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Steel Fiber Reinforced Self-Compacting Concrete: A Comprehensive Review

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Abstract

Self-compacting concrete (SCC), which flows under its own weight without being compacted or vibrating, requires no outside mechanical force to move. But like normal concrete, SCC has a brittle character (weak in tension) that causes sudden collapse with no advance notification. The tensile capacity of SCC has increased owing to the addition of steel fiber (SF). Various research concentrates on increasing the tensile strength (TS) of SCC by incorporating SF. To collect information on past research, present research developments, and future research directions on SF-reinforced SCC, however, a detailed review of the study is necessary. The main aspects of this review are the general introduction of SCC, fresh properties namely slump flow, slump T50, L box, and V funnel, and strength properties such as compressive, tensile, flexure, and elastic modulus. Furthermore, failure modes of steel fiber-reinforced SCC are also reviewed. Results suggest that the SF decreased the filling and passing ability. Furthermore, improvement in strength properties was also observed. However, some studies reported that SF had no effect or even decreased compressive capacity. Additionally, SF improved the tensile capacity of SCC and avoid undesirable brittle failure. Finally, the review recommends the substitution of secondary cementitious materials in SF-reinforced SCC to improve its compressive capacity.

Keywords Self-compacting concrete, Steel fiber reinforced concrete, Fresh concrete, Failure modes and durability

1 Introduction

In Europe, a kind of concrete was in use before the 1970s that required less vibration (SCC); however, SCC was not created until the late 1980s. Although Sweden was the first European nation to build transportation buildings using SCC in the 1990s (Kim & Han, 1997), the original principles for SCC were developed in Japan. SCC is one of the major improvements in the concrete industry during the last 20 years. SCC is an extremely flowable, non-segregating concrete that may fill the formwork, spread into position, and encase the reinforcement without the need for mechanical consolidation. It can pass down small openings without segregation or excessive bleeding, and it does not need vibration for compaction (ACI PRC-237 2007).

The research found that by adjusting the water/cement percentage and the quantity of superplasticizer. Aggregate contents may be maintained constant for better self-compatibility. Theoretically, an SCC must be flexible enough to allow self-compaction without the need for external energy, maintain consistency in appearance throughout the placement, pour easily through reinforcement, and be highly fluid so that it may be pumped further (Bartos, 2000). Fig. 1 illustrates the several advantages of SCC in the building sector.

SCC mix is composed of aggregate, cement, water, admixtures, and a mineral additive, much like conventional concrete (CC). In contrast to CC, SCC has a large amount of fillers and superplasticizers added to increase its flow qualities [such as silica fume (Kansal, 2016),

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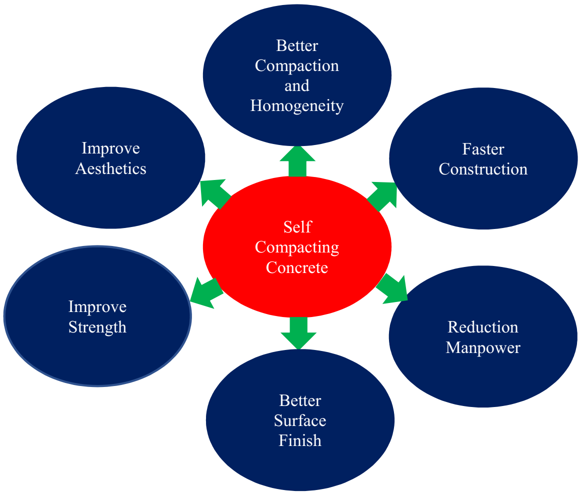

Fig. 1 Advantages of SCC

waste glass (Du & Tan, 2014), limestone (Li et al., 2015), and waste marble (Ashish, 2019)]. As SCC flows under its own weight without or with very little usage of vibration, it saves labor and makes concreting more affordable (Iqbal et al., 2015a). SCC compacts under its own weight without vibrating due to its excellent workability. Adding extra-fine aggregates and superplasticizer admixture will help SCC achieve the necessary flowability. Additionally, SCC also required less maximum size of aggregate should be used than in ordinary concrete. The application of the superplasticizer causes a rise in creep and shrinkage cracks and greater segregation. The workability of SCC is enhanced by the inclusion of filler and fly ash, which also enhances the mortar volume (Khaloo et al., 2014). A mixture design, which is connected to the flowability, structural qualities, and durability of in-service concrete mixture, is comparable to this and is the most crucial component in the manufacture and application of concrete (Shi et al., 2015).

In comparison to traditional concrete, hardened SCC has comparable mechanical characteristics (Bouzoubaâ & Lachemi, 2001). Considering that SCC is brittle, it would be wise to utilize materials that can solve this issue. Concrete that contains fibers is much less brittle and less likely to fracture (Khaloo & Afshari, 2005). SCC characteristics have been researched in relation to fixing workability issues with regular concrete, namely the low slump value (Wang & Li, 2005). Cement should be added in greater quantities, aggregate should be reduced, and concrete additives should be used to create this kind of concrete mix and improve the flow ability (Ferrara et al., 2007). On the other hand, adding more cement will make the concrete brittle, which will cause the concrete to expose to fail and raise the cost of manufacture. By adding SF to SCC, mechanical characteristics, and durability will all be improved. Any cracks will also be bridged (Ahmad et al., 2022a; b). On the premise that cement replacement materials have identical qualities to cement, cementing materials may partially replace with cement, lowering the overall cost (Alabduljabbar et al., 2019).

By adding fibers to concrete, brittle fracture is considerably reduced and becomes ductile (Neves & Fernandes de Almeida, 2005). Fibers tend to maintain concrete's integration over extreme deformation by bridging between the sides of fissures, which avoids brittle failure. Fiber-reinforced concrete is used in many different places nowadays, including slabs, bridges, walkways, and tunnel portions (Khaloo & Afshari, 2005). It was discovered that introducing SF makes the SCC less workable. More precisely, intensifying this decrease means introducing fiber at a volume fraction of more than 2%. The material compressive strength (CS) was similarly reduced with the addition of SF, but its TS and flexural strength (FS) were increased. Additionally, the SCC beams' flexural toughness improved as SF content increased (Khaloo et al., 2014). Research that looked at how the length and shape of SF affected concrete and concluded that long-hooked end fibers performed better at wide fracture widths. The beginning and growth of the microcracks are postponed by the microfibers (Vandewalle, 2006).

Brief literature shows that different studies focus to improve the tensile capacity of SCC with the addition of SF and reported that SF could improve the tensile capacity of SCC and avoid undesirable brittle nature. However, the information is scattered, and a detailed review is required to collect the information on past research, current research progress, and future research direction on SF-reinforced SCC. Therefore, this review is carried out to compile the research already done by other researchers on SF-reinforced SCC. The main aspects of a review are the general introduction of SCC, fresh properties, namely slump flow, slump T50, L box, and V funnel, and strength properties such as compressive, tensile, and flexure strength. Furthermore, failure modes of SF-reinforced SCC are also reviewed.

2 Fresh Properties

2.1 Slump Flow

The slump flow test detects the flowability of SCC. When there are no impediments, the deformability of SCC horizontal free flow (slump flow) is assessed. The procedure is quite similar to the procedure for determining concrete's slump. The distinction is that slump flow is measured as the diameter of the spread concrete in two perpendicular directions as opposed to the height loss. Concrete has a greater capacity to fill formworks when the slump flow is higher. The period needed for the concrete to expand to a diameter of 500 mm during a slump flow test reflects the concrete's viscosity and stability. Greater fluidity or a lesser workability loss is indicated by a shorter time (Gencel et al., 2011). The slump T500 test without aggregate segregation along the borders of the spread-out takes place in the range of 2.2–3.5 s and slump flow widths of 600–700 mm. Consequently, it may be said that all concrete mixes fall within the limit of SCC as predicted, adding fibers decreases SCC slump flow, increasing the probability of obstruction. In general, adding fibers reduced the SCC viscosity because fibers prevent clumps from freely moving (Madandoust et al., 2015). Figs. 2 and 3 show slump flow and slump T500 of SCC with the addition of SF, respectively.

SF with hooked ends that were 30 mm long was utilized by Liao et al. to create SCC with a 600 mm slump flow (Liao et al., 2006). All SCCs show positive findings between 550 and 800 mm, which is a sign of good deformability. To prevent segregation, all mixtures, in other words, required sufficient deformability under their own weight and a reasonable viscosity (Gencel et al., 2011). According to the study, the slump flow diminishes with increasing fiber concentration, notably over 0.75% SF. The slump flow for the concrete blend with 1.25% fiber dropped under the minimum requirement of 600 mm. So, to improve workability, the water–cement ratio and powder content was both slightly raised (Iqbal et al., 2015b). According to Dieb et al., using the greatest SF dose resulted in a decreased slump flow of roughly 12%. (0.52%). A change in admixture dose is necessary if the slump value must be unchanged (El-Dieb, 2009). The droop flow diminishes as the fiber rises, particularly at 0.75% SF. The slump flow for the concrete blend with 1.25% fiber dropped under the minimum threshold of 600 mm (Iqbal et al., 2015b). A study demonstrates that adding 0.25% hooked end SF to SCC decreased the slump flow by 50 mm; however, adding 0.5% of these fibers resulted in a much greater slump flow reduction of 220 mm (Torrijos et al., 2008).

According to the study, no segregation of aggregates was seen in any of the mixes towards the edge of the spread-out concrete, and the slump flow diameter of the mixes ranged from 560 to 700 mm (Sahmaran & Yaman, 2007). According to (Rambo et al., 2014), the slump flow diameters with 0.5 and 1% addition of SF in SCC were 625–750 mm and 620–720 mm, respectively. Each value fell within the boundaries set by EFNARC (EFNARC, 2002). In contrast, the research found that the flow velocity of SCC dropped with the addition of SF (0.5–2% by volume), and as a result, it cannot be deemed an acceptable combination for divinely reinforced portions since passing through it was impenetrable (Gencel et al., 2011).

Additionally, T500 values raised as coarse particles' maximum size increased. Greater energy loss occurs during the movement of concrete containing bigger aggregate particles, especially when there are more fibers present (Madandoust et al., 2015). The largest increase in slump flow time (T500) was reached when silica fume concentration was increased from 7 to 14% in reinforced self-compacting mixes with a fiber content of 0.75%. This

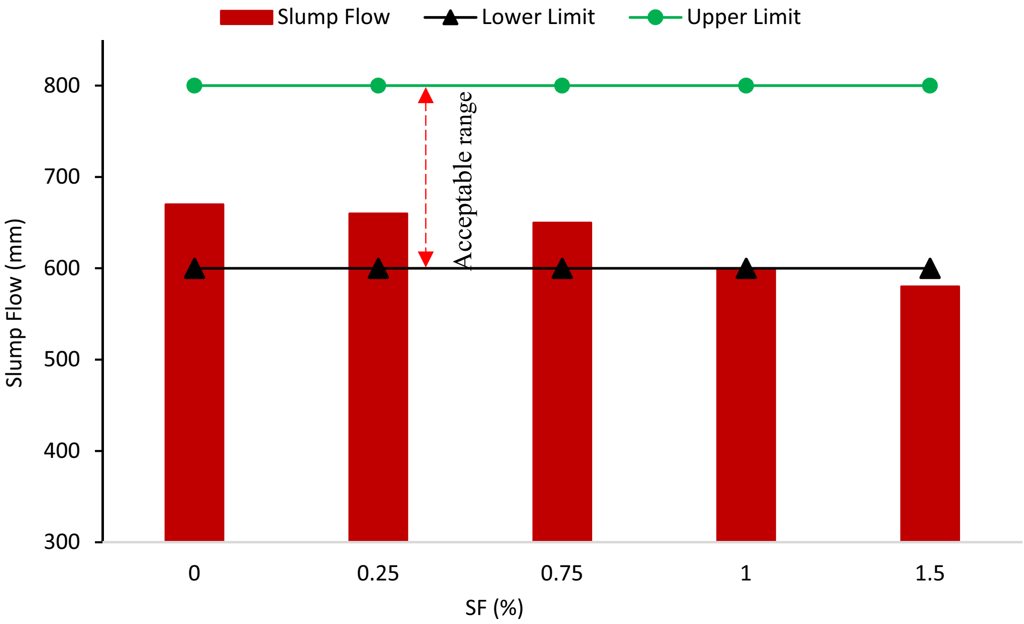

Fig. 2 Slump flow (Saba et al., 2021)

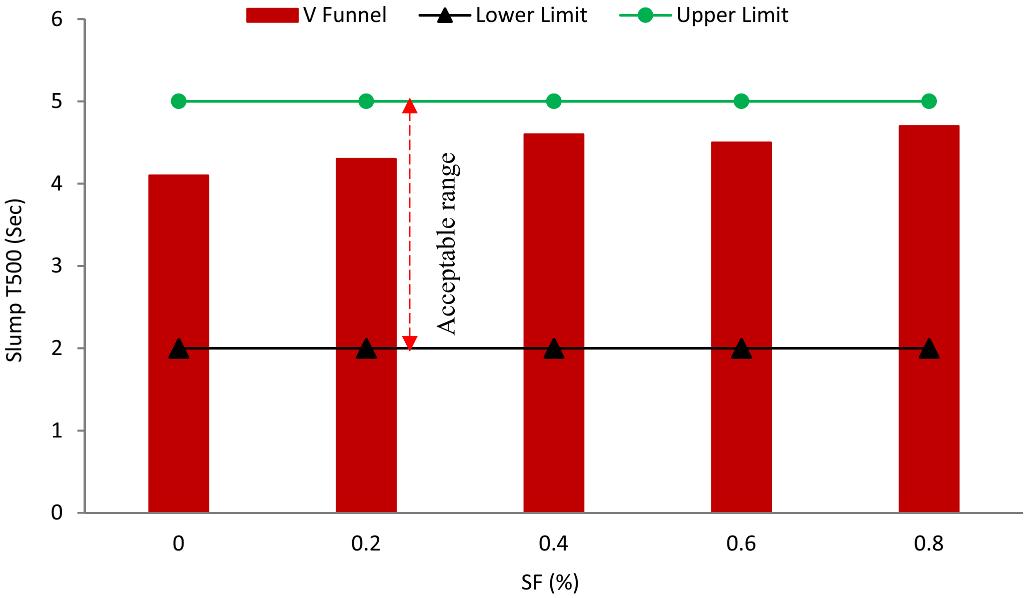

Fig. 3 Slump T500 (Gencel et al., 2011)

was the result of substituting cement with silica fume (about 25%). Therefore, the use of silica fume and SF further prolonged the slump flow time (T500). The sample containing 0.75% fiber and 14% silica fume had the highest T500 rise when compared to the control combination (Mastali & Dalvand, 2016). The amount of fiber content in the concrete mix cause to decrease in the flow, which occurs when fibers with hooked ends force concrete particles to jam during flow. Workability was shown to diminish as the amount of SF increased (Siddique & Kaur, 2016).

2.2 V Funnel and L Box Ratio

SCC capacity for the filling was assessed using V-funnel testing. The amount of time it took to flow SCC through the device during the test was recorded for flowability. The EFNARC (2002) standard specifies that test time values should fall between 6 and 12 s to get satisfactory characteristics in freshly poured SCC. In accordance with the advice of EFNARC (2002), an L box exam was administered to gauge their aptitude for passing. This test is used to assess the concrete's filling capacity's obstruction. The EFNARC standard requires the filling ability, which is calculated as the ratio of the height of the concrete in H_2 at one end to H_1 at the outlet of the L box (H_1/H_2). This ratio (H_1/H_2) should be in the range of 0.8–1.0, to show the slope of the concrete while at rest (EFNARC, 2002). Figs. 4 and 5 show the V funnel and L box ratio of SCC with the addition of SF, respectively.

Higher SF inclusion in the mix results in a deterioration in the SCC mixes workability. This indicates that the amount of SF utilized in the concrete mix has an inverse link to how well the SCC mixes function (Ghorbani et al., 2020). The time needed to empty the V funnel increased due to increased friction between fibers and aggregates as well as friction between fibers themselves. With the addition and percentage of fiber content in the mixes, V funnel and flow time values increase (Gencel et al., 2011).

A study concluded that for mixes with 0, 0.25, 0.75, and 1.0% fibers, correspondingly, the V-funnel value increased with fiber addition, and the V-funnel times were in the range of 8–13 s. The initial time was quite short, which was attributed to the concrete's greater paste volume and lack of fiber content. However, the impact of fibers on aggregates, which creates obstruction and, therefore, exhibits poorer filling capacity, is what is responsible for the trend of increased V-funnel times (longer v-funnel time). Therefore, increasing the number of SF by 0.25%, 0.5%, 0.75%, and 1.0% causes the V-funnel flow time to increase by 11%, 38%, 50%, and 63%, respectively (Saba et al., 2021). According to research, adding more SF to SCC mixtures causes the friction between the SF and aggregates to increase. As a result, it takes longer to discharge the V funnel (Ghorbani et al., 2020). The sample of SF at 0.9% showed the greatest decrease in slump flow diameter and greatest increases in T50 and V-funnel time in SCC. In certain ways, fibers improved the concrete's surface hardness, which subsequently reduced when fiber volume was raised. The concrete's uniformity was excellent in all mixtures,

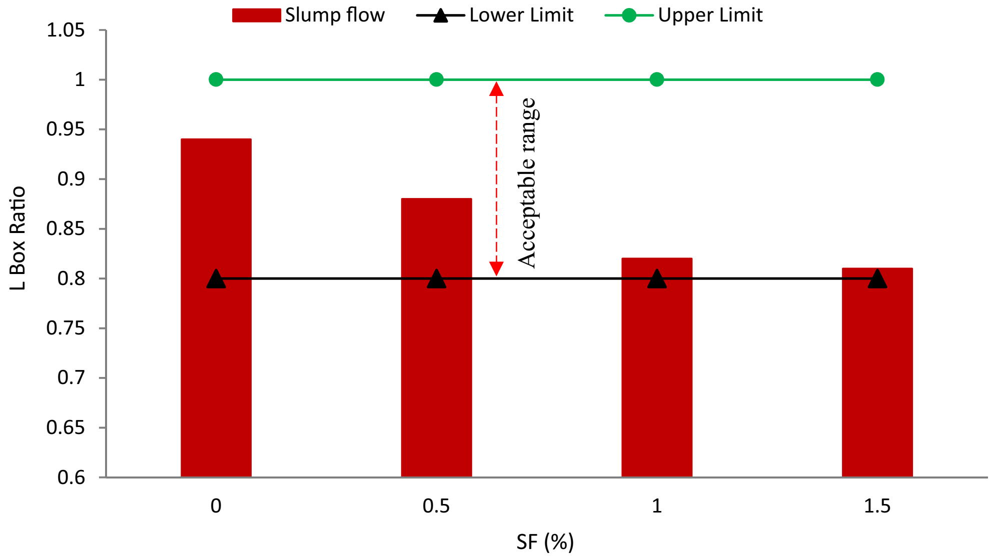

Fig. 4 L box ratio (Rao & Ravindra, 2010)

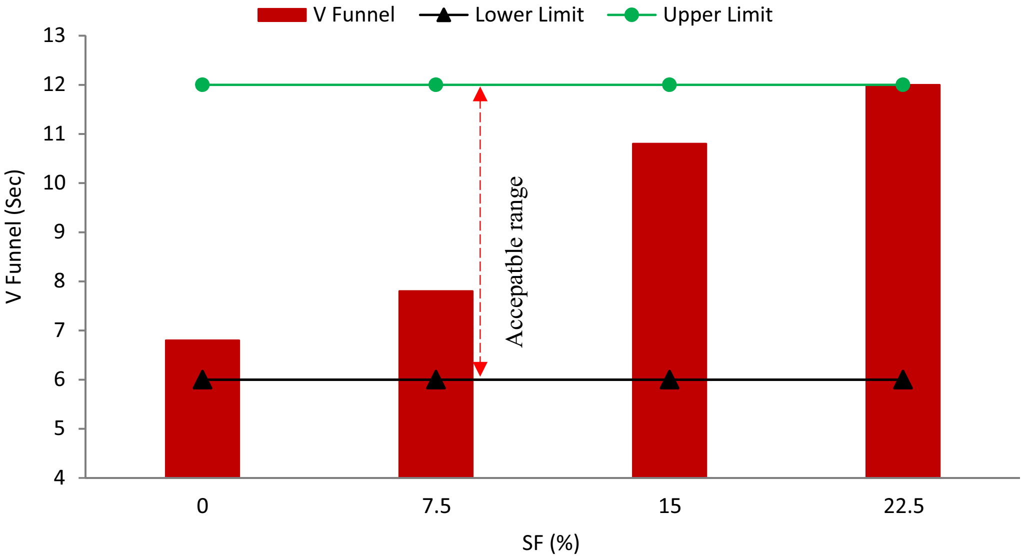

Fig. 5 V funnel (Ghorbani et al., 2020)

although somewhat diminished as the proportion of fiber increased, (Sanjeev & Nitesh, 2020). Fly ash, according to a study, aids in the equal distribution of fibers during blending. Fly ash granules that are roughly spherical have sliding impacts on fresh concrete, reducing friction force and improving flow and compaction (Gencel et al., 2011).

According to the investigation, adding silica fume to self-compacting mixes at a rate of between 7 and 14% results in the greatest possible increase in V-funnel time (about 25%). Furthermore, silica fume and recycled SF added together resulted in the largest increase in V-funnel time with a rise of around 85% for specimens containing 0.75% fiber and 14% silica fume in comparison to the control mixture (Mastali & Dalvand, 2016). As fiber content is added to the mixtures, the blocking ratio decreases. All mixtures that meet the SCC blocking ratio approval threshold (less than 0.8), except mixtures with 1% fiber content (Saba et al., 2021). This reduced blocking ratio could be caused by friction and intermeshing that occur along with the inclusion of SF (Borhan et al., 2020). These results imply that finer materials would fulfill the ERNARC (EFNARC, 2002) recommended flowability standards at a greater replacement rate. Table 1 shows the summary of fresh properties of SCC with the addition of SF.

3 Strength Properties

3.1 Compressive (CS)

Fig. 6 and Table 2 show the compressive strength (CS) of SCC with the addition of SF. Most researchers noted that SF does not improve the CS of SCC. A decrease in the workability of the concrete may be the cause of a loss of strength. Increasing the amount of SF causes the workability of concrete to decline, which in turn causes

Table 1 Summary of flow and passing ability of SCC reinforced with steel fiber

Refs.	Steel fiber percentages (%)	Additional materials	Length (mm)	Water–cement ratio	Slump (mm) (600–800)	Slump T500 (Sec) (2.0–5.0)	V funnel (Sec) (6.0–12)	L box ratio (0.8–1.0)	Remarks
Madandoust et al., (2015)	0–1.0	–	50	0.45	–	2.2–2.6	–	–	Slump T500 Within the limit
Iqbal et al., (2015b)	0–1.25	–	13	0.58	790–630	5–9	–	–	Slump T500 does not fall within the limit
Rao and Ravindra (2010)	0–1.5	Fly ash	13.8	0.43–0.31	715–650	3.3–4.5	7.1–9.8	0.94–0.81	All mix within the limit
Khaloo et al., (2014)	0–2.0	–	20.6	0.48	–	2.0–3.4	4.5–19	0.84–0.65	V funnel and L box are not in limit
El-Dieb (2009)	0–0.52	–	25	0.23	776–700	–	–	–	Slump flow within the limit
Gencel et al., (2011)	0–0.8	Fly ash	30	0.4	769–582	4.1–4.7	14.1–20.7	–	V funnel and slump flow are not within the limit
Mastali and Dalvand (2016)	0–0.75	–	40	0.44	630–580	5–7	–	–	Slump flow and slump T500 are not in limit
Alabduljabbar et al., (2019)	0–2.0	–	20	–	680–670	–	8.0–7.0	0.80–0.86	All mix within the limit
Saba et al., (2021)	0–1.0	Silica fume	30	0.40	670–580	5–7	-	0–1.0	All mix not within the limit
Ghorbani et al., (2020)	0–1.65	–	30	0.50	750–550	–	6.8–12.0	–	Slump flow not in limit
Iqbal et al., (2015a)	0.5–1.25	–	13	0.58	710–630	7–9	–	–	Slump T500 does not fall within the limit
Li et al., (2021)	0–1.0	–	35	0.35	700–645	2.6–9.8	–	–	Slump T500 does not fall within the limit
Siddique and Kaur (2016)	0–1.5	Fly ash	30	0.45	720–650	–	7.0–12.0	0.98–0.80	All mix within the limit
Sanjeev and Nitesh (2020)	0–0.9	–	35	0.36	550–270	3.2–8.4	4.3–11.3	–	Slump flow and slump T500 are not in limit

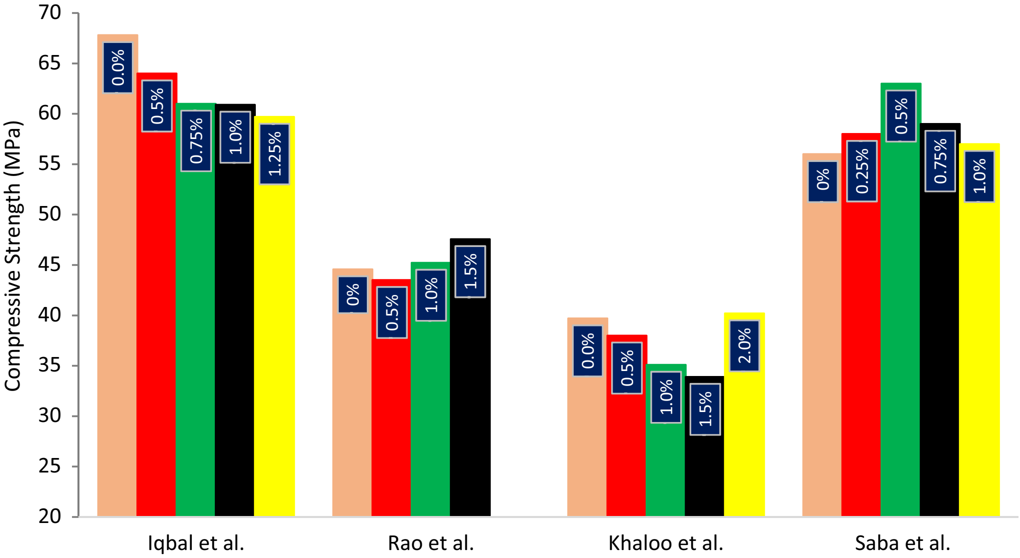

Fig. 6 Compressive strength: Source (Iqbal et al., 2015b; Khaloo et al., 2014; Rao & Ravindra, 2010; Saba et al., 2021)

the compaction levels of vibrated concrete to decrease (Mohammadi et al., 2008). When no compaction technique is used for molding SCC mixes and just their own weights are used to compress them, this problem might be emphasized. In this context, one should exercise caution when using these kinds of SCCs for substantially reinforced structural sections due to the larger drop in CS at higher SF volume fractions.

The results showed that the maximum CS recorded for the reinforced mixture was associated with the recycled SF volume of 0.5%, but the maximum TS and FS were noted in the reinforced samples with the recycled SF volume of 0.75% (Aghaee et al., 2015). According to research, adding SF to concrete may enhance its mechanical qualities. However, a higher fiber content does not necessarily result in a rise in the improvement in CS (Gencel et al., 2011). The researcher noticed a negligible increase in the CS values when silica fume and SF were added at the same time. The CS is increased by 2.6% when 0.25, 0.50, 0.75, and 1.0% of SF with 20% replacement silica fume is added relative to the control batch. Due to the bridging capacity provided by fibers, adding SF (up to 0.50%) marginally enhances the CS, however, introducing more fibers causes the CS to drop (Saba et al., 2021). CS usually declines a little bit as SF content rises. In this investigation, increasing the amount of SF from 0.5 to 1.25% resulted in a 7% loss in CS (Iqbal et al., 2015a).

The research looked at how hooked-shape SF affected the rheological and mechanical characteristics of SCC with various strength classes of 40 MPa and 60 MPa and utilizing four different SF volume fractions of 0.5–2%. The findings show that the presence of SF decreases the workability of SCC, which in turn leads to a drop in vibrated concrete's compaction levels. This decreases the CS in both strength classes (Khaloo et al., 2014). Atis et al., conclude that the addition of SF to concrete have little to no effect on its CS (Atiş & Karahan, 2009). The CS is unaltered by the insertion of SFs, according to study results utilizing fibers with lengths ranging from 22 to 44 mm; however, compression failure mode changes from brittle to ductile with the specimens retaining their integrity throughout the test (Olivito & Zuccarello, 2010). According to findings, the insertion of SF reduced the CS of high-strength SCC by around 7.5% (Khaloo et al., 2014). Song et al. noted that CS rises as SF content rises to 1.5%volume fraction before dropping down somewhat to 2%, although it still stands at 12.9% more than the CS of concrete without fibers (Song & Hwang, 2004). The research found that adding 0–2% short SF with a 13 mm length and 65 aspect ratio increased the CS of various concretes by 19–42% (Ma et al., 2013). The CS nonetheless decreased by 6.3 and 9.5%, respectively, with further additions of SF (0.75 and 1.0%). This decrease is related to SCC mixes' decreased workability and filling capacity, which caused them to lose their self-compacting capabilities (Mardani-Aghabaglou et al., 2013).

According to findings (El-Dieb, 2009), the most notable testing finding is the concrete's failure mode significantly changes as SF is added to the mix and as the volume percentages of SF rise. Fig. 7 shows the cube specimens for the various mixtures following failure. The cracking changes from an abrupt explosive failure that destroys the specimen to a more ductile failure in which the specimen

Table 2 Summary of strength properties of SCC reinforced with steel fiber

Refs.	Steel fiber percentages (%)	Additional materials	Length (mm)	W/C	Aspect ratio	Days	Optimum (%)	Compression strength (MPa)	Flexure strength (MPa)	Split tensile strength (MPa)
Madandoust et al., (2015)	0–1.0	–	50	0.45	62.5	14 28 90	1.0	− 14.8% − 10.0% − 11.1%	– + 28.5 –	+ 25.0% + 33.3% + 45.1%
Iqbal et al., (2015b)	0–1.25	–	13	0.58	–	28	1.25	− 11.9%	+ 105.4%	+ 36.5%
Rao and Ravindra (2010)	0–1.5	Fly ash	13.8	0.43–0.31	0–35	7 28 56	1.5	− 0.34% + 6.70% + 4.04%	+ 14.4% + 11.8% + 8.5%	+ 12.1% + 4.45% + 7.50%
Khaloo et al., (2014)	0–2.0	–	20.6	0.48	20	7 28 91	2.0	− 23.8% − 18.63% − 15.01%	– + 46.0% –	+ 25.0% + 28.4% + 28.0%
El-Dieb (2009)	0–0.52	–	25	0.23	50	7 28	0.52	+ 14.45% + 23.00%	–	+ 105.71% + 107.31%
Gencel et al., (2011)	0–0.8	Fly ash	30	0.4	60	28	0.8	0.00%	–	+ 18.18%
Mastali and Dalvand (2016)	0–0.75	–	40	0.44	80	28	0.75	+ 15.7%	+ 26.6%	+ 22.8%
Alabduljabbar et al., (2019)	0–2.0	–	20	–	100	7 28 91	2.0	+ 22.3% + 17.2% + 13.3%	– + 1.96% –	– + 104.3% + 91.4%
Saba et al., (2021)	0–1.0	Silica fume	30	0.40	120	28	1.0	+ 1.78%	+ 54.7%	+ 57.1%
Ghorbani et al., (2020)	0–1.65	–	30	0.50	60	7 28	1.65	− 3.12% − 1.51%	+ 26.98% + 28.57%	+ 50.00% + 44.44%
Iqbal et al., (2015a)	0.5–1.25	–	13	0.58	-	7 28	1.25	− 5.76% − 6.69%	– + 18.48%	– + 72.39%
Abbas et al. (2021)	0–2.0	–	15	0.43	60	28	2.0	+ 40.0%	–	+ 16.67%
Miao et al. (2003)	0–1.5	–	30	0.32	60	7 14 28	1.5	+ 16.66% + 11.42% − 11.11%	+ 50.00% + 45.71% + 100.0%	–
Li et al., (2021)	0–1.0	–	35	0.35	–	7 28	1.0	− 8.57% − 5.45%	– + 66.15%	–
Siddique and Kaur (2016)	0–1.5	Fly ash	30	0.45	50	7 28	1.5	–	+ 55.55% + 45.45%	+ 66.66% + 50.00%
Sanjeev and Nitesh (2020)	0–0.9	–	35	0.36	46.66	28	0.9	+ 20.20%	+ 21.30%	+ 8.83%

W/C water–cement ratio

− Decreased

+ Increased

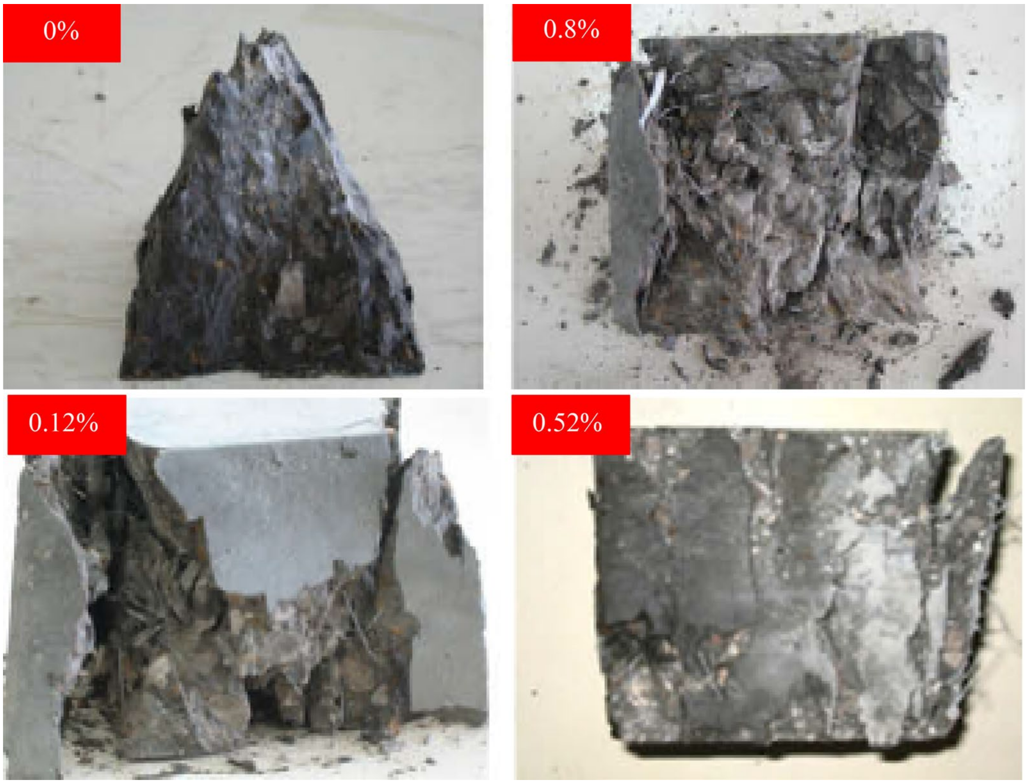

Fig. 7 Failure of cubes under compressive (El-Dieb, 2009)

is still intact. It is possible to see that specimens are more intact as the fiber volume percentage rises. This is a result of the ability of the fibers to avoid unexpected abrupt collapse of the concrete and their tight connection with it.

Self-lightweight compacting concrete combined with SFs has excellent integrity of compressive failure morphology following compression fracturing. The sample took a long time to break under the influence of the compression force, and the cracking sound was loud and unpleasant. The position of the crack opening also revealed the SF that connects the broken surface (Li et al., 2021). It was determined that fiber bridging mechanisms across the fracture surfaces allowed SF to convert from brittle to ductile compression failure (Caggiano et al., 2012). This occurred as a result of the hoop effect, which limited the cracking and transverse expansion of the concrete specimen, produced by the three-dimensional network structure of fibers.

3.2 Tensile Strength (TS)

Fig. 8 and Table 2 show the results of the tensile strength (TS) of SCC with the addition of SF.SF bridge the space between the two sides of the fracture formation to increase the TS. Adding hooked end fiber increased the TS (Haddadou et al., 2014). When compared to the control mix of SCC, the increase in TS with 0.5%, 1.0%, and 1.5% fiber content was 11.6%, 32.1%, and 38.7%, respectively. SF ability to stop fracture advancement is thought to be the cause of the improvement in strength. The presence of fibers prevents the formation of internal microcracks, which increases the TS. Additionally, the enhanced bonding of the fiber–matrix, which is supplied by SF with hooked ends, increases pull-out strength and yields a high rise in strength as a result of an increase in fiber content (Siddique & Kaur, 2016). According to TS tests, a 0.75% increase in SF content results in a rise in TS of around 18% (Iqbal et al., 2015a). In comparison to standard SCC without fibers, the researchers found that using 1.5% SF by volume increased FS and TS by around 33% and 24%, correspondingly (Siddique & Kaur, 2016).

The high parameters of SFs, such as aspect ratio, modulus of elasticity, and TS of fiber, are responsible for the improvement in concrete TS because they allow SF to bridge concrete microscopic cracks effectively (Tabatabaeian et al., 2017). When the proportion of SF increases, the ductility in the region of elastic deformation increases which results in more TS (Ali et al., 2020a; b). According to the finding, there is a definite rise in the TS of the concrete mixes with an increase in SF. Results indicate that increasing the SF content of the tested samples from 0.5%

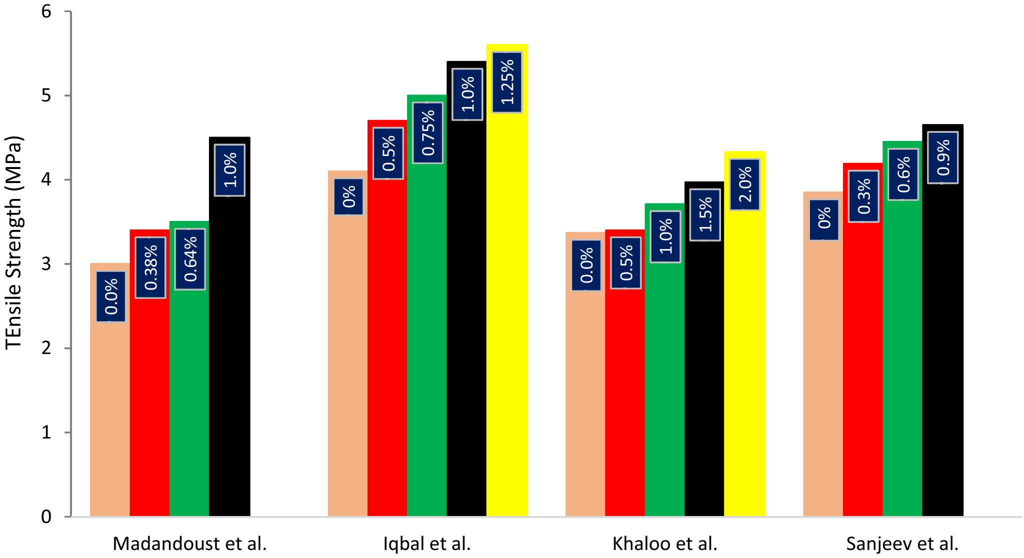

Fig. 8 Tensile strength: Source (Iqbal et al., 2015b; Khaloo et al., 2014; Madandoust et al., 2015; Sanjeev & Nitesh, 2020)

to 1.25% increases their TS by around 18% (Iqbal et al., 2015a).

A study found that the amount of SF in hardened concrete had a variety of effects, including increasing SF content from 0.5% to 1.25%, which decreased CS to 7%and 18% and enhanced TS and FS to 70%, respectively (Sun et al., 2015). Higher content may, thus, contribute to improved cracking processes as well as improved flexural and TS. The method by which SF bridge the space between two sides of a crack opening is unquestionably relevant to the strength improvement brought on by the presence of SF. The fibers help concrete gain more TS by preventing the emergence of interior microcracks. Additionally, the form of the SF and increased pull-out strength may be credited for better fiber–matrix bonding, which can be seen as crucial to raising TS (Madandoust et al., 2015).

The failed specimen of the tensile test is shown in Fig. 9. As shown in Fig. 9a, the fiber was entirely pulled out of the matrix on both sides, and a piece of the matrix was still connected to the SF. It illustrates the SF and matrix's strong bonding behavior. The quantity of fiber was smaller for the same percentage of the fiber content in recycled SF (extracted from tires) compared to manufacturing SF because of the difference in density. This difference in strength may be the result of SF's larger length, uniform undulating length, and high stiffness compared to recycled SF, which provided greater bridging length and substantially increased fracture resistance (Mastali et al., 2018). According to Sanjeev et al., the collapse in unreinforced concrete happened rapidly; however, in fiber-reinforced concrete, the fibers show many fractures and the concrete has a higher energy absorption than unreinforced concrete, thus the collapse is not brittle (Sanjeev & Nitesh, 2020).

3.3 Flexural Strength (FS)

Fig. 10 and Table 2 show that the flexural strength (FS) of SCC improved with the addition of SF. A study claim that although concrete CS was decreased with the addition of SF, but its TS and FS were enhanced. Additionally, the SCC beams' flexural toughness improved as the amount of SF increased (Khaloo et al., 2014). Similar studies claim that fibers improved the flexural capacity of concrete (Ding et al., 2021; Yadav et al., 2020; Łach et al., 2021; Mashrei et al., 2018; Turlapati & Vineel, 2020).

According to findings (Olivito & Zuccarello, 2010), adding SF to concrete boosts its ductility, initial crack strength, and FS while having less of an impact on the CS. Additionally, it was determined that concrete displays hardening behavior with longer fibers whereas softening behavior is produced by the insertion of shorter SFs. The highest value of FS is reached with an SF content of 3.5%. FS of concrete increases as SF content increases. FS is reduced when fiber content is increased more than optimum percentages (Jatale & Mangulkar, 2013).

Concrete TS increased between 19 and 98.3%, while its FS increased between 28 and 266.6% when SF between 0.5 and 2% was added (Song & Hwang, 2004). Concrete reinforced with 1.5% SF showed increases in TS of up to 71% and FS of 30–60% (Atiş & Karahan 2009). It was found that the FS increased with the quantity of SF in concrete, and this was due to the SF random distribution in SCC, which controlled the cracks and stitched them,

Fig. 9 Failure of SF concrete under tensile loading (Simalti & Singh, 2021)

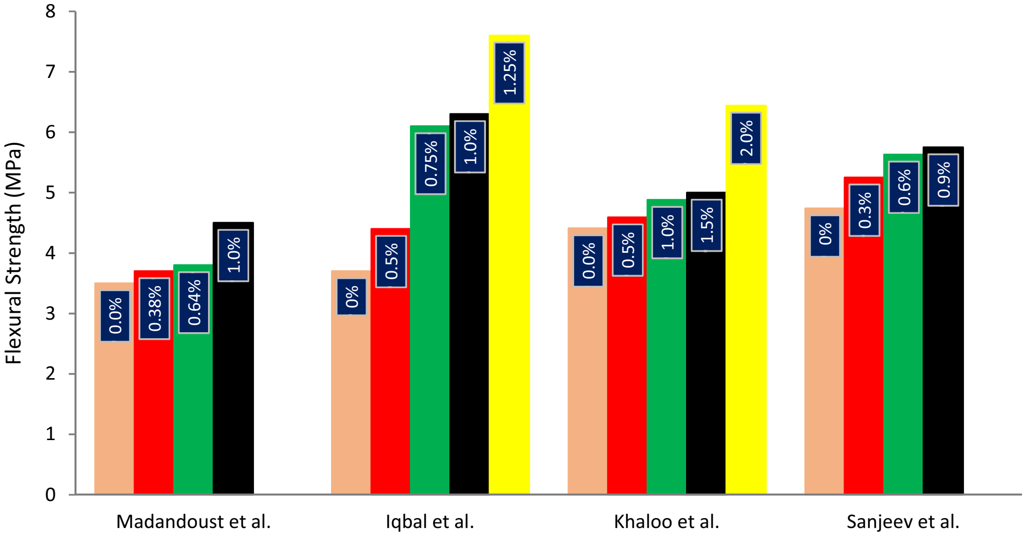

Fig. 10 Flexural strength: Source (Iqbal et al., 2015b; Khaloo et al., 2014; Madandoust et al., 2015; Sanjeev & Nitesh, 2020)

enhancing the load-bearing capability of tested beams (Gencel et al., 2011). The FS was evaluated throughout the ranges of 0–15% silica fume, 0–1% fiber steel, and 65–80 aspect ratios. The greatest results were achieved at 15% silica fume, 1% fiber steel, and 85 aspect ratios, correspondingly (Saba et al., 2021). Additionally, increasing the volume percentage of the fibers by up to 1.0% might somewhat improve the bending post-cracking strength (Koksal et al., 2008). Although the inclusion of SF might prevent the start and spread of fractures and increase the FS of concrete, it should also be taken into account that the addition of SF would make the concrete matrix less compact, which would negatively impact the FS (Li et al., 2017). Owing to improved concrete qualities that lessen the brittleness of SF SCC, which is a consequence of an increase in TS attributed to the prevalence of SFs, the elastic modulus also increases as the proportion of SF increases (Ali et al., 2020a; b).

Concrete FS increases as the percentage of SF increases, reaching its maximum value at 3.5% SF content. FS is reduced when fiber content is increased more (Jatale & Mangulkar, 2013). With a rise in SF content from 0.5%to 1.25%, the FS significantly improves, by about 70%, while the first crack load only slightly rises, by about 11% (Iqbal et al., 2015a). The use of SF with hooked ends results in enhanced fiber–matrix mortar binding, which boosts FS in specimens containing SFs. SFs' ability to release fracture energy in the vicinity of crack tips, which is required to extend crack growth by transferring energy from one side to another, is largely responsible for this performance. When tensile stress is transmitted to fibers, the transferred load stops macro fractures from spreading and significantly improves the material (Rambo et al., 2014).

The broken beams shown in Fig. 11 demonstrate the ability of the fibers to bridge gaps and effectively increase the mechanical performance of reinforced concrete (Haddadou et al., 2014). According to the study, adding SF is crucial for converting SCCs' brittle failure state into one that is more ductile. Additionally, it may be inferred that shorter fibers in concrete serve as a bridge to lessen microcracks but have little impact on the post-peak behavior of load against displacement at the mid-span of the prism. The longer fibers do not significantly alter the load versus displacement curve of the prisms' post-peak response region, which leads to a high value of FS. However, the longer fibers do influence the creation of microcracks (Haddadou et al., 2014).

3.4 Elastic Modulus

Fig. 12 shows that the modulus of elasticity of concrete somewhat decreases as SF content increases, although this decrease is extremely tiny and the values essentially stay the same (Iqbal et al., 2015a).

According to one study, the elastic modulus was improved by increasing the volume percentage of glass fibers in SCC (SCC) from 0 to 1.5% (Atewi et al., 2019). According to the investigation, 0.25% fibers caused a 7% decrease in elasticity when compared to control concrete. Concretes made with glass fibers have a slightly lower modulus of elasticity than concretes made with banana fibers. This is because banana fibers have a higher elastic modulus than glass fibers (Kizilkanat et al., 2015). Results indicate that when SF concentration increases, there is a very minor fluctuation in the modulus of elasticity of concrete, but the cause of this variation is unclear, and the values stay essentially unchanged. The findings suggest that the inclusion of SF does not affect the modulus of elasticity (Iqbal et al., 2015b).

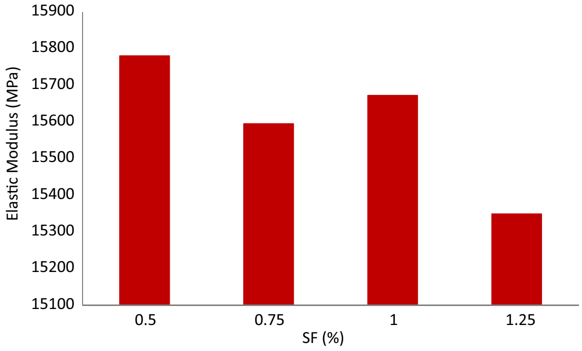

Fig. 12 Elastic modulus (Iqbal et al., 2015a)

Fig. 11 Bridging effect of fiber (Sanjeev & Nitesh, 2020)

The study also found that SCC-containing fibers had an approximately 10% greater elasticity modulus than plain SCC (Basheerudeen & Anandan, 2015). The results of the laboratory experiments demonstrate that adding fibers has no discernible effect on the concrete's modulus of elasticity. The concrete's elasticity modulus largely decreased with low fiber density (Beigi et al., 2013). The addition of fibers improves elastic modulus by 0.5–5%, and there is little difference between the elastic modulus values of plain concrete and concrete with 1% fibers (Ali et al., 2020a; b). A more thorough study is needed since there are often fewer studies on the elastic modulus of concrete accessible.

4 Durability

4.1 Rapid Chloride Ion Penetration

Adding steel fiber to SCC improves the amount of charge passed as the volume fraction of fiber increases. However, all mixtures comprising new steel fiber, recycled steel fiber, and control fall within the low to extremely low chloride ion permeability range. With values of 1140, 1227, and 1066.5 C at 28 days, Fig. 13 demonstrates the low chloride ion permeability of the steel fiber mixes of 0.5, 1.0, and 1.5%. However, at a later age of 90 days, all of the mixes, including the control mix, are within the range of extremely low chloride ion porosity. The corrosion that accumulated on the surface of the concrete in the SF samples, whether they were SCC or had a high fiber content, is seen in Fig. 14a, b. However, the portion of the fibers covered in concrete has not shown any deterioration. According to a study (Yehia et al., 2016), the volume proportion of fibers increased along with the total charge transmitted. This may likely be attributed to the electrical conductivity of SFs, and all of the mixtures had extremely low limits of chloride ion penetration.

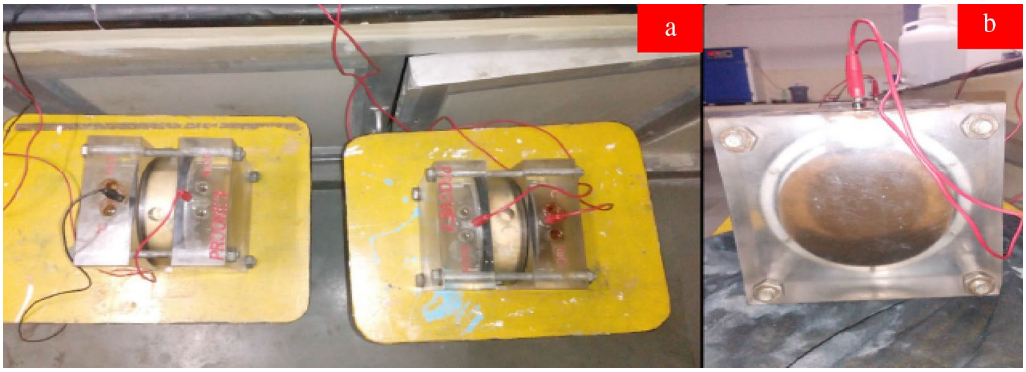

Fig. 13 Rapid chloride ion penetrability (Simalti & Singh, 2021)

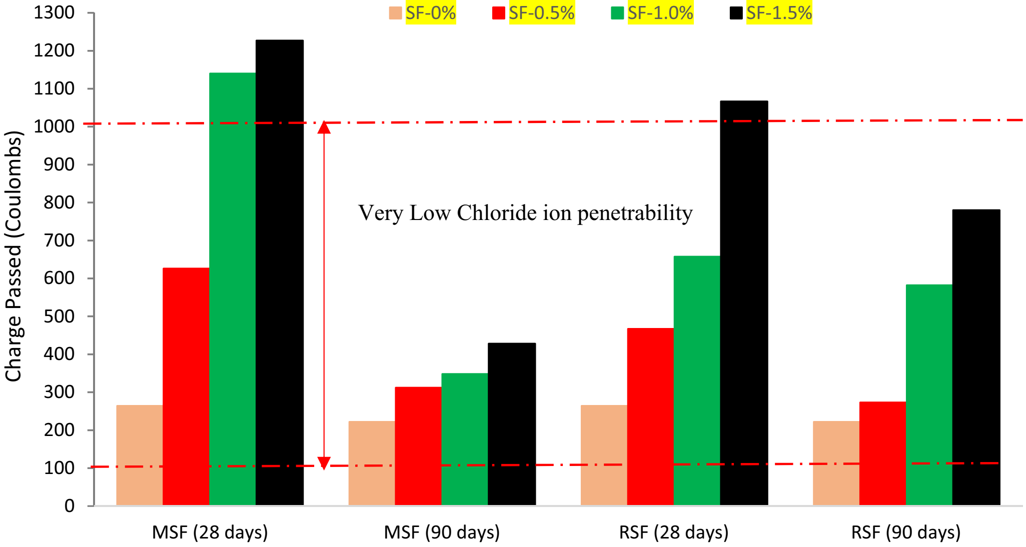

Fig. 14 Sign of corrosion (Simalti & Singh, 2021)

The development of steel fires in SCC had no impact on the material's ability to withstand chloride penetration. Only a little rise in chloride concentration was seen in the mixture with a volume percentage of 0.7% fiber (Anastasiou et al., 2014). It was discovered that all SCC mixtures had extremely high resistivity values, which suggested very effective protection for steel reinforcement against corrosion. In comparison to the control mix, the maximal chloride ion penetration resistance was 766 Coulombs when SF concentration was 1.5% by volume (Siddique & Kaur, 2016). Even with the inclusion of SFs, research supported their findings that the rate of chloride diffusion was limited owing to the relatively low matrix porosity (Corinaldesi & Moriconi, 2004). The research found that the total charge flowing increased as the amount of SF increased, probably due to the fiber's electrical conductivity. All of the mixtures also exhibited extremely low levels of chloride ion permeability (El-Dieb, 2009).

4.2 Porosity

The findings indicate that the porosity decreased with aging because of increased or improved hydration and pozzolanic reaction rates. The lowest porosity was attained in the control mix but mix SCC4 (1.5% SF) increased porosity relative to the reference mix by roughly 6%. As seen in Fig. 15, the permeability of concrete gradually decreases as it ages. Research (El-Dieb, 2009) found that no significant change in porosity was seen following fiber insertion after examining specimens at ages 28, 56, and 91 days. This may be because the microstructure of cement paste has a major role in the progression of water. Since the cement paste is roughly the same for all the combinations, the variances were caused by the sensitivity of the experiment. Research (De Oliveira et al., 2013) further shows that the SF fraction has no appreciable impact on the porosity of SCC with fibers.

4.3 Ultra-sonic Pulse Velocity (UPV) and Rebound Hammer Test

The uniformity of plain concrete may be decreased by adding fibers. Fig. 16a, b provides the traditional concrete and SCC UPV and rebound numbers. According to the relevant standard codes, the UPV values and rebound numbers are used to grade concrete. The SF concrete matrix's surface hardness was noted as a material surface. Additionally, the surface hardness of the glass fiber concrete was lower than that of SF-reinforced concrete and was rated as a good layer. In contrast to regular concrete, reinforced concrete often has a lower uniformity. As the amount of fiber rise, the UPV dropped. Concrete with SF has a lower UPV than concrete with glass fiber (Sanjeev & Nitesh, 2020). In comparison to traditional reinforced concrete, the reinforced SCC showed more homogeneity. The fiber-reinforced concrete matrix was rated as an acceptable layer since its surface hardness was less than that of RCC. Reinforced concrete has less uniformity than regular concrete. The study's uniformity was increased using reinforced concrete with a considerable fiber volume. Fiber-reinforced SCC had greater homogeneity as compared to reinforced vibrated concrete (Sanjeev & Nitesh, 2020).

The control mix obtained a maximum pulse velocity of 4.7 km/s, but the mix (1.5% SF) only managed a minimum

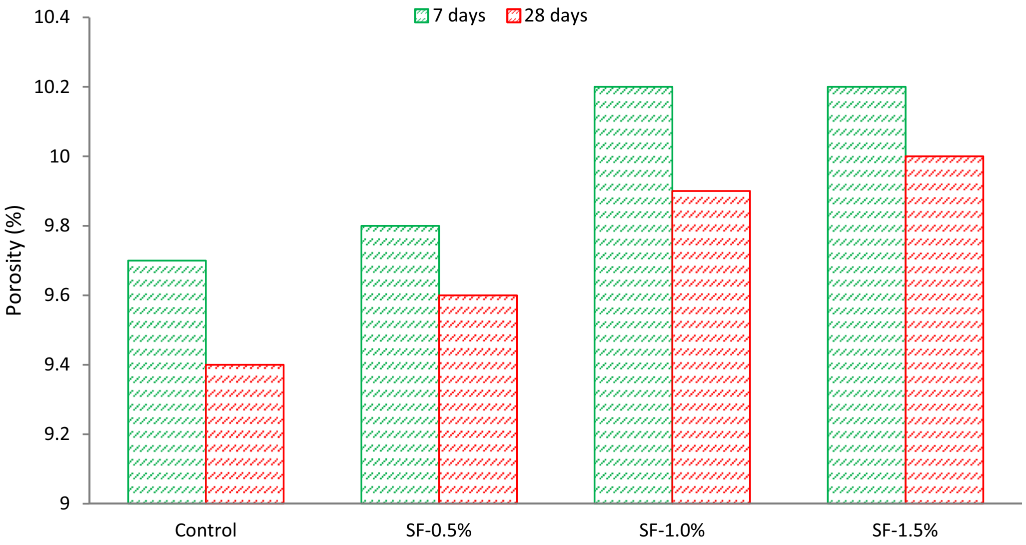

Fig. 15 Porosity (Siddique & Kaur, 2016)

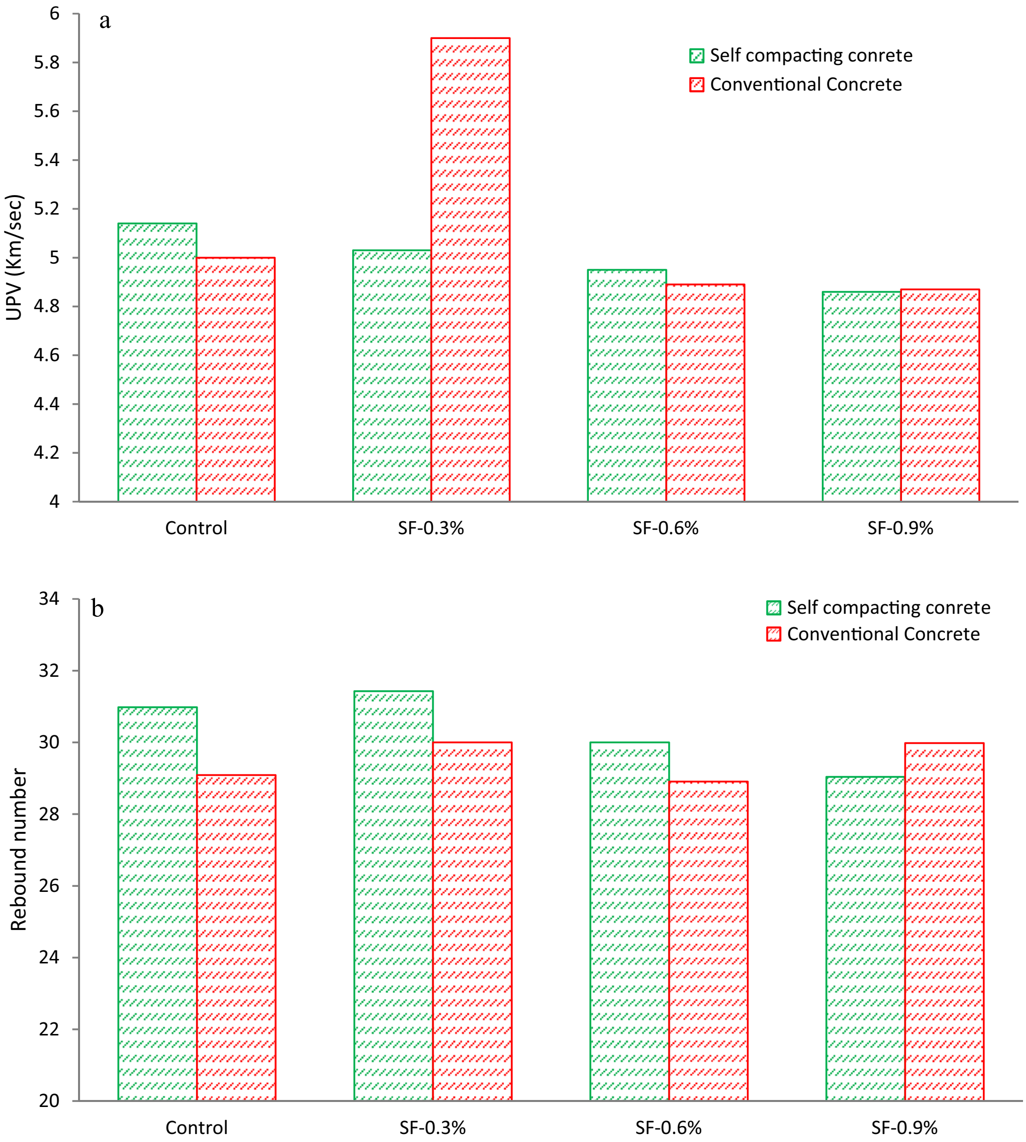

Fig. 16 **a** UPV and (**b**) Rebound number (Sanjeev & Nitesh, 2020)

pulse velocity of 3.9 km/s, which is 17% less than the control (Siddique & Kaur, 2016). In accordance with ASTM C597 (ASTM 2009), concretes are classified as excellent, good, questionable, poor, and extremely poor for pulse velocity values of 4.5 km/s and above, 3.50–4.50, 3.0–3.5, 2.0–3.0, and 2.0 km/s and below, respectively. Between pulse velocity values of 4.1 and 4.7 km/s, the lower border of excellent-grade concrete is located. At the age of 28 days, every concrete sample created for this study is of high quality.

The accessibility of voids in the mixes containing SF more so than in the control mix may be the source of the decreased pulse velocity, which will shorten the time needed for an ultrasonic wave to bypass (Gencel et al., 2011). Additionally, since the SF in cubes is randomly oriented, waves that pass through them may, to a limited degree, be diverted in different ways rather than traveling straight ahead to the other end of the cube. However, researchers (Sahmaran & Yaman, 2007) found that adding SF to SCC mixes did not affect the pulse velocity, in contrast. Acebes et al. (2011) concluded that the presence of SF reduced pulse velocity. The ultrasonic pulse velocity of mortar with long fibers decreased by around 8.3% in comparison to normal mortar.

4.4 Dry Shrinkage

Steel fiber (SF) had a considerable impact on drying and autogenous shrinkages. According to Fig. 17, drying shrinkages both linearly dropped as fiber content increased, and they roughly decreased at a rate of 170×10^6% more SFs. This is most likely due to the self-compacting fiber concrete having a greater paste content and being more sensitive to fiber content than regular fiber concrete. Research (Miao et al., 2003) indicates that the addition of fiber lowers the percentage of fractures. With 0.30% fiber, plastic shrinkage cracks were completely invisible (by volume).

In research, it was discovered that the dry shrinkage deformations of fiber concrete were less than those of the basic concrete without fibers, suggesting that they were more stable. By strengthening their bond with the concrete matrix and reducing dry shrinkage during the drying process, fibers may assist reduce shrinkage in concrete (Li et al., 2006). The most important feature of concrete fibers to limit shrinkage is fracture prevention, which has a substantial impact on fibers in concrete (Ahmad et al., 2022a, b; Barr et al., 2003). These findings are consistent with those made by other researchers who found that adding fibers to a composite may aid to lessen cracking brought on by dry shrinkage in a composite (Kaikea et al., 2014).

The addition of 0.10–0.25% fibers dramatically decreased the crack width as compared to the control sample. The fracture width shrank by 72–93% with the addition of fiber up to 0.25%. Shrinkage cracking is reduced by 50–99% by adding fibers up to 0.30% (Islam et al., 2016). Research also found that adding polypropylene fiber outperformed adding SF in terms of avoiding shrinkage cracking. Concrete's cracking area was decreased by 98% when polypropylene fibers were added at a concentration of 0.5% (Sivakumar & Santhanam, 2007). When contrasted to plain prepacked aggregate concrete specimens, it has been found that the dry shrinkage values of all prepacked aggregates of fiber-reinforced concrete samples with blended polypropylene fibers were much reduced up to 180 days. Fibers stop the development of microcracks on the concrete's surface, which stops the mobility of dangerous components in the sample. As a consequence, the adverse effects of dry shrinkage are minimized and the fracture density and size are decreased (Alrshoudi et al., 2020).

5 Elevated Temperature

Researchers investigated the effects of steel (1%), polypropylene (1%), and hybrid fibers (0.5% steel and 0.5% polypropylene) on the strength characteristics of concrete at high temperatures. For each test, the samples were heated at a rate of 5 degrees Celsius per minute to a range of temperatures (200, 400, 600, and 800). The compressive strength of fiber-reinforced concrete at various temperatures is shown in Fig. 18. The results showed that using heating temperatures (200, 400, 600, and 800 °C) for specimens with 1.0% SF and specimens with hybrid fibers (0.5% steel + 0.5% PP) had a compressive strengths greater than those of SCC specimens (without fibers). In terms of steel fiber, this rise is around 15, 42.8, 100, and

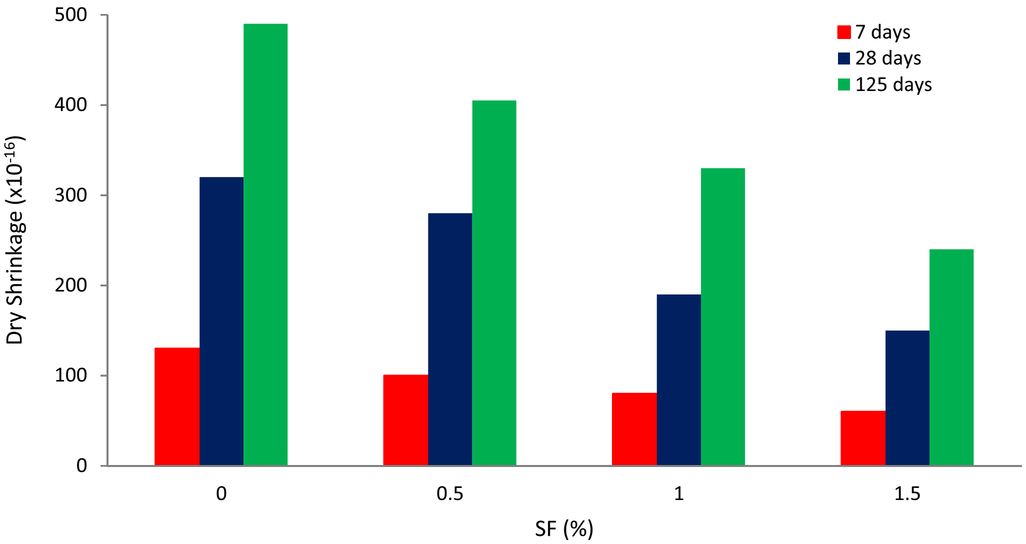

Fig. 17 Dry shrinkage: Source (Miao et al., 2003)

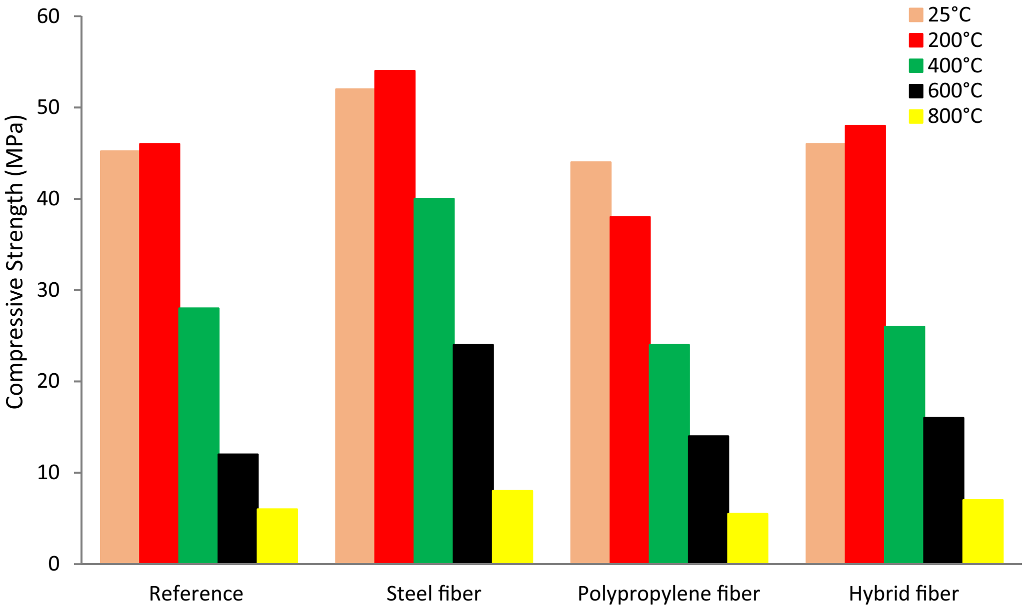

Fig. 18 Compressive capacity at elevated temperature (AL-Radi et al., 2021)

33%; in terms of hybrid fiber, it is 4.3%, 7.6%, 33.3%, and 16.7%. According to a study, reinforced concrete corbel's load-carrying ability and ductility are improved by steel fiber both before and after exposure to high temperatures (Abdulhaleem et al., 2018). When subjected to tensile stresses, steel fibers increase the SCC matrix's ability to bear loads, which accounts for the enhancement of the material's mechanical characteristics (AL-Radi et al., 2021). To minimize cracking and lessen the severe damage brought on by high temperatures, which may affect all mechanical qualities of concrete, steel fibers are utilized.

The impact of polypropylene, steel, and glass fibers on the mechanical and physical characteristics of SCC at high temperatures was studied by researchers (Boğa et al., 2022). By volume of concrete, the fibrous mixes included 0.1, 0.3, and 0.5% of polypropylene fiber, 0.1, 0.2, and 0.3% of steel fiber, and 0.1, 0.3, and 0.5% of glass fiber. The results show that the mechanical characteristics of SCC up to 600 °C were enhanced by the inclusion of steel or glass fiber (up to 0.5% by volume). However, when employing polypropylene fiber in the same fiber quantities, similar benefits were not seen. Therefore, the performance of steel fiber-reinforced concrete at elevated temperatures is better than that of polypropylene fiber.

6 Scan Electronic Microscopy (SEM)

The interface between the fibers (F) and the cement paste (CP) demonstrates a very strong bond, as can be seen in Fig. 19 where cement paste residues can be seen on the surface of the fiber after it has been pulled out during specimen fracture. This is visible by looking at the microstructure around the fiber particles.

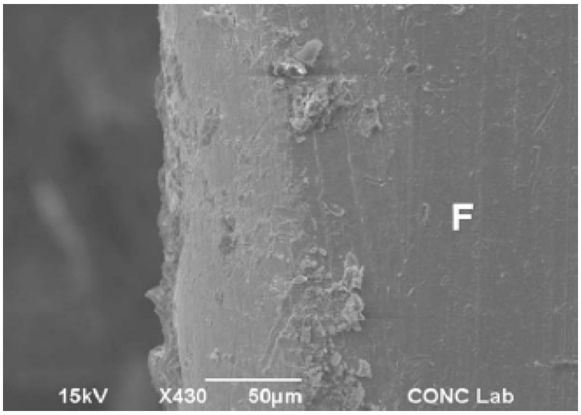

Fig. 19 Paste on SF (El-Dieb, 2009)

Further investigation of additional fibers revealed the presence of cement paste including SFs, as shown in Fig. 20a, b. Additionally, the cement paste near the fibers was found to have some microcracking. These findings show that the cement paste and fibers have a very strong connection. The micrographs also reveal two additional toughening processes for energy consumption in the fiber concrete matrix that are not present in traditional concrete, fibers being pushed out and internal microcracks in the cement paste around it. These processes

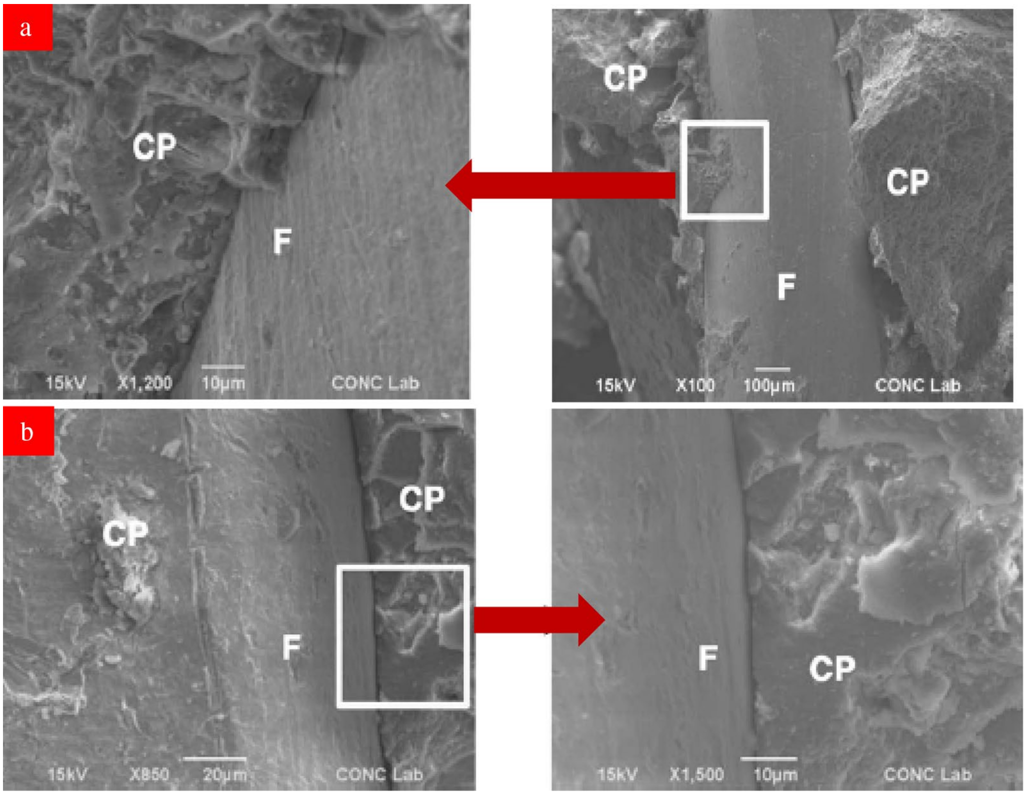

Fig. 20 **a** Interface at fiber surface (**b**) dense paste around the fiber with tiny cracks (El-Dieb, 2009)

assist concrete in obtaining a significant increase in fracture toughness and shifting the failure mode to one that is more deformable.

In freshly laid concrete, the use of SF may prevent water from rising, and the water is likely to collect close to the thin SF. As a result, the water–cement ratio of the fiber surface is higher than that of the concrete matrix. The weak link that easily causes the pull-out failure of long SF is the ITZ between the fiber and cement paste. In addition, the development of calcium hydroxide (CH) and ettringite (AFt) crystals is helped by the greater water–binder ratio. The aforementioned explanations clarified why there were so many needle-like AFt crystals in the ITZ between cement paste and long SF (Li et al., 2021). During a study, After the concrete has cracked, the fiber may move the adhesion and friction between the fiber and matrix to transfer the internal force from the fiber to the cement matrix (Bolat et al., 2014). The SEM experiment's goal was to find out more about the relationship between mortar and fiber. The excellent connection between concrete and fibers was shown to increase the binding strength between reinforcing steel and concrete (George et al., 2019).

7 Applications of Steel Fiber-Reinforced Self-Compacting Concrete

SCC has good flowability and rheological stability in its fresh form. SCC works very well for components with intricate forms and crowded reinforcement. Superior surface polish is produced by SCC. The SCC strong performance in fresh conditions may be used to the benefit of the inclusion of fibers to obtain a more uniform dispersion of fibers, which is essential for a more extensive and dependable structural application of FRC. The SCC matrix's homogeneity, which results from the presence of more fine and extra-fine particles, may improve the characteristics of the interface zone and, as a result, the link between the fibers and the matrix, increasing the material's post-cracking toughness and energy absorption capacity (Ferrara et al., 2007). SCC with SF reinforcement is used to build structural parts as an alternative to conventional vibrated concrete since it is easier to place the reinforcement and compact it.

Self-compacting SFRC was utilized to increase the tensile resistance of concrete and replace the traditional steel bars used as reinforcement, which increased the manufacturing efficiency of tetrahedron-like pervious frames for river revetment as illustrated in Fig. 21. For the 6 m deep canal revetment project, 5000 self-compacting

Fig. 21 Pervious frame structures (Geng et al., 2022)

SFRC pervious frames were created and installed in the first bid segment. The submersion channel had a length of approximately 100 m, covered an area of about 1000 square meters, and had a placement density of around five pervious per square meter.

The viability of using self-compacting SFRC pervious frames for river revetment is finally shown through a series of experiments on the preparation, manufacturing, and loading performance of these frames. These experiments show that the bottom layer of the frame is more likely to sustain damage during lifting than the upper layer, which may break on the inclined rods. When stacking, the upper-layer frame is more vulnerable to failure and cracking than the first-layer frame, excluding rod breakage. Nineteen layers may be stacked and six can be lifted together without any harm due to the frames. As a result, the self-compacting SFRC pervious frames have been used effectively in a river revetment project. Self-compacting SFRC has a novel technical use in this case. SCC with steel fiber reinforcement is a useful alternative to traditional reinforced concrete structures. This is a result of the material's promising qualities, which enable it to be used in slab constructions to resist fractures and to partly or completely replace traditional reinforcing (Ahmad et al., 2016). Thus, self-compacting SFRC is better strength and more durable than conventional concrete structures.

8 Conclusions

This evaluation's goal is to provide accurate and relevant information on the most recent findings and developments in the performance of SF-reinforced SCC. A database for the selection of SF-reinforced SCC in the building and construction industries is also provided in this review paper. The key conclusions from recent studies on SF-reinforced SCC are summarized below.

- SF decreased the flow and passing ability of SCC due to the larger surface area and offer more flow resistance. However, the concrete has good passing and filling ability with suitable adjustment of water–cement ratio and plasticizer dose. Most researchers reported that concrete fall within the limit of SCC with SF up to 1.5% addition. For further addition (beyond 2.0%), some researchers claimed that concrete falls out of the SSC limit and, therefore, behaves as conventional concrete. Therefore, the review recommends to used SF up to 1.5%.
- Tensile and FS improved considerably with the addition of SF into SCC. However, a decrease in CS and elastic modulus was observed with the addition of SF. Furthermore, failure mode shows that SF successfully changes the undesirable brittle nature of concrete into ductile failure.
- The durability of SCC improved with the addition of SF due prevention of cracks (shrinkage cracks). Therefore, harmful chemicals or water cannot penetrate into concrete which causes degradation.
- Steel fiber-reinforced SCC performance at elevated temperatures is better than polypropylene fiber-reinforced SCC.
- SEM results reveal that an excellent connection between cement paste and fibers was observed which increases the binding strength between reinforcing steel and concrete.

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Author contributions

JA writes the original draft; ZZ and AFD reviewed and edited. All authors read and approved the final manuscript.

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Consent for publication

Not applicable.

Competing interests

No competing interest is present among the authors.

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