Total (%v)	
Samarakoon et al. [6]	0	0	0	29.2
	15	0	15(0.5%)	30.6
	30	0	30(1%)	32.9
	0	39	39(0.5%)	34.3
	0	78	78(1%)	35.1
Skarżyński et al. [56]	0	0	0	42.91
	0	25	25(0.25%)	48.71
	50	0	50(0.5%)	52.42
Grzymski et al. [69]	0	0	0	41.61
	0	25	25	53.66
	25	0	25	69.04
Peng et al. [66]	0	0	0	135.5
	0	60	60	145.1
	0	60	60	139.8
	60	0	60	154.3
	60	0	60	141.3
Leone et al. [58]	0	0	0	34.03
	16	0	16(0.3%)	35.71
	0	23.45	23.45(0.3%)	34.32
Abdul Awal et al. [104]	0	0	0	55.85
	25	0	25(1%)	58.2
	37.5	0	37.5(1.5%)	59
	50	0	50(2%)	58.7
Najim et al. [112]	0	0	0	60
	30	0	30(0.4%)	62
	45	0	45(0.6%)	62.5
	60	0	60(0.8%)	65
Shi et al. [105]	0	0	0	36.96
	79	0	79(1%)	36.71
	157	0	157(2%)	40.78

Table 4 Results of splitting strength

Authors	Fibre Content(kg/m^3)			Splitting Strength MPa
	Recycled Steel Fibre	Steel Fibre	Total (%v)	
Smrkić et al. [41]	0	0	0	3.1
	20	20	40	4.5
	0	40	40	4.1
Mastali et al. [39]	0	0	0	3.42
	0	117	1.50%	4.42
	11.7	105.3	1.50%	4.4
	23.4	93.6	1.50%	4.4
	35.1	81.9	1.50%	4.37
	46.8	70.2	1.50%	4.28
	58.5	58.5	1.50%	4.29
	70.2	46.8	1.50%	4.23
	81.9	35.1	1.50%	4.20
	93.6	23.4	1.50%	4.23
	105.3	11.7	1.50%	4.20
	117	0	1.50%	4.2
Leone et al. [37]	0	0	0	5.06
	35	0	0.46%	4.55
	0	36	0.46%	4.5
Samarakoon et al. [6]	0	0	0	2.18
	0	39	0.50%	2.86
	0	78	1%	2.97
	15	0	0.50%	2.58
	30	0	1%	2.49
Peng et al. [66]	0	0	0	6.91
	0	60	60	8.84
	0	60	60	8.99
	60	0	60	8.75
	60	0	60	9.39
Leone et al. [58]	0	0	0	4.55
	16	0	0.30%	4.73
	0	23.45	0.30%	4.56
Skarżyński and Suchorzewski [56]	0	0	0	2.17
	25	0	0.25%	3.54
	0	50	0.50%	3.87

Authors	Fibre Content(kg/m^3)			Splitting Strength MPa
	Recycled Steel Fibre	Steel Fibre	Total (%v)	
Bartolac et al. [64]	0	0	0	3.5
	0	0	0	3.2
	0	0	0	3.1
	0	40	1.50%	3
	0	40	1.50%	3.3
	0	40	1.50%	2.9
	45	10	2.50%	3.6
	45	10	2.50%	3.2
	45	10	2.50%	3.7
Abdul Awal et al. [104]	0	0	0	3.8
	25	0	1%	7.1
	37.5	0	1.50%	8.15
	50	0	2%	9.45
Shi et al. [105]	0	0	0	4.51
	79	0	1%	5.6
	157	0	2%	6.79
Sengul [95]	0	0	0	8.1
	0.50%	0	0.50%	12.6
	1%	0	1%	13.9
	2%	0	2%	18.4
	3%	0	3%	20.1
	4%	0	4%	22.1
	5%	0	5%	25.4
Rossli and Ibrahim [59]	0	0	0	3.886
	9.11	0	0.20%	3.392
	18.23	0	0.40%	3.988
	27.35	0	0.60%	3.903
	35.58	0	0.80%	3.503
	36.46	0	1%	4.436
Grzymski et al. [69]	0	0	0	3.15
	0	25	25	3.06
	25	0	25	2.93

Table 5 Results of flexural strength with the addition of RSF

Authors	**Year**	**RSF (%v)**	**Strength (MPa)**
Mastali et al. [98]	2017	0	4.41
		0.35%	4.89
		0.70%	4.98
		1.05%	5.31
Abdul Awal et al. [104]	2015	0	4.6
		1%	5.75
		1.50%	6.15
		2%	6.95
Rossli and Ibrahim [59]	2012	0	5.355
		0.20%	5.339
		0.40%	7.486
		0.60%	6.243
		0.80%	6.358
		1%	6.321
Dehghanpour et al. [128]	2018	0	5.21
		1%	6.83
		1.50%	7.34
		2%	8.09
		2.50%	8.19
Modtrifi et al. [129]	-	0	3.77
		0.30%	4.07
		0.70%	4.9
		1%	4.285

Table 6 Results of strength with the addition of RSF

Authors	**Year**	**RSF (%v)**	**Flexural Strength (MPa)**	**Compressive Strength (MPa)**	**Splitting Strength (MPa)**
Mastali et al. [39]	2017	0.00%	4.41	52.57	3.8
		0.35%	4.89	57.31	7.1
		0.70%	4.98	61.73	8.15
		1.05%	5.31	65.81	9.45
Abdul Awal et al. [104]	2015	0.00%	4.6	55.85	3.8
		1.00%	5.75	58.2	7.1
		1.50%	6.15	59	8.15
		2.00%	6.95	58.7	9.45
Rossli and Ibrahim [59]	2012	0.00%	5.355	45.96	3.886
		0.20%	5.339	51.99	3.392
		0.40%	7.486	59.17	3.988
		0.60%	6.243	34.5	3.903
		0.80%	6.358	40.13	3.503
		1.00%	6.321	42.26	4.436
Dehghanpour et al.	2018	0.00%	5.21	57.16	-
		1.00%	6.83	62.74	-
		1.50%	7.34	66.62	-
		2.00%	8.09	70.5	-
		2.50%	8.19	64.55	-
Shi [105]	2020	0.00%	-	36.96	4.51
		1.00%	-	36.71	5.6
		2.00%	-	40.78	6.79
Skarżyński and Suchorzewski [56]	2018	0.00%	3.59	42.91	2.71
		0.50%	4.67	52.42	3.87
Tlemat et al. [114]	2006	0.00%	3.45	51.5	-
		0.50%	4.26	49.5	-
		1.00%	5.32	50	-
		2.00%	6.24	45	-
Leone et al. [37]	2018	0	3.25	33.61	-
		0.46%	3.29	32.6	-
Leone et al. [58]	2016	0	3.32	34.03	-
		0.30%	3.35	35.71	-

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Environment-Friendliness of Recycled Steel Fibre Reinforced Concrete

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Highlights

• The paper is a critical review of more than 140 research articles available in the literature.
• The properties of recycled steel fibre with respect to cleaner applications are presented.
• Sustainability analysis of recycled steel fibre reinforced concrete is performed.
• The outcomes highlight the mechanical properties improvement with the addition of recycled steel fibres.
• Comprehensive insight into the RSF reveals existing research gaps for recycled steel fibre and industrial steel fibre reinforced concrete.