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Flow Characteristic and compressive strength of self-compacting concrete containing steel fiber: A comprehensive review

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Abstract: In this study, flow characteristics and compressive strength of self-compacting concrete (SCC) reinforced with steel fiber were reviewed from past 35 experimental works. Different steel fibers were used such as straight, hooked, crimped and wavy. The workability of fresh SCC was assessed via using slump flow diameter, slump flow T50, L-box, J-ring, V-funnel, and V-funnel T5 tests. Results indicate that in general, there is a slump flow diameter decrease, J-ring diameter decrease, T50 time increase and V-funnel time increase with the addition of steel fiber to the mix, depending on the type of steel fiber and mineral additives. There is a vital role of steel fiber to cause blocking. The passing ability and filling ability were found to conform to the specification limits for the SCC mixes containing fiber up to 1.5%. There is a consistent increase in the V-funnel T5 time with the increase of steel fibers in the SCC mix. Positive effect of steel fiber on compressive strength is not clear. Many parameters can govern the residual strength such as fiber parameters (mainly fiber volume, aspect ratio, geometry and surface roughness), compressive strength of control concrete and the existence of mineral fillers or admixtures.

Keywords: Self-compacting concrete, Fillingability, Flowability, Steel fiber, Compressive strength.

1. Introduction

The geometric circumstances of precast reinforced concrete members introduce difficulties in reinforcement placement, leading to a time-consuming phase of the industrial process (Naik, 2008). Further, in the case of congested steel reinforcement concrete sections, appropriate concrete pouring performance could not be well ensured. As a result, defects will produce that able to impair the mechanical performance of concrete and visual look of the finishing surface (Brouwers and Radix, 2005; Nuruddin et al., 2014). The solution to the problem might be a type of concrete named self-compacting concrete (SCC) as an alternative of the conventional concrete. SCC can be consolidated into every corner of the mold and spaces between steel reinforcement under its own weight without the need for compaction. Since its introduction in Japan during the 1980s, SCC has been extensively studied to enhance its properties for use in concrete structures (Goodier, 2003). SCC saves time and effort during construction because it flows easily and evenly, even around tight reinforcement bars (Albiajawi et al., 2021). The main positives of SCC are no need to be vibrated and it leads to reduce noise pollution resulted from vibration machine. Further, due to high flow ability it provides dense matrix of concrete and better surface finishing. For this concrete, there is an enhanced bond between concrete and steel reinforcement bar (Kadhim, 2020). SCC is composed of a large content of cement, aggregates containing high amount of fines, a low water-to-cement ratio, and various additives including pozzolanic materials, limestone powder, marble powder, and chemical additives. These components usually contribute to its distinguished properties, in particular high flowability, excellent workability, impressive strength, reduced permeability, and resistance to segregation (Nanthagopalan and Santhanam 2011; Corinaldesi and Moriconi, 2011; Anastasiou et al., 2014; Kamal et al., 2014; Jalal et al., 2015). The superior flowability and segregation resistance of SCC are achieved through the addition of high amounts of superplasticizers while incorporating viscosity-modifying admixtures is important to enhance stability (Khatib, 2008; Rao and Ravindra, 2010; Ferrara, 2014; Tripathi et al., 2020). In SCC, various filler materials have been extensively used as partial replacements for cement (Coppola et al., 2004; Jalal et al., 2015) and commonly utilized fillers include silica fume (SF), fly ash (FA), iron slag, and rice husk ash (RHA) (Nehdi et al., 2004, Aggarwal et al., 2008, Yazıcı, 2008).

A variety of fiber types are available for construction purposes, including steel, carbon, polypropylene, synthetic, glass, and natural fibers, both organic and inorganic (Aslani and Nejadi, 2012). Steel fiber is the most widely used type in concrete for construction purposes (Katzer and Domski, 2012; Ali et al., 2020). Steel fibers are able to arrest cracks propagation and, in this way, has an ability to enhance peak stresses (Katzer, 2008; Ardeshana and Desai, 2012; Yehia et al., 2016). The action of low dosage of steel fiber on SCC properties is limited, while fiber volumes exceeding 2% have the ability to reduce workability and cause passing ability problem, especially for sections with high congested steel bars (Löfgren, 2005; Kulasegaram et al., 2011; Awoyera, 2016). Fiber length has a crucial effect on the behavior of SCC containing steel fiber, in which, shorter fiber under the same aspect ratio, offer better crack bridging and better stress transfer across cracks, due to their larger number compared to longer length fibers (Song and Hwang, 2004; Luo, 2014). Also, there is a good chemical bond between steel fiber and surrounding cement matrix, in which there is a compatibility with the binder, and this can serve as a bridge to inhibit the micro-cracks propagation. It will be noted that, on using larger aspect ratio, there is an improvement in strength performance. Fiber’s aspect ratio has a major effect on both workability and strength properties of concrete (Majain et al., 2019).

One of the purposes behind using SCC is to enhance durability of reinforced concrete structures. Aspects of durability of SCC were discussed by the past researchers. Wang et al. (2020) studied freeze-thaw durability of steel fiber-reinforced rubber SCC. The concrete samples were prepared with replaced rubber aggregate based on fine aggregate ratios of 10%, 15%, and 25% (by volume) and steel fiber ratio of 0.2%. The designed specimens showed excellent freeze-thaw resistance after 600 freezing-thawing cycles. On the other hand, Corinaldesi and Moriconi (2004) investigated resistance to freezing and thawing of concrete treated with hydrophobic agent in addition to carbonation and chloride penetration tests. This to assess durability behavior of fiber reinforced SCC. The rate of chloride ion diffusion was low and this was attributed to the very low porosity of the cementitious matrix. The resistance to freezing and thawing was found moderate and can be improved by the superficial application of a hydrophobic agent, which notoriously reduces water ingress into concrete. In an experiment, Frazão et al. (2013) performed durability tests to compare the performance of SCC with or without steel fiber. Durability tests included water absorption by immersion and by capillarity, permeability to air, electrical resistivity, chloride diffusion by migration under non steady state and carbonation. They observed that addition of steel fibers resulted in a very slightly increase of open porosity, did not change significantly the water absorption by capillarity, indicating that the capillarity pore size was not substantially changed, the air penetrability was not substantially affected by the steel fibers, and the presence of steel fibers reduced the electrical resistivity. Also, due to the relatively high compactness of SCC mixes, they presented good resistance to carbonation. They also pointed that in extremely aggressiveness conditions, corrosion of steel fibers can induce cracking in concrete and decrease tensile strength of concrete. Further, tests on rapid chloride ion penetration on SCC containing steel fiber showed that addition of steel fiber has an effect to increase the total charge transmitted, and this was attributed to the electrical conductivity of steel fibers. However, all of the mixtures had extremely low limits of chloride ion penetration (Ahmad et al., 2023).

In this paper, flow characteristics and compressive strength of SCC mix modified with steel fiber have been chosen for investigation. A comprehensive review was made which aims to understanding SFR-SCC flow characteristics as affected by steel fiber addition and different mineral admixtures or powers. Also, this review aims to consolidate recent research on SFR-SCC examining various factors such as fiber types, lengths, shapes, aspect ratios, and their impact on the compressive strength. Having thorough idea about this topic, the concrete technologists are able to select the best choice to design SCC mixture for numerous applications, especially for concrete members made of SCC in which post-peak response of concrete needed to be active.

2. Fresh properties of SRF-SCC

The main fresh properties of self-compacting concrete as compared to normal concrete are distinguished by the self-compactability. This behavior is in mechanism terms related to the rheological properties in fresh state of concrete, while in practice the term of handling is related to workability parameters.

In Table 1, description of steel fiber properties and dosage and also mineral admixture content attempted by the past researchers are given. This table is also contains the results of slump flow diameter and V-funnel flow time. Below, in some detail, the experimental results are presented and discussed.

2.1 Slump flow

Fig. 1 shows variation of flow diameter of SCC mixes with respect to the steel fiber content, from which one can observes a reduction in the flow diameter except an observation drawn by Alabduljabbar et al. (2019) in which there is an enhancement from 720 mm to 738 mm on using 1% steel fiber in the mix containing 30% fly ash (FA). Also, there is no flow loss for the mix containing 1% steel fiber and 10% silica fume (SF). Unexpectedly, there is a flow diameter reduction from 685 mm to 625 mm on using 1% fiber and enhancement when fiber increased to 1.5% for the mix containing rice husk ash (RHA) indicating the different role of mineral admixture on the flow characteristics. The maximum slump flow diameter measured is equal to 760 mm observed for SCC with 41% limestone powder (LP) without steel fiber being well reduced with increasing fiber volume up to 0.4% reaching 6.6% tested by Tavakoli et al. (2016). The minimum slump flow diameter is 560 mm, seen for SCC mix with 35% FA ash and 0.5% steel fiber tested by Zeyad et al. (2018). One can observed a steep flow reduction with increasing fiber up to 0.5% tested by these researchers which is in contrast with the slow variation of the flow measured by Alabduljabbar et al. (2019) all used FA in their mixes. A continuous slump flow diameter reduction is observed for SCC mix containing 23% LP tested by Abbas (2013) reaching 22.1% on using 1.5% steel fiber. Although addition of steel fiber affects well the slump flow loss, SCC mixes falls within the limits of EFNARC (2005) since the flow diameter is larger than 550 mm, indicating the suitability of the steel fiber reinforced SCC mixes for practical applications.

Comparative observation of data obtained by Alabduljabbar et al. (2019), Barragan et al. (2004) and Alyousif (2010) indicates the usefulness of SF to control flow loss because of steel fiber addition as compared with the other mineral admixtures or limestone powder. One can find that the type and proportion of mineral admixtures used in the SCC mix can impact the slump flow diameter. For instance, the addition of FA may enhance the workability of the concrete, leading to a higher slump flow diameter compared to mixtures with higher LP content. The interaction between steel fibers and the concrete matrix can affect the flow ability of SCC. Higher steel fiber volumes may disrupt the flow of the concrete, resulting in a decrease in slump flow diameter. Overall, the variations in slump flow diameter in Fig. 1 highlight the complex relationship between steel fiber content, mineral admixtures, and the flow characteristics of SCC.

2.2 T50 (Rate of flow of a SCC mixture)

The time required for concrete slump flow to extend to a circle with a diameter of 500 mm known as slump flow T50, serves as an indicator of the mixture's viscosity. A longer T50 time signifies higher viscosity, whereas a shorter T50 time indicates lower viscosity. Concrete with a T50 time of 2 seconds or less is typically categorized as having low viscosity, while a T50 time exceeding 5 seconds is generally associated with high-viscosity SCC mixtures (ACI 237, 2007). Changes in flow time T50 reflect the workability and viscosity of the SCC mixtures. Higher flow times suggest higher viscosity and potentially lower workability, while lower flow times indicate better flowability and workability of the concrete.

Fig. 2 presents the flow time T50 measured by different examiners for SCC with varying steel fiber ratio. The graph illustrates how the flow time T50 changes with different percentages of steel fibers, providing insights into the flowability and workability of the concrete mixtures. One can find that all mixes are within the limits of ACI 237 (2007) since the T50 did not exceeded 5 seconds, except two mixes by Tavakoli et al. (2016) contained hooked steel fiber. The maximum flow time T50 is 6.5 seconds, observed for SCC with 0.4% steel fiber content, while the minimum flow time T50 is 2 seconds, seen for SCC with 7.5% SF and 27% LP content. From

Fig. 2, different responses are observed indicates different action of steel fiber on the T50 values. Higher steel fiber content tends to increase the flow time, as observed in the curve for 0.2% steel fiber, 30% FA and 25% ground granulated blast slag (GGBS) content. Generally, there is a good action of SF to control the T50 increase but test data on this observation are limited. One can find a relatively high T50 time increase based on tests by Tavakoli et al. (2016) and this could be attributed to using higher LP by 41% and using hooked steel fiber. The increase in flow time can be attributed to the interference of steel fibers in the concrete mixture, which may resist the flow and affects the workability of concrete. The type and proportion of mineral admixtures, namely FA, GGBS, SF and LP have an appreciable effect on the T50 flow time. Totally, the T50 flow time of steel fiber reinforced SCC depends on parameters of steel fiber type, aspect ratio and volume in addition to the characteristics of the mineral admixtures used in the mixture. More tests seem to be required to assess the true action of FA, SF and other admixtures such as RHA and bagasse ash in the SCC mixture containing steel fiber.

2.3 V-funnel time

The time taken for a concrete mixture to flow through a V-funnel, measured in seconds as it passes through the bottom outlet of the apparatus, is crucial for evaluating its self-compactness. V-funnel time should be between 6 and 12 seconds according to EFNARC (2002) standard in order to get satisfactory characteristics in freshly poured SCC. This test specifically assesses the filling ability of SCC mixes, applicable to aggregates with a nominal maximum size of up to 20 mm. The V-funnel flow time serves as an indicator of the SCC's ability to pass through a narrow opening and can also be utilized to assess its resistance against segregation (De Schutter, 2005).

In Fig. 3, the results of V-funnel time test for different SCC mixtures are presented. The graph indicates how the addition of steel fibers can lead to an appreciable change in the filling ability time of different mixes. Majority of test data show us that SCC mixes containing up to 1% steel fiber fall within the limits of EFNARC (2002). Using 1% fiber in the mix has no effect to enhance the V-funnel time based on test data by Alabduljabbar et al. (2019). One can observe that the existence of mineral admixture has an appreciable impact on the V-funnel time and this could be attributed to the material particles' shape and surface characteristics affecting water demand. Although different mixes were tested by Abbas (2013) and Rao and Ravindra (2010) nearly the same results were obtained. Based on tests by Alabduljabbar et al. (2019), action of FA is good in which there is no V-funnel time loss on using 1% steel fiber, but the time for the mixes contained SF and RHA is relatively large regardless of the fiber content. A linear V-funnel time increase is observed, by different ratios, according to test data by Gencel et al. (2011), Abbas (2013) and Zeyad et al. (2018).

Two mixes have the highest V-funnel time, one contained 10% RHA and 1.5% steel fiber and the other contained 12% SF and 20% LP reinforced with 1.25% steel fiber, but the enhancement because of steel fiber addition is higher for the later mix reaching 277%. This high V-funnel time enhancement indicates the potential effect of steel fiber on filling ability and vulnerability to segregation. The reason of V-funnel time increase was attributed to the increased friction between fibers and aggregates as well as friction between fibers themselves (Ahmad et al., 2023). Indeed, this friction is affected by the steel fiber characteristics and the existence of the additives in the mixture. As a result, different V-funnel time is expected to occur.

2.4 Passing ability

To study the passing ability of SFR-SCC, J-ring and L-box tests needed to be evaluated. Some researchers were worked to examine these properties; however, there is a limited published work.

2.4.1 J-ring test (flow spread and flow time T50)

The J-Ring test, as per ASTM 1621 (2006), is utilized to assess the passing ability of SCC with aggregates up to 25 mm in size. It evaluates both filling and passing abilities, particularly regarding passing through reinforcement bars. Key parameters measured include flow spread, flow time (T50), and blocking tendency. Flow spread indicates SCC's restricted deformability due to reinforcement bars, while T50 reflects the rate of deformation over a specified distance. The test is straightforward and can be conducted at concrete plants or job sites. A higher J-Ring slump flow signifies greater transportability through reinforcement bars and faster filling of molds, as per ACI 237 (2007).

In Fig. 4, the J-ring diameter for different SCC mixtures with varying steel fiber content by volume is presented. Analyzing this graph provides insights into the resistance to passing ability of the SCC mixes and the impact of steel fibers on the flow diameter. As the steel fiber content in the SCC mixtures increases, there is a general trend of decreasing J-ring diameter. This decrease in diameter indicates a reduction in the flow spread and passing ability of the concrete, which can be attributed to the interference of steel fibers hindering the smooth flow of the mixture. For the mix contains 30% FA and 25% GGBS, the J-ring diameter decreased rapidly by 17% when the steel fiber content increased up to 0.5% by volume. For the other two mixes, one containing SF and the other containing both SF and LP, the J-ring diameter decreased by approximately 2% when the amount of steel fiber increased to 0.5%.

One can observes good action of silica fume to keep the passingability of the mixture after steel fiber addition from test data by Alyousif (2010), while the combination of fly ash and GGBFS has not useful action in which after steel fiber addition an appreciable filingability loss is observed based on the experiment of Aslani and Nejadi (2013).

It is better to highlight the role of steel fiber on blocking based on the limits provided by ASTM C 1621 (2017), and this could be done via comparing the results of Fig. 4 and Fig. 1. According to data by Barragan et al. (2004), the difference between slump flow and J-Ring flow diameters is 50 mm for control mix and increased to be 70 mm on using 0.5%. Accordingly, noticeable to extreme blocking is observed indicating an appreciable effect of steel fiber on blocking. Based on work by Alyousif (2010), blocking was occurred for the control mix since the difference between slump flow and J-Ring flow diameters is 80 mm, and adding fiber up to 0.5% has no effect to change this value. For the mix tested by Aslani and Nejadi (2013), the difference is only 15 mm well increased to be 90 mm on using 0.2% and 0.4% indicating a vital role of the steel fiber on blocking.

2.4.2 L-box test

This method evaluates the passing ability of SCC by measuring the height reached by fresh SCC after passing through specified gaps in steel bars and flowing a certain distance. A height ratio closer to 1.0 suggests better flow potential, implying fewer restrictions in passing through bars. Visual inspection can reveal issues like coarse aggregate blocking behind bars or segregation at the end of the horizontal section. SCC mixes showing these issues should be adjusted to maintain stability (Rahim et al., 2021). According to ACI 237 (2007) and EFNARC (2002), the L-box ratio (H2/H1) should not be lower than 0.80.

Fig. 5a demonstrates the results of passing and filling capabilities by applying the L-box test done by Rao and Ravindra (2010), Abbas (2013) and Tavakoli et al. (2016). The results showed that the replacement of cement by 23% LP improved the passing ability of SSC as compared with cement replacement by 35% FA. The passing and filling capabilities for both set of mixes were decreased with steel fiber ratio increase. The results conform to the specification limits for the SCC mixes containing fiber up to 1.5%, except the mix containing 0.4% tested by Tavakoli et al. (2016). The steep reduction of H2/H1 value obtained by these authors may be attributed to the shape of steel fiber in which they used hooked steel fiber. Fig. 5b shows L-box height variation with steel fiber ratio tested by Aslani and Nejadi (2013). Increasing silica fume content from 5% to 10% has no appreciable effect on the height ratio variation. Based on their results, addition of steel fiber up to 0.2% has no serious effect on the passing ability using L-box test.
Fig. 5c offers valuable information on the passing ability of SCC mixtures with steel fibers tested by Alabduljabbar et al. (2019). The action of SF and RHA is better than that of FA, and addition of steel fiber up to 2% has no appreciable effect on the height ratio change. All mixes conform to the specification limits and this highlights the importance of optimizing steel fiber content to achieve the desired flow characteristics and performance of SCC.

2.5 V-funnel at T5 min

V-funnel at T5 minutes (T5) is the concrete left for 5 minutes and start to emptying it. The V-funnel time at 5 minutes (T5) ranging from 6 seconds to 15 seconds provides insights into the resistance to segregation of SCC. Fig. 6 illustrates the V-funnel T5 variation with steel fiber ratio tested by different authors. It is observed that the addition of steel fibers impacts the V-funnel time after 5 minutes. There is a consistent increase in the time relative to the control mix with increasing dosage of steel fiber. In Fig. 6a, the highest V funnel T5 is recorded at 22 seconds for fiber reinforced SCC containing 12% silica fume (SF), 20% limestone powder (LP), and 1.25% steel fiber content, compared with 9 seconds for the mix without fiber. Notably, as the steel fiber content increases, there's a corresponding increase in V funnel time. Fig. 6b present the highest V-funnel T5 which is 20.2 seconds for fiber reinforced SCC with 10% SF, 15% FA and 0.2% steel fiber content. One can find that increasing steel fiber ratio and increasing silica fume from 5% to 10% have an effect to increase the flow time. Comparing the results of Fig. 6a and 6b show us that using limestone powder has good action to reduce the V-funnel T5 time for the mixture containing high fiber content. From the results of Fig. 6c, one can find that the V- funnel time is directly proportioned to the increasing steel fiber content. The time increased by approximately 47% when the amount of steel fiber increased up to 0.8%. Also, comparing results of Fig. 6b and 6c indicates that there is no good action of SF in the mix since it further extends the filling ability time.
Reviewing of past experimental works (Rixom and Mailvaganam, 1999) indicate that there are many factors affecting properties of fresh concrete containing water reducing admixture. Firstly, amount of air entrained, which affects workability, is obviously varied according to the type and quantity of the admixture used. Also, the amount of deformation of fresh concrete obtained under standard conditions would depend on the volume fraction of the aggregate and the shear resistance or viscosity of the cement paste. The later properties are well governed by the type and the dosage of water reducing admixture. Experimental studies indicate that the relationship between initial and final slump for water reducing admixtures at normal dosage levels are depend on the type of the admixture used. The hydroxycarboxylic acid type appears to be generally superior to the lignosulfonates in increasing the value of slump. By different investigators,

different types of admixture were used and indeed different flow characteristics are expected to occur. Several types of water reducing admixture were used by different authors worked on SCC containing steel fiber. This may be another reason of different actions of steel fiber on fresh SCC properties as discussed in the previous sections.

Based on the foregoing review, adding steel fiber up to 0.5% has small effect on the flow characteristics. So, there is a chance to design a mix containing steel fiber to be used for SCC sections with congested steel reinforcement.

3. Compressive strength of steel fiber reinforced SSC

3.1 Review of literature

Compressive strength of SFR-SCC was measured experimentally by many investigators that conducted numerous laboratory works to explore the topic thoroughly. In Table 2, a description of material properties and compressive strength of control mixture without fiber are given. Below, results obtained by numerous investigators are given and briefly discussed.

Ahmad et al. (2023) in their review paper reported that steel fiber does not improve the compressive strength of SCC based on researchers' conclusions. They noted that a decrease in workability of SCC because of steel fiber may be the cause of a loss of strength. A study arranged by Barragán et al. (2004) aimed to assess the compressive strength of SCC by using two different approaches. In the first program, three distinct mixes of SCC reinforced with hooked end steel fibers were examined, with varying dosages of 20, 40, and 60 kg/m^3, and a water-to-cement ratio (w/c) of 0.37. The second program involved two SCC mixes with a w/c ratio of 0.44, one mix contained no steel fibers, while the other mix included hooked end steel fibers at a dosage of 40 kg/m^3, with both programs utilizing steel fibers of 30 mm length and 0.5 mm diameter. At 28 days, the compressive strength of SFR-SCC with 20 and 60 kg/m^3 steel fibers was measured at 32.3 and 34.1 MPa, respectively. Additionally, the compressive strength of the second program, comparing SCC and SFR-SCC with 40 kg/m^3 steel fibers, was recorded at 76.3 and 72.7 MPa, respectively. The researchers concluded that the incorporation of steel fiber resulted in a decrease in compressive strength of SCC.

Test results of SCC at the age of 28 and 56 days by Sahmaran and Yaman (2007) indicated that increasing the amount of steel fiber led to a reduction in compressive strength. Notably, hybrid steel fibers exhibited the least detrimental effect on the compressive strength of steel fiber reinforced SCC. Specifically, at 56 days, the reduction in compressive strength for hooked end, straight, and hybrid steel fibers was measured at 14.34%, 11.19%, and 8.74% respectively.

Atiş and Karahan (2009) tested specimens at the age of 7, 28, 90, and 365 days and found that the introduction of steel fibers increase compressive strength by 5.15% at 360 days when 0.25% of steel fibers and 120 kg/m^3 of fly ash were added. However, the experiment revealed inconsistent results in compressive strength, indicating unclear effects of steel fiber. This inconsistency may be attributed to difficulties in achieving uniform distribution of steel fibers within the concrete, impacting strength compared to plain concrete. Overall, the addition of steel fibers did not significantly improved long-term compressive strength, with only slight enhancements observed with higher fiber content. Further, the inclusion of fly ash reduced average compressive strength by 10% and 14% for replacement ratios of 15% and 30%, respectively, compared to plain concrete. The presence of steel fibers did not counteract the strength reduction caused by fly ash. Nonetheless, with time, the pozzolanic reaction of fly ash and the incorporation of steel fibers gradually restored the strength lost due to the fly ash replacement. This suggests that it is possible to substantially regain the reduction in compressive strength resulting from fly ash inclusion.

According to an experiment by Boulekbache et al. (2010), compressive strength decreased by 6.56% after 28 days curing on using hooked steel fiber added by 40 kg/m^3.

By Gencel et al. (2011), incorporating steel fibers into SCC at rates of 15, 30, 45, and 60 kg/m^3 resulted in an increase of 3.2% and decreases of 3.4%, 2.0%, and 1.0%, respectively. Initially, the addition of steel fibers at lower rates strengthened the concrete and increased compressive strength. However, as the concentration of fibers increased, it disrupted the homogeneity of the concrete, leading to a decline in compressive strength. Nevertheless, with further addition of steel fibers, there was a gradual increase in strength due to the reinforcement effect.

In a study conducted by Hatim Khuthair Alubaidi (2011), 150 x 300 mm cylindrical specimens were tested under both water curing and dry conditions at 4 and 6 weeks. Upon the addition of 0.5% steel fiber, there was a respective increase in compressive strength by 5.71% and 4.44% at 4 and 6 weeks. With 1% steel fibers, the increases were 8.57% and 6.94% for the same periods. For dry specimens, the addition of 0.5% steel fibers resulted in a 6.9% increase at 4 weeks and 5.05% increase at 6 weeks, while with 1% steel fibers, the increments were 10.69% and 10.1% for the corresponding periods. The study concluded that the enhancement in compressive strength was more pronounced at early ages due to the influence of limestone powder as a filler in the mix.

Sable and Rathi (2012) tested specimens at the age of 3, 7, and 28 days, and observed that the inclusion of steel fibers led to an increase in compressive strength. The highest compressive strength at 28 days was achieved with the addition of hook-ended steel fibers with an aspect ratio of 80 (exhibited the maximum normalized compressive strength of 1.42). Straight steel fiber with an aspect ratio of 50 showed the minimum normalized compressive strength of 1.13. The research findings highlighted that the shape and aspect ratio of steel fibers have distinct effects on enhancing the compressive strength of steel fiber reinforced SCC.

The findings by Abbas (2013) indicated that the highest enhancement in compressive strength was achieved with the addition of 0.75% of steel fiber, resulted in increases of 29.45%, 27.68%, and 7.10% at 7, 28, and 90 days respectively.

In a study, Salih et al. (2014) tested three different SCC mixes, one with plain SCC, another with fly ash and a third with silica fume. In the first mix, the addition of steel fibers resulted in increases in compressive strength of 1.66%, 14.73%, and 7.02% at 7, 28, and 90 days, respectively. For the second mix, there were increases in compressive strength at 7 and 28 days, but a reduction of 6.53% was observed at 90 days. The third mix experienced reductions in compressive strength of 27.41%, 4.64%, and 9.34% at 7, 28, and 90 days, respectively, with the addition of steel fiber. These findings underscore the importance of carefully selecting and proportioning cementitious materials and steel fibers to mitigate any adverse effects on compressive strength and durability in SCC. The authors concluded that incorporating mineral admixtures can help to minimize the compressive strength reduction of SCC induced by steel fibers, and proper proportioning of cementitious materials, especially mineral admixtures, can enhance the compressive strength of steel fiber reinforced SCC.

Khaloo et al. (2014) created two base mixes of plain SCC: one without silica fume and the other with varying proportions of silica fume. Their findings revealed that increasing the dosage of steel fiber led to a decrease in strength due to decreasing concrete workability. For the first group of SCC, the addition of fiber volume fractions ranging from 0.5% to 2% resulted in reductions in compressive strength values at 28 days by 4.3%, 11.6%, 14.6%, and 18.6%, respectively.

Similarly, for the second mix of plain SCC, the 28-day compressive strength decreased with increasing fiber volume fraction, showing reductions of 0.7%, 2.2%, 4.2%, and 7.5%, respectively. Interestingly, the second group specimens experienced a lesser decrease in compressive strength compared to the first group specimens, possibly due to their higher workability. Also, the addition of silica fume to the second group mixes influenced the interaction with the mortar matrix and steel fiber, leading to a stronger interfacial structure and improved interactions between the fiber and cement matrix. While compressive strength tended to improve with age, the rate of enhancement diminished as the samples aged.

Experimentally, Frazão et al. (2015) investigated the performance of two types of SCC with a constant w/c of 0.31. The first type consisted of SCC containing limestone filler but no fiber, while the second type was contained steel fiber. It was observed that the addition of steel fiber increased compressive strength at 7, 28, and 90 days by 16.05%, 2.69%, and 3.57%, respectively.

In a study, Sachdeva and Singla (2015) investigated the influence of steel fibers on the compressive strength of SCC utilizing different viscosity modifying agent (VMA) concentrations ranging from 0.1% to 0.2% by weight of cement in addition to FA. Their findings revealed that the compressive strength of the mix containing 0.35% steel fibers exceeded that of traditional SCC, while the mix with 0.70% steel fibers performed even better on any given day. Furthermore, the mix with 1% steel fibers exhibited superior compressive strength compared to both the 0.35% and 0.70% mixes. This suggests a positive correlation between higher steel fiber content and increased compressive strength. Specifically, for the mix with 1% added steel fibers, the compressive strength increased by 13.78%, 18.82%, and 34.22% at 3, 7, and 28 days, respectively.

Tests by Haddadou et al. (2015) indicate that initially the concrete exhibited sudden and explosive failure, leading to complete specimen damage. However, as the percentage of steel fibers increased, the failure mode transitioned to a more ductile behavior. The improved integrity of specimens with higher fiber dosages was attributed to the strong bond between the fibers and concrete, effectively mitigating sudden explosive failure. The results of the compressive strength tests indicated varying outcomes among the mixes, with some experiencing reductions and others showing increases in compressive strength. The extent of enhancement depended on the mix constituents, properties of the steel fibers, and their uniform distribution with proper orientation in the mix. The highest improvement in compressive strength among the mixes was observed at 7, 28, and 90 days, with increases of 16.67%, 14.5%, and 9.11%, respectively, achieved with a fiber dosage of 0.8% and an aspect ratio of 30.

In a study conducted by Madandoust et al. (2015), the impact of aggregate maximum size (10 mm and 20 mm) on the compressive strength of SCC and SFR-SCC was investigated. Compressive strength tests were conducted over a period of 14, 28, 42, and 90 days. The results indicated that the addition of steel fibers decreased the compressive strength across all mixes, being increased with increasing fiber dosage.

Findings by Facconi et al. (2016) revealed that the use of double hooked end steel fibers increased the compressive strength by 8.2%, whereas single hooked end steel fibers decreased the compressive strength of SCC by 10.9% and 3.39% for dosages of 20 and 25 kg/m³, respectively. Hence, the study emphasized the significance of selecting the most suitable steel fiber to enhance the compressive strength of SCC.

Yehia et al. (2016) conducted an assessment of hooked steel fibers' influence on the compressive strength of SCC in two phases. In the first phase, samples were kept under laboratory conditions

(25°C with 75% relative humidity) and tested at 3, 7, 21, and 28 days. The second phase involved subjecting samples to wetting and drying cycles before testing at 28 days. Results indicated a 2.73% increase in compressive strength for cube samples at 7 days but a 0.97% reduction at 28 days. Correspondingly, cylindrical samples showed a 5.26% and 9.43% increase in compressive strength at the corresponding ages.

By Irki et al. (2017), compressive strength tests were conducted at 7, 28, and 90 days for a control mix and three groups of SFR-SCC with varied fiber lengths and percentages. For 35 mm fiber length, dosages ranged from 0.3% to 1.2%, for 40 mm length dosages ranged from 0.3% to 0.8%, and for 50 mm length dosages ranged from 0.3% to 0.5%. The findings indicated that increasing the dosage of steel fibers led to a decrease in compressive strength across all types of wavy steel fibers. However, at 90 days, steel fibers with a length of 35 mm exhibited the lowest normalized compressive strength of 0.93, whereas fibers with a length of 50 mm demonstrated a normalized compressive strength of 0.99.

In an experiment, Nehme et al. (2017) found that the addition of steel fibers resulted in an improvement in the 28 days compressive strength of SCC specimens. The highest normalized compressive strength achieved was 1.17 for SCC with a dosage of 60 kg/m^3 of steel fiber, however, when the steel fiber dosage increased to 90 kg/m^3 the enhancement reduced to be 7%.

Anil (2018) found that the addition of steel fibers led to enhancements in compressive strength, with the minimum and maximum enhancements of 2.03% for 0.5% straight steel fibers and 7.32% for 1% hooked end steel fibers at the age of 28 days, respectively.

According to Begum et al. (2018) experiment, at a dosage of 0.5% steel fibers the compressive strength increased by 6.51%, 7.22%, and 7.7%, while the highest enhancement in compressive strength was observed with the addition of 1% steel fibers, resulting in enhancement percentages of 12.95%, 13.92%, and 14.02% at 28, 56, and 90 days, respectively.

Experimentally, Zeyad et al. (2018) observed that while the addition of steel fibers increased the compressive strength at 7 days, it led to a reduction in strength at 28 and 90 days, which was attributed to the presence of fly ash. Specifically, at 7 days, the compressive strength increased by 4%, 5%, 3.5%, and 2% with each 0.25% increase in fiber dosage. Conversely, at 90 days, there was a slight decrease in compressive strength of 1%, 2%, 2.5%, and 4% with each respective increase in fiber dosage.

According to a study by Majain et al. (2019), the addition of steel fibers at both 0.5% and 1% volumes increased compressive strength by 1.96% and 2.15% at 7 days, and by 6.6% and 8.12% at 28 days, respectively. The maximum compressive strength was achieved with 1.0% steel fiber addition to SCC. The presence of steel fibers altered the failure mode, primarily by arresting cracks within the microstructure of the mix.

Mukilan et al. (2019) examined how crimped and hooked end steel fibers influenced the compressive strength of SCC. They added these fibers at rates of 25, 40, 60, and 70 kg/m^3 with an aspect ratio of 50. Testing at 7 and 28 days showed that hooked end fibers consistently yielded higher compressive strength compared to crimped end fibers across all mixes. The addition of hooked steel fibers improved compressive strength by 8.47%, 4.24%, 23.48%, and 10.76% at rates of 25, 40, 60, and 70 kg/m^3 respectively. The study concluded that the choice of steel fiber type significantly impacts the enhancement of compressive strength.

Experimentally, da Silva et al. (2020) observed that compressive strength at 28 days decreased compared to the reference mix (without steel fibers). The lowest normalized compressive strength was observed with 1% hooked end steel fiber of 33 mm length. However, steel fibers

with a length of 60 mm and a dosage of 0.5% achieved a normalized compressive strength of 0.99.
The findings by Dalvand and Ahmadi (2021) indicated that the addition of steel fiber led to an overall improvement in compressive strength across all mixtures. The highest enhancement, reaching 16.13%, was observed when 1% of wavy steel fibers were added to the mix without silica fume. For mixtures with silica fume, the enhancement in compressive strength ranged from 10.14% to 12.39% for different steel fiber dosages. Also, when 1% of steel fibers were added, the compressive strength increased by 21.73% and 33.96% with the addition of 60 kg/m³ and 180 kg/m³ of fibers respectively.
Patel et al. (2022) investigated the compressive strength of SCC by incorporating fly ash and hooked steel fiber at a dosage of 32 kg/m³. The steel fiber used had a length of 35 mm and a diameter of 0.55 mm. The study revealed that the introduction of steel fibers into SCC increased the 28 days compressive strength by 6.3%.
Further, Alrawashdeh and Eren (2022) experimental results revealed that as the dosage of steel fibers increased, the compressive strength decreased. For aspect ratio 60, the reduction in compressive strength at 28 days was 10.26%, 20.38%, and 24.13% for dosages of 0.35%, 0.45%, and 0.55% respectively, while for aspect ratio 80, the reductions were 9.54%, 6.36%, and 8.96%. Furthermore, Liu et al. (2022) test results indicate that the compressive strength surpassed that of the control mix at all dosages. Addition of wavy steel fibers increased the compressive strength by 24.54%, 18.85%, 16.88%, and 19.1% respectively for dosages of 0.25%, 0.5%, 0.75%, and 1.0%.
It is of interest herein to give information on compressive stress-strain relationship of SCC containing steel fiber since this property has some important practical applications, but test data on this property are quite limited. In a study by Zhao et al. (2019), expanded lightweight aggregate SCC mixes were designed with steel fiber volume fractions of 0%, 0.4%, 0.8%, 1.2%, 1.6%, and 2.0%. 150x300 mm cylindrical specimens were tested to measure the uniaxial compressive stress–strain relationships. Results indicated that, with increasing steel fiber ratio, the compressive strain corresponding to peak-stress of the stress–strain curve increased, while the slope of the descending portion decreased. This increased the energy absorption of steel fiber lightweight SCC with a higher compression toughness. On comparing test results with four groups of calculation models, a group of formulas was selected to express the complete stress–strain curves of lightweight SCC containing steel fiber under uniaxial compression. Experimentally, Frazão et al. (2013) measured compressive stress-strain relationship of SCC with or without steel fiber tested at 7, 28 and 90 days. Results demonstrate that the addition of steel fibers was mainly contributed for the increase of the compressive strength in the post peak phase of the material, with a favorable effect in terms of its energy absorption capability. Further, Aslani and Natoori (2013) investigated compressive stress-strain relationship of steel fiber SCC; modeling was made for the relationship since the available material models are not able to accurately simulate the behavior of SFRSCC as they thought. Steel fiber SCC mechanical properties mixtures included in the database were taken from 21 references. Key parameters to contrast the complete relationship were compressive strength, elastic modulus, strain at peak stress and the compressive stress-strain relationship.

3.2 Variation of compressive strength with steel fiber ratio

Data collected from previous studies reveals a relationship between steel fiber dosage and normalized compressive strength, as depicted in Figs. 7 to 11. In these figures, the number beside the symbol is fiber aspect ratio/fiber length. Notably, there is a fluctuation in normalized compressive strength for specimens tested at 3 days. Conflicting findings exist regarding the impact of fiber dosage on SCC, with some studies reporting a decrease in strength with increased dosage, while others observe an increase. The highest recorded normalized compressive strength was 1.53, achieved with 1% wire steel fibers of aspect ratio equal to 30. Conversely, the lowest recorded strength was 0.73, attributed to 0.55% hooked end steel fibers with aspect ratio equal to 80. One can find that the action of steel fiber is useful for lower strength concrete (control compressive strength of 22.5 MPa) compared with high strength concrete mix (control compressive strength of 69.2 MPa) and the action of FA added to the mixture is better than that of SF. Also, the geometry and type of steel fibers significantly influence compressive strength, with findings from Sable and Rathi (2012) indicating that while 2.5% crimped steel fibers led to a strength drop to 0.98, hooked steel fibers with an 80 mm aspect ratio and 60 mm length increased strength to 1.26.

At 7 days, the highest recorded normalized compressive strength was 1.29%, achieved with 0.75% hooked end steel fibers with aspect ratio equal to 60. Conversely, the lowest strength recorded was 0.73%, attributed to 0.55% hooked steel fibers with aspect ratio equal to 60. Based on data by Irki et al. (2017) and Alrawashdeh and Eren (2022) and also Khaloo et al. (2014) there is an appreciable strength loss for the mixes contain no mineral admixture indicating their portential to control compressive strength loss. Although, concrete mixtures prepared by Abbas (2013) contain no any suplementary mineral admixture, there is a strength enhancement because of steel fiber addition. This enhancement may be due to the use of hooked steel fiber and the control mix was of low compressive strength.

At 28 days, the maximum normalized compressive strength reached is 1.42 with 2.5% hooked steel fiber with aspect ratio equal to 80, while the lowest recorded strength is 0.76, obtained with 0.55% hooked steel fibers with aspect ratio equal to 80. According to Tavakoli et al. (2016) results, using hooked steel fiber with aspect ratio of 51 has no benefical effect to enhance compressive strength of SCC mix containing 41% LP. In contrast, there is a continuous strength reduction with increasing steel fiber content reaching 7% at 0.4% fiber content.

By the 90-day mark, normalized compressive strength generally increased with steel fiber dosage, but beyond 0.8% strength began to decline. The highest recorded normalized compressive strength is 1.09, achieved with 0.8% hooked end steel fibers with aspect ratio equal to 30. Conversely, the lowest recorded strength is 0.85, attributed to 2% hooked steel fiber with aspect ratio equal to 20.

It is better herein to mention the cause of compressive strength changes. The cause of any compressive strength enhancement could be attributed to the positive action of steel fiber to bridge microcracks and preventing cracks extension through bridging effect. Dalvand and Ahmadi (2021) attributed the strength enhancement to the combined effects of crack bridging and pozzolanic activity from both steel fiber and silica fume. Oppositely, the decrease in strength was attributed to the decreased workability of steel fiber reinforced SCC due to the inclusion of steel fiber (Haddadou et al., 2015). Yehia et al. (2016) attributed the strength loss to possible non-uniform distribution of steel fibers in the samples and reduced workability. By Irki et al. (2017), the reduction was likely attributed to decreased concrete compactness and increased porosity with higher fiber content, while Zeyad et al. (2018) reported that higher dosages of steel fiber are able to cause the formation of air bubbles in the hardened concrete microstructure, consequently lowering the compressive strength. Further, the decrease in strength was attributed to the accumulation of steel fibers at specific points, resulting in a non-homogeneous mix (da Silva et al., 2020).

One can find a continuous strength reduction with increasing fiber volume based on tests by Khaloo et al. (2014) and Irkil et al. (2017). The reason of this may be because of the absence of mineral admixture, especially fly ash, which has an ability to enhance the chemical bond of steel fiber with hardened cement paste. Although, concrete mixtures prepared by Haddadou et al. (2015) contain no any suplementary mineral admixture, there is a strength enhancement because of steel fiber addition. This enhancement may be due to the fact that they used hooked steel fiber and the control mix was of low compressive strength.

4. Conclusion

Flow characteristics of fresh SCC and compressive strength of hardened SCC as affected by steel fiber inclusion were assessed in this paper based on reviewing 35 past experiments. Further, the following conclusions are drawn.

1- In general, there is a slump flow diameter decrease, J-ring diameter decrease, T50 time increase and V-funnel time increase with the addition and increasing of steel fiber in the mix and the loss varied depending on the type of steel fiber and existence and type of mineral additives. Maximum loss of slump flow was 22.1% for the mix containing 1.5% steel fiber and 23% limestone powder. The flow diameter, T50 time (except for two mixes) and V-funnel time for all mixes falls within the limits of EFNARC (2005) or ACI 237 specification.

2- As one compares the results of slump flow diameter and J-ring diameter, in some mixes, because of steel fiber existence, a noticeable to extreme blocking is observed even at low fiber contents indicating a vital role of the steel fiber on blocking.

3- The replacement of cement by 23% limestone powder improved the passing ability of SSC as compared with cement replacement by 35% fly ash. The passing and filling capabilities for both set of mixes were decreased with steel fiber ratio increase, but the results conform to the specification limits for the SCC mixes containing fiber up to 1.5%. The action of SF and RHA is better than that of FA, and addition of steel fiber up to 2% has no appreciable effect on the height ratio change. All mixes, except one mix, were found to conform to the specification limits.

4- There is a consistent increase in the V-funnel T5 time with the increase of steel fibers in the SCC mix, and the action of SF seems to be not good to reduce the time enhancement.

5- Careful attention to mix design, appropriate selection and dosage of steel fibers, and other pertinent parameters is crucial to maximize the performance of steel fiber reinforced SCC, particularly in achieving desired mechanical properties like compressive strength and suitability for practical applications.

6- There is no certainty about the positive effect of steel fiber on compressive strength, since there is an enhancement for some mixes reaching 53% and decline for others reaching 27%. Many parameters can govern the residual strength such as fiber parameters (mainly fiber volume, aspect ratio, geometry and surface roughness), compressive strength of control concrete and the existence of mineral fillers or admixtures. In some researches, results show that it is possible to substantially regain the reduction in compressive strength resulting from fly ash inclusion. In another tests, good action of silica fume to control strength loss was noted.

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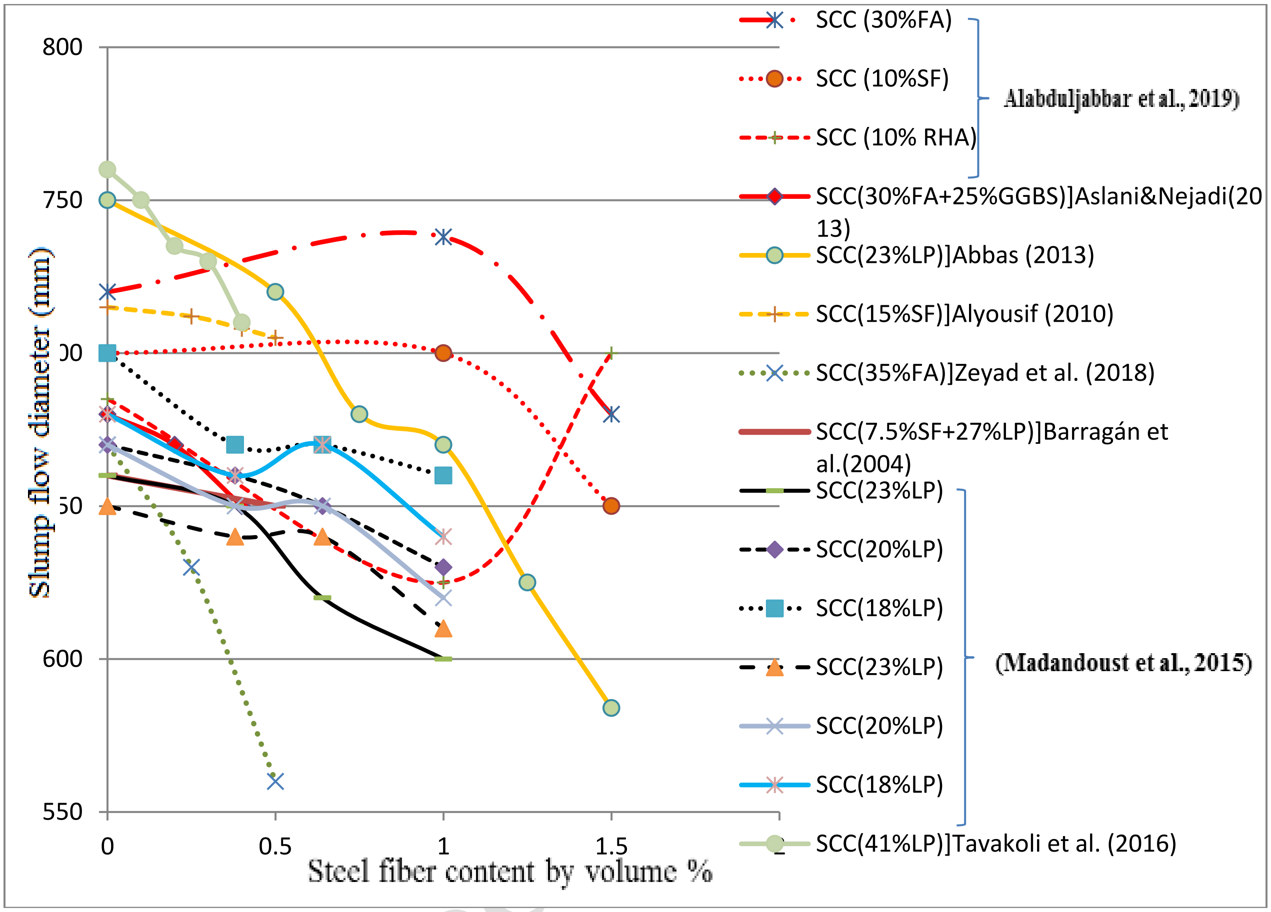


Fig. 1 Slump flow diameter variation with steel fiber ratio

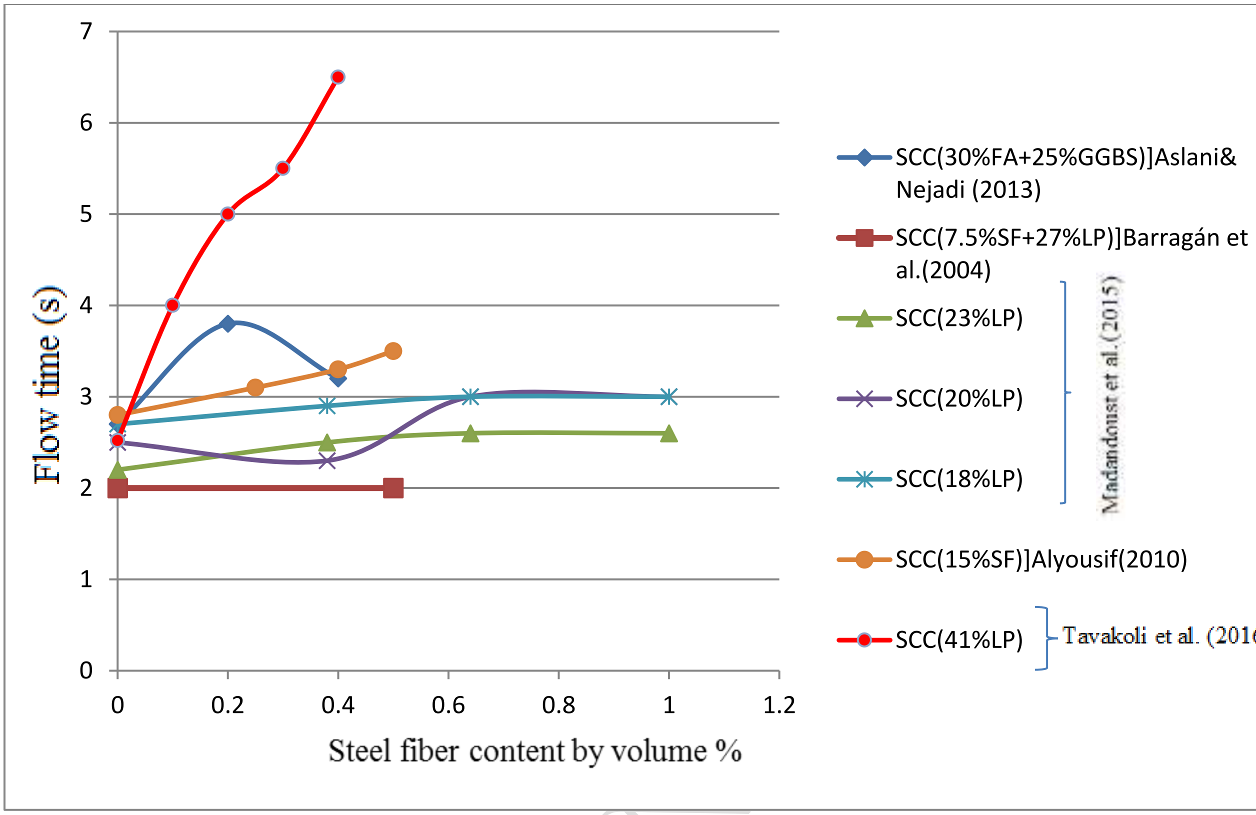


Fig. 2 Flow time T50 variation with steel fiber ratio

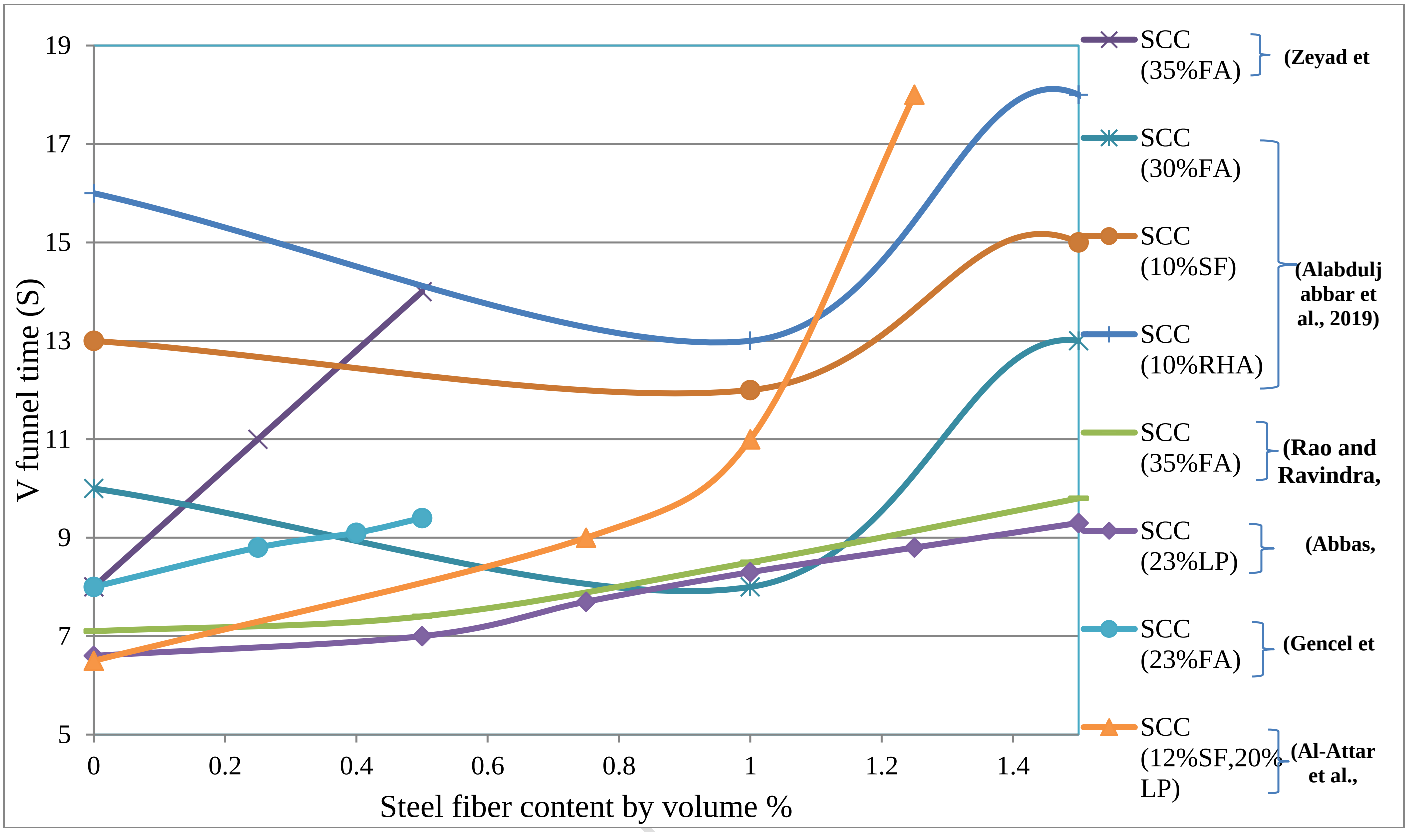


Fig. 3 V-funnel time variation with steel fiber ratio

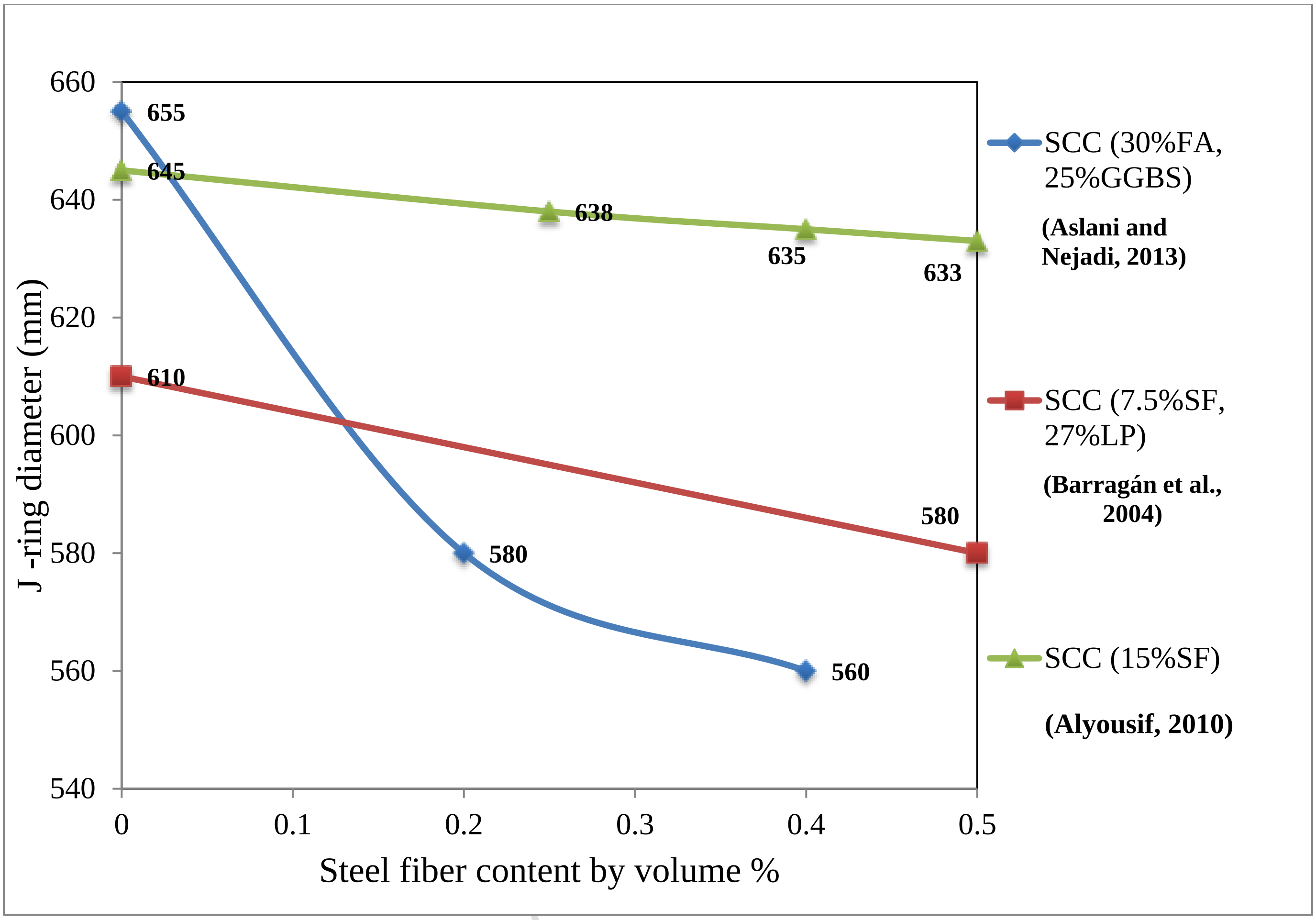
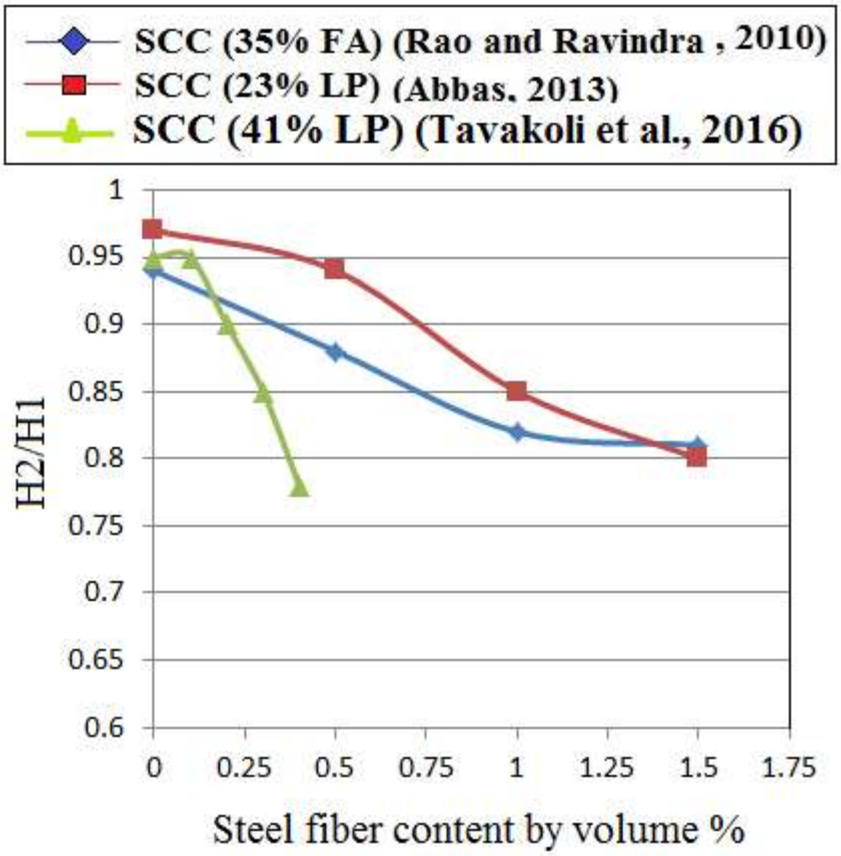
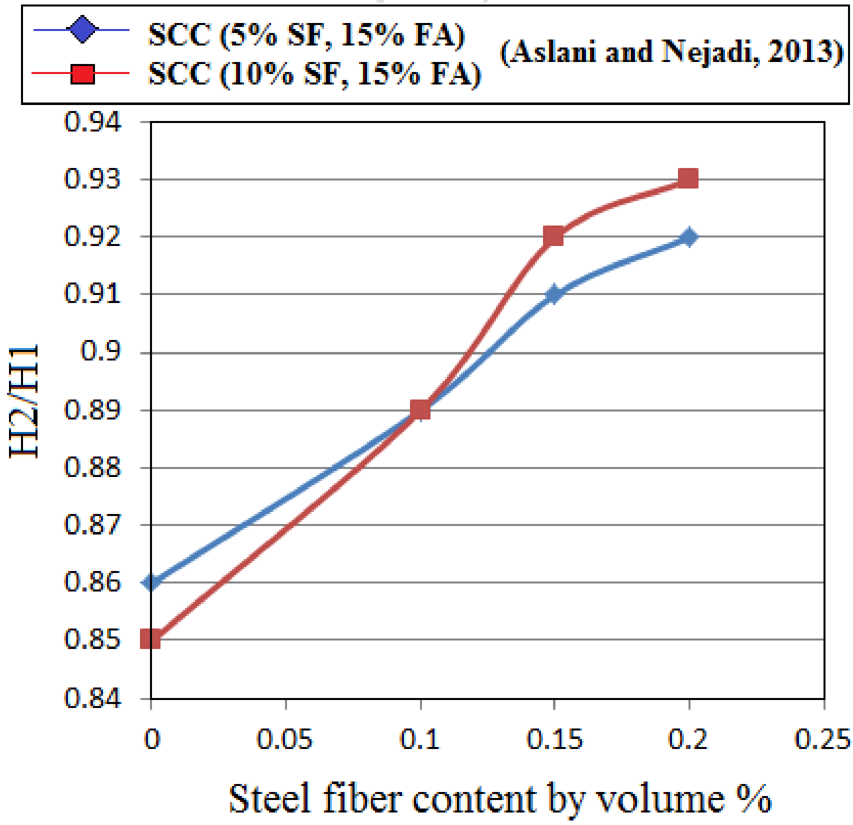


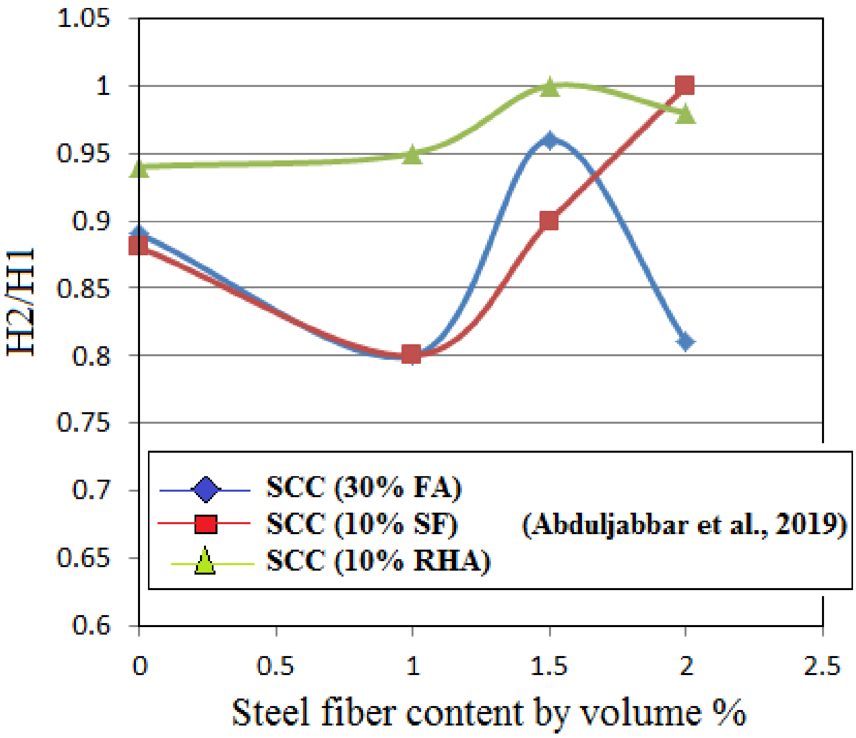
Fig. 4 J-ring diameter variation with steel fiber content


SCC (35% FA) (Rao and Ravindra , 2010)
SCC (23% LP) (Abbas, 2013)
SCC (41% LP) (Tavakoli et al., 2016)
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
H2/H1
0
0.25
0.5
0.75
1
1.25
1.5
1.75
Steel fiber content by volume %

(a)

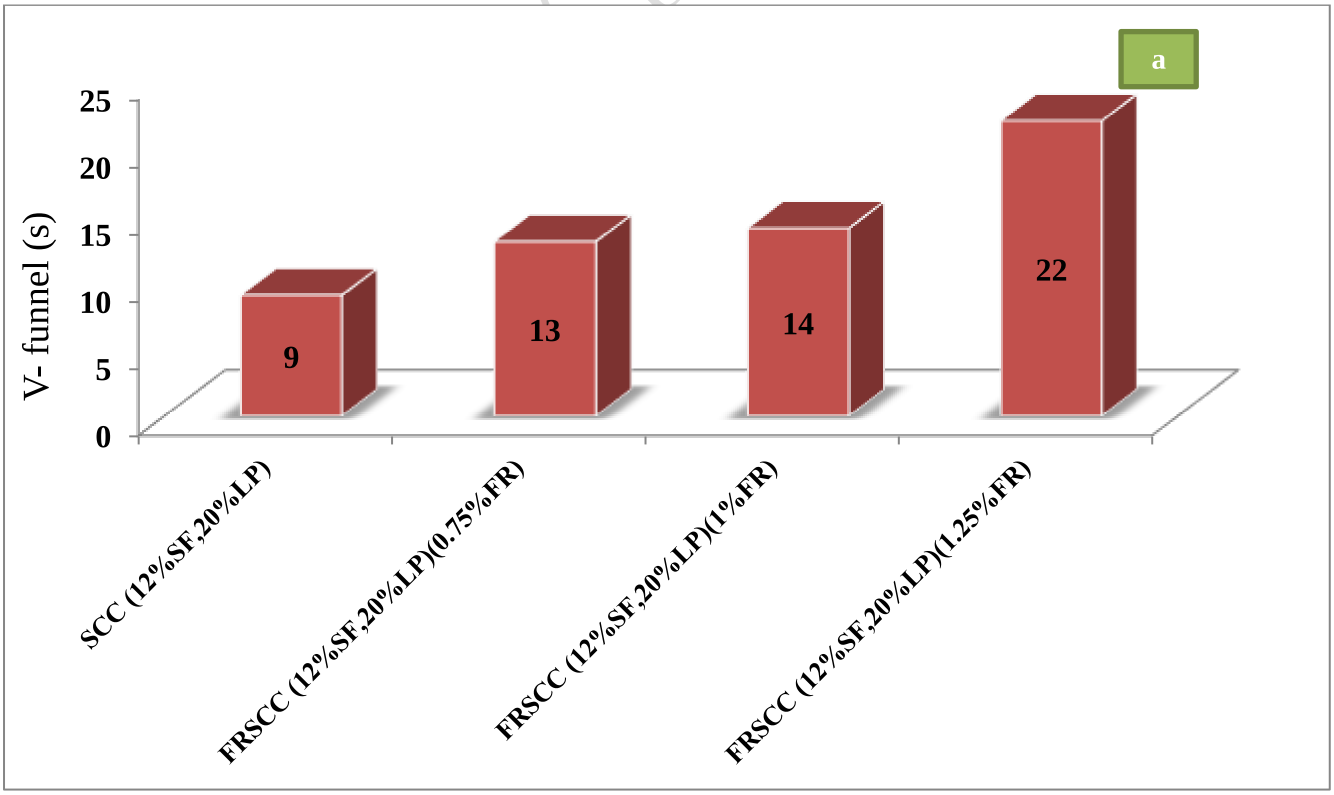

SCC (5% SF, 15% FA)
SCC (10% SF, 15% FA)
(Aslani and Nejadi, 2013)
0.94
0.93
0.92
0.91
0.9
0.89
0.88
0.87
0.86
0.85
0.84
H2/H1
0
0.05
0.1
0.15
0.2
0.25
Steel fiber content by volume %

(b)



(c)

Fig. 5 L-Box height variation with steel fiber ratio, (a) Rao and Ravindra (2010), Abbas (2013), Tavakoli et al. (2016), (b) Aslani and Nejadi (2013), (c) Alabduljabbar et al. (2019)



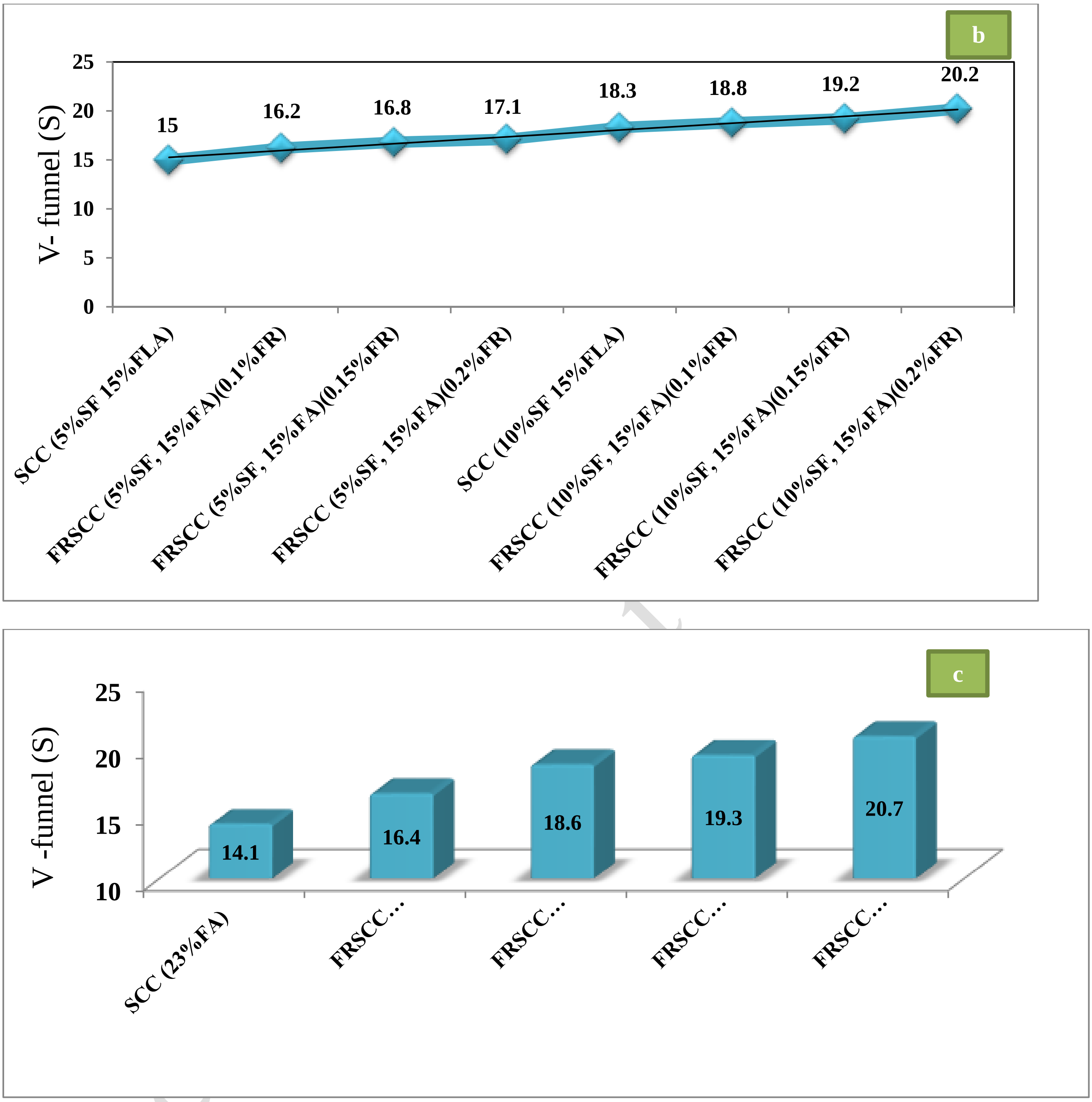


Fig. 6 V-funnel T5 variation with steel fiber ratio, (a) Al-Attar et al. (2018), (b) Memon et al. (2023), (c) Gencel et al. (2011)

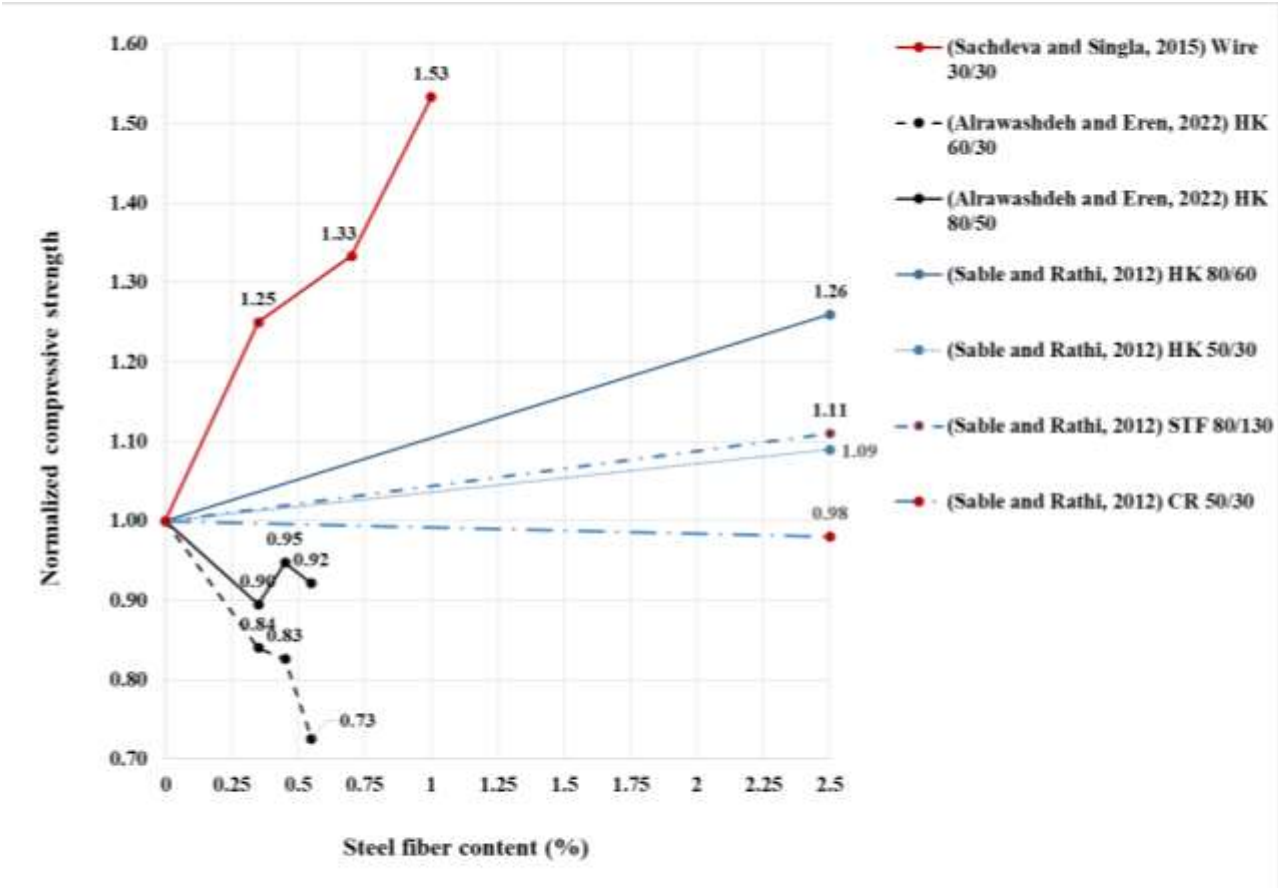


Fig. 7 Variation of normalized compressive strength with steel fiber ratio (age of 3 days)

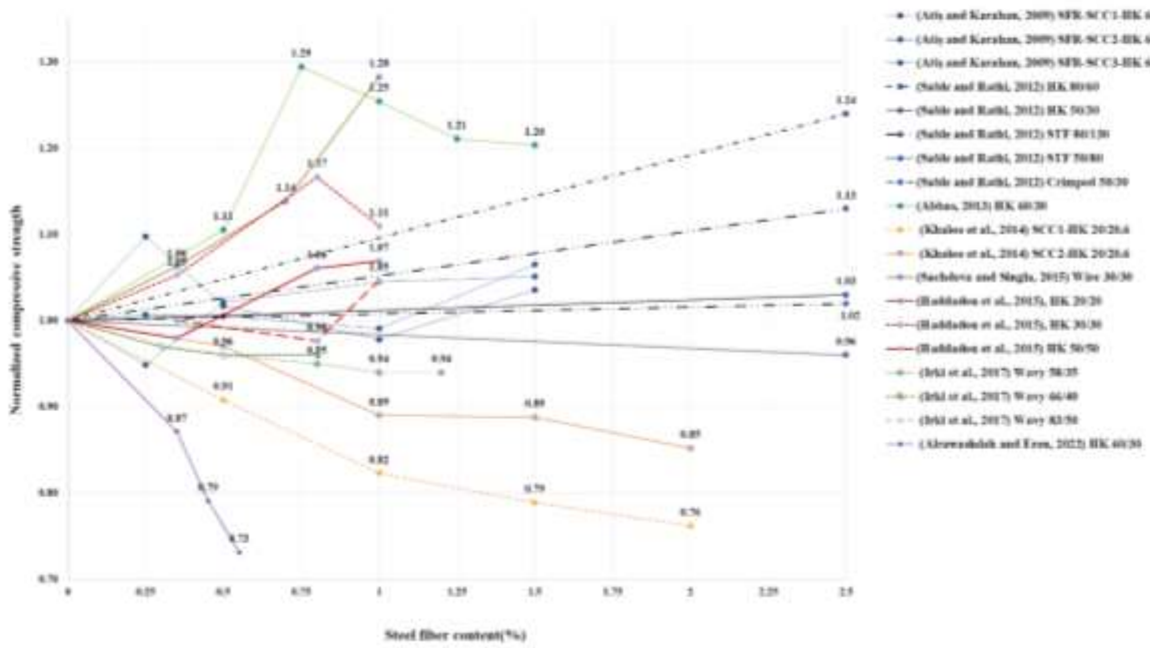


Fig. 8 Variation of normalized compressive strength with steel fiber ratio (age of 7 days)

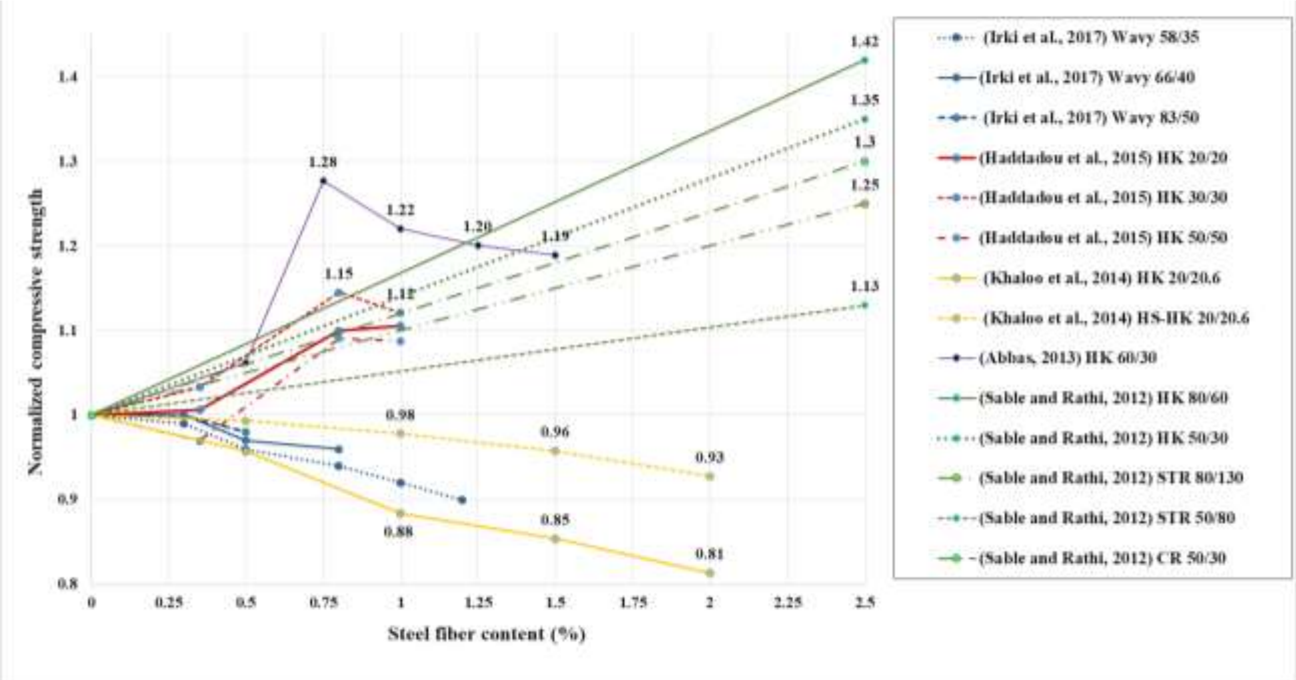


Fig. 9 Variation of normalized compressive strength with steel fiber ratio (age of 28 days)

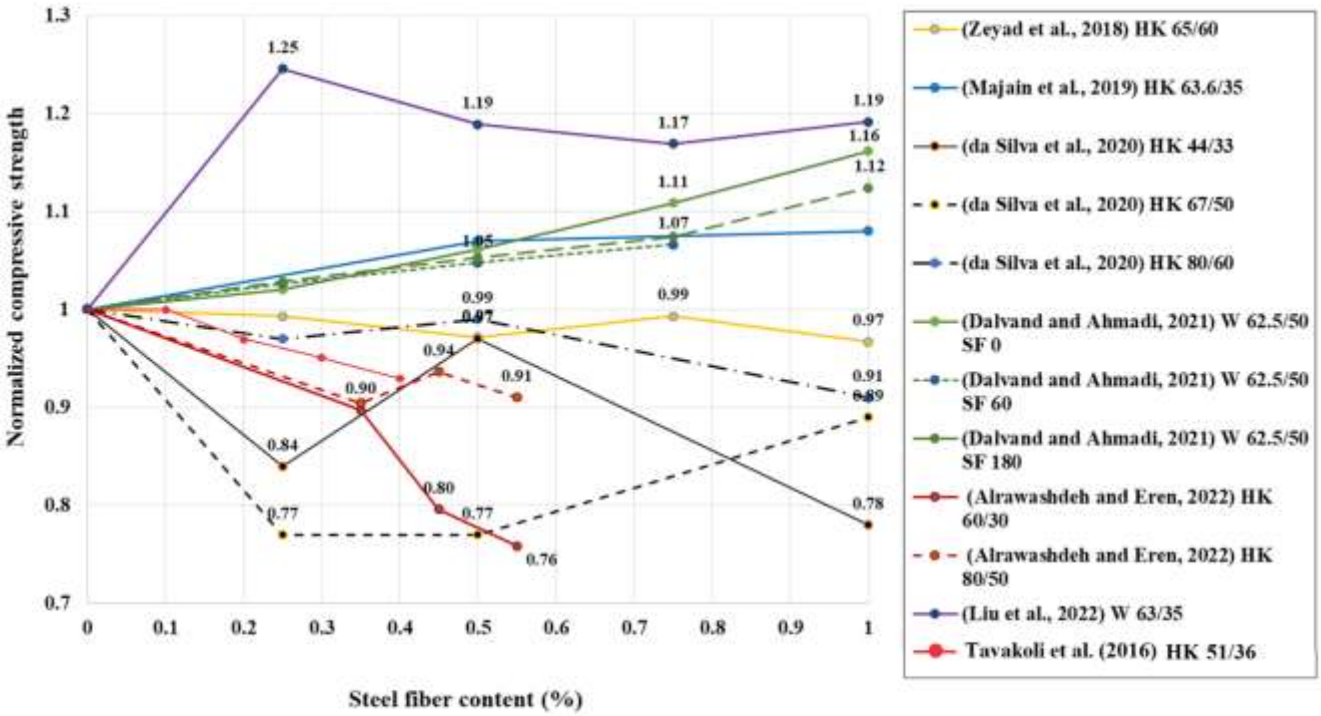


Fig. 10 Variation of normalized compressive strength with steel fiber ratio (age of 28 days)

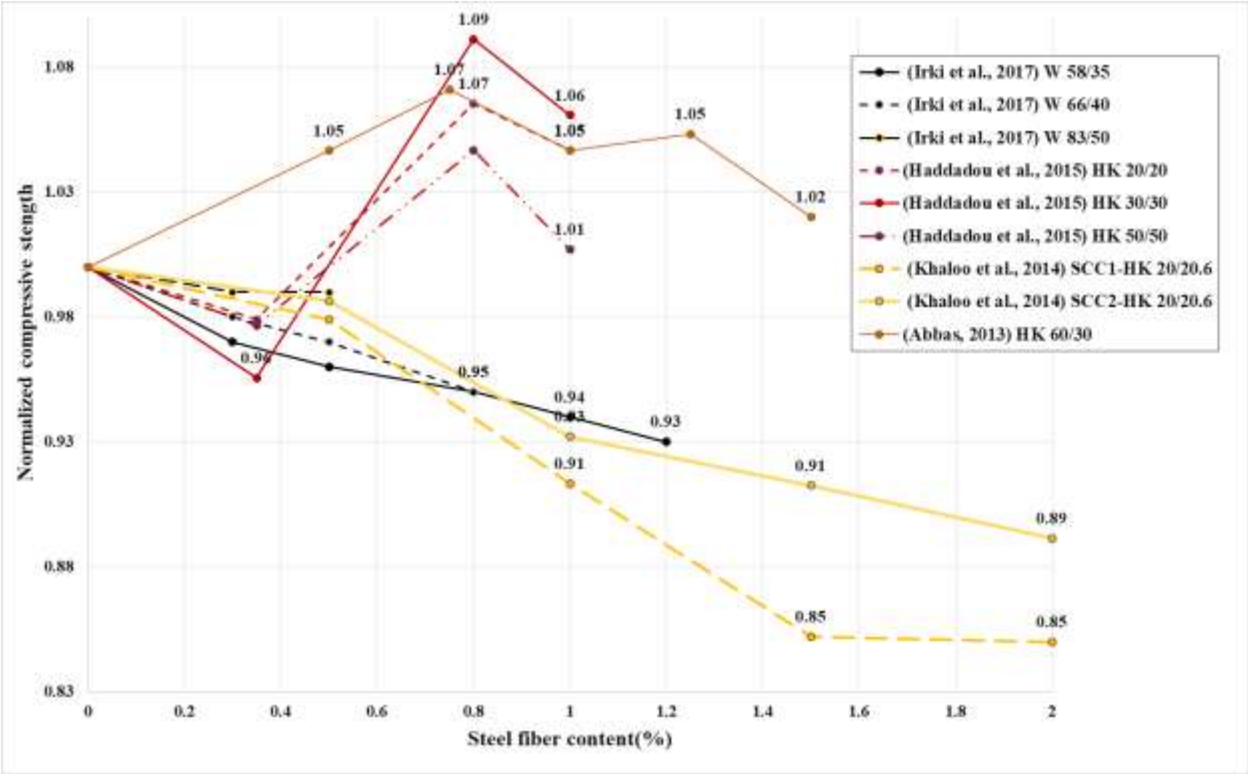


Fig. 11 Variation of normalized compressive strength with steel fiber ratio (age of 90 days)

Table 1 Description of material properties and results of flow diameter and time of SFR-SCC given by the researchers

Reference	Steel fiber properties			Mineral admixture type and %	Slump flow diameter (mm)	Flow time V-funnel (s)
	Shape of fiber	Aspect ratio	V_f (%)			
(Aslani and Nejadi, 2013)	Circular Straight	80	0	SCC(30%FA, 25%GGBS)	680	6
			0.4	FRSCC(30%FA, 25%GGBS)(0.4%FR)	670	7
			0.2	FRSCC(30%FA, 25%GGBS)(0.2%FR)	650	blocked
(Memon et al., 2023)	Circular Straight	20	0	SCC(5%SF, 15%FA)	746	11.8
			0.1	FRSCC(5%SF, 15%FA)(0.1%FR)	739	12.6
			0.15	FRSCC(5%SF, 15%FA)(0.15%FR)	733	13.1
			0.2	FRSCC(5%SF, 15%FA)(0.2%FR)	728	13.8
			0	SCC(10%SF15%FLA)	755	13.2
			0.1	FRSCC(10%SF, 15%FA)(0.1%FR)	751	13.7
			0.15	FRSCC (10%SF, 15%FA)(0.15%FR)	748	14.1
			0.2	FRSCC(10%SF, 15%FA)(0.2%FR)	741	14.2
(Zeyad et al., 2018)	Hooked end	65	0	NC	690	10
			0	SCC (35%FA)	670	8
			0.25	FRSCC(35%FA)(0.25%FR)	630	11
			0.5	FRSCC(35%FA)(0.5%FR)	560	14
(Alabduljabbar et al., 2019)	Straight circular	100	0	SCC	680	8
			1	FRSCC (1%FR)	770	7
			1.5	FRSCC (1.5%FR)	700	10
			2	FRSCC (2%FR)	675	7
			0	SCC (30%FA)	720	10
			1	FRSCC (30%FA)(1%FR)	738	8
			1.5	FRSCC (30%FA)(1.5%FR)	680	13
			2	FRSCC (30%FA)(2%FR)	730	6
			0	SCC (10%SF)	700	13
			1	FRSCC (10%SF)(1%FR)	700	12
			1.5	FRSCC (10%SF)(1.5%FR)	650	15
			2	FRSCC (10%SF)(2%FR)	690	6
			0	SCC (10%RHA)	700	16
			1	FRSCC (10%RHA)(1%FR)	685	13
			1.5	FRSCC (10%RHA)(1.5%FR)	625	18
			2	FRSCC (10%RHA)(2%FR)	700	7
(Barragán et al., 2004)	Hooked-ended	60	0.25	FRSCC (12%LP)(0.25%FR)	660	4
			0.5	FRSCC (12%LP)(0.5%FR)	650	5
			0.75	FRSCC (12%LP)(0.75%FR)	650	11
			0	SCC (7.5%SF, 27%LP)	620	6
			0.5	FRSCC (7.5%SF,	650	8

				27%LP)(0.5%FR)		
(Rao and Ravindra, 2010)	-	15,25,35	0	SCC (35%FA)	715	7.1
			0.5	FRSCC (35%FA)(0.5%FR)	685	7.4
			1	FRSCC (35%FA)(1%FR)	660	8.5
			1.5	FRSCC (35%FA)(1.5%FR)	650	9.8
(Madandoust et al., 2015)	Rounded shape	62.5	0	SCC (23%LP)	660	
			0.38	FRSCC (23%LP)(0.38%FR)	650	
			0.64	FRSCC (23%LP)(0.64%FR)	620	
			1	FRSCC (23%LP)(1%FR)	600	
			0	SCC (20%LP)	670	
			0.38	FRSCC (20%LP)(0.38%FR)	660	
			0.64	FRSCC (20%LP)(0.64%FR)	650	
			1	FRSCC (20%LP)(1%FR)	630	
			0	SCC (18%LP)	700	
			0.38	FRSCC (18%LP)(0.38%FR)	670	
			0.64	FRSCC (18%LP)(0.64%FR)	670	
			1	FRSCC (18%LP)(1%FR)	660	
			0	SCC (23%LP)	650	
			0.38	FRSCC (23%LP)(0.38%FR)	640	
			0.64	FRSCC (23%LP)(0.64%FR)	640	
			1	FRSCC (23%LP)(1%FR)	610	
			0	SCC (20%LP)	670	
			0.38	FRSCC (20%LP)(0.38%FR)	650	
			0.64	FRSCC (20%LP)(0.64%FR)	650	
			1	FRSCC (20%LP)(1%FR)	620	
			0	SCC (18%LP)	680	
			0.38	FRSCC (18%LP)(0.38%FR)	660	
			0.64	FRSCC (18%LP)(0.64%FR)	670	
			1	FRSCC (18%LP)(1%FR)	640	
(Abbas, 2013)	Round wire	60	0	SCC (23%LP)	750	6.6
			0.5	FRSCC (23%LP)(0.5%FR)	720	7
			0.75	FRSCC (23%LP)(0.75%FR)	680	7.7
			1	FRSCC (23%LP)(1%FR)	670	8.3
			1.25	FRSCC (23%LP)(1.25%FR)	625	8.8
			1.5	FRSCC (23%LP)(1.5%FR)	584	9.3
(Alyousif, 2010)	Round steel fiber	20-100	0	SCC (15%SF)	715	8
			0.25	FRSCC (15%SF)(0.25%FR)	712	8.8
			0.4	FRSCC (15%SF)(0.4%FR)	708	9.1
			0.5	FRSCC (15%SF)(0.5%FR)	705	9.4
(Gencel et al., 2011)	Cylindrical with hooked end	60	0	SCC (23%FA)	769	
			0.2	FRSCC (23%FA)(0.2%FR)	692	
			0.4	FRSCC (23%FA)(0.4%FR)	645	
			0.6	FRSCC (23%FA)(0.6%FR)	603	
			0.8	FRSCC (23%FA)(0.8%FR)	582	
(Al-Attar et al., 2018)	Straight circular	75	0	SCC (12%SF,20%LP)	770	6.5
			0.75	FRSCC (12%SF,20%LP)(0.75%FR)	660	9
			1	FRSCC (12%SF,20%LP)(1%FR)	610	11
			1.25	FRSCC (12%SF,20%LP)(1.25%FR)	480	18
			0	SCC (41%LP)	760	

(Tavakoli et al., 2016)	Hooked end circular section	51	0.1	FRSCC (41%LP)(0.1%FR)	750	
			0.2	FRSCC (41%LP)(0.2%FR)	735	
			0.3	FRSCC (41%LP)(0.3%FR)	730	
			0.4	FRSCC (41%LP)(0.4%FR)	710	

Table 2 Description of steel fiber properties, mineral admixture and control compressive strength given by the researchers

Reference	Steel fiber properties				Concrete properties	
	Shape	Aspect ratio	(%)	(kg/m^3)	Mineral admixture type, (%)	28 days compressive strength (MPa)
(Sahmaran and Yaman, 2007)				0	FA (250 kg/m3)	23.3
	hooked end	55		60		
	hooked+ straight			30+30		
	straight	37.5		60		
(Atiş and Karahan, 2009)	hooked end	64	0	0	0	77.1
			0.25	19.625		
			0.5	39.25		
			1	78.5		
			1.5	117.75		
			0	0	FA (60 kg/m3)	67.8
			0.25	19.625		
			0.5	39.25		
			1	78.5		
			1.5	117.75		
			0	0	FA (120 kg/m3)	63.6
			0.25	19.625		
			0.5	39.25		
			1	78.5		
			1.5	117.75		
(Boulekbache et al., 2010)	hooked end	35/0.55		0	0	61
				40		
(Gencel et al., 2011)	hooked end	60		0	FA (120 kg/m3)	56.8
				15		
				30		
				45		
				60		
(Hatim Khuthair Alubaidi, 2011)	hooked end	60	0			35
			0.5			
			1			
(Sable and Rathi, 2012)			0		FA (149.9 kg/m3)	32.5
	hooked end	80	2.5			
	hooked end	50				

	straight	80				
	straight	50				
	crimped	50				
(Abbas, 2013)	hooked end	60	0			35.4
			0.5			
			0.75			
			1			
			1.25			
			1.5			
(Salih et al., 2014)		100		0		86.2
				12		
				0	FA (180 kg/m3) (30%)	69.6
				12		
				0	SF (60 kg/m3) (10%)	90.6
				12		
(Khaloo et al., 2014)	hooked end	20	0			39.7
			0.5			
			1			
			1.5			
			2			
			0		SF (50 kg/m3)	59.5
			0.5			
			1			
			1.5			
			2			
(Frazão et al., 2015)	hooked end	70		-		60.28
				60		
(Sachdeva and Singla, 2015)	wire	30	0		FA (200 kg/m3)	22.5
			0.35			
			0.7			
			1			
(Haddadou et al., 2015)	hooked end		0			33.1
		20	0.35			
			0.8			
			1			
		30	0.35			
			0.8			
			1			
		50	0.35			
			0.8			
			1			
(Madandoust et al., 2015)	hooked end	62.5	0	0		30.4
			0.38	30		

			0.64	50		
			1	80		
			0	0		29.3
			0.38	30		
			0.64	50		
			1	80		
			0	0		26.8
			0.38	30		
			0.64	50		
			1	80		
			0	0		32.7
			0.38	30		
			0.64	50		
			1	80		
			0	0		30.9
			0.38	30		
			0.64	50		
			1	80		
			0	0		29.4
			0.38	30		
			0.64	50		
			1	80		
(Facconi et al., 2016)			0	0		56.1
	double hooked end	65	0.32	25		
	single hooked end	80	0.25	20		
			0.32	25		
(Yehia et al., 2016)	hooked end	67	0	0	SF (110 kg/m3)	72.1
				38.8		
				0		
				38.8		
(**Tavakoli et al., 2016)**	Hooked end	51	0		LP (288.9 kg/m3)	70.2
			0.1			
			0.2			
			0.3			
			0.4			
(Irki et al., 2017)	wavy		0	0		55.74
		58.33	0.3	15		
			0.5	25		
			0.8	40		
			1	50		

			1.2	60		
		66.67	0.3	15		
			0.5	25		
			0.8	40		
		83.33	0.3	50		
			0.5	25		
(Nehme et al., 2017)	hooked end	64		0		53
				30		
				60		
				90		
(Anil, 2018)			0	0	FA (180 kg/m3)	57.75
	hooked end	65	0.5	39		
	hooked end	64	1	78		
	straight	81	0.5	39		
	hybrid		0.5 + 0.5	78		
(Begum et al., 2018)	-	40	0		FA (240 kg/m3)	60.7
			0.5			
			1			
(Zeyad et al., 2018)	hooked end	65	0	0	FA (150 kg/m3)	42.4
			0.25	19.6		
			0.5	39.2		
			0.75	58.5		
			1	78.5		
(Majain et al., 2019)	hooked end	63.6	0		FA (178.64 kg/m3)	69.99
			0.5			
			1			
(da Silva et al., 2020)	hooked end		0		FA (181 kg/m3)	63
		44	0.25			
			0.5			
			1			
		67	0.25			
			0.5			
			1			
		80	0.25			
			0.5			
			1			
(Dalvand and Ahmadi, 2021)	wavy	62.5	0		0	58.9
			0.25			
			0.5			
			0.75			
			1			

			0		SF (60 kg/m3)	
			0.25			
			0.5			
			0.75			
			1			
			0		SF (180 kg/m3)	
			0.25			
			0.5			
			0.75			
			1			
(Alrawashdeh and Eren, 2022)	hooked end		0			69.2
		60	0.35			
			0.45			
			0.55			
		80	0.35			
			0.45			
			0.55			
(Liu et al., 2022)	wavy	63	0		FA (241.6 kg/m3)	40.47
			0.25			
			0.5			
			0.75			
			1			

Table 3 Main aspects of behavior of SCC containing steel fiber

No.	Property	Remark
1	Slump flow	Slump flow is reduced with increasing fiber, but the flow is within the boundaries set by EFNARC for fiber up to 1.25%. Out of 14 tests, one mix containing fly ash showed deviation from the limit.
2	T50	T50 increased with increasing steel fiber up to 1%, but all tested SCC mixes fall within the boundaries of ACI 237. Existence of silica fume in the mix has larger effect on the T50 enhancement compared with the other additives. As compared with the other additives (fly ash and GGBS) limestone powder has good action to control T50 increase occurred because of steel fiber.
3	V-funnel time	Different SCC mixes could be designed for different V-funnel times according to the mix proportion and additives type and ratio. Steel fiber addition enhances V-funnel time, but for the majority of tested mixes V-funnel time is within the boundaries set by EFNARC for fiber content up to 1%. In general, mixes containing rice husk ash and silica fume, in contrast to limestone powder, have no good action on the V-funnel time, while the action of fly ash is not clear.
4	J-ring diameter	Studies of this property of SCC containing steel fiber are limited, and no clear conclusion is obtained. However, a reduction in J-ring diameter is observed

		depending on the mix characteristics being increased with GGBS and fly ash addition to the mix.
5	L-box height ratio	Addition of steel fiber up to 2% has low effect to change the L-box height ratio (H2/H1), all tested mixes conform to the specification limits and additives have no serious effect to change the height ratio.
6	V-funnel at T5 minutes	Identical to the case of V-funnel time, V-funnel T5 increased with increasing steel fiber and the existence of additives has an impact on the variation.
7	Compressive strength	There is a compressive strength enhancement or reduction of SCC containing steel fiber and no unique conclusion is drawn for the change. The variation depends on SCC mix proportion, existence of additives, curing time and fiber characteristics mainly fiber ratio, type, aspect ratio and surface characteristics.
8	Compressive stress-strain relationship	With increasing steel fiber volume, strain corresponding to peak-stress of the compressive stress–strain curve increased, while the slope of the descending portion decreased, leading to the energy absorption capacity and toughness enhancement.
9	Tensile strength	Tensile strength increases because of steel fiber addition to SCC depending on fiber aspect ratio and pull-out bond between fiber and hardened matrix. The presence of fibers prevents the emergence of interior microcracks and has the ability to stop fracture advancement leading to tensile strength improvement.
10	Flexural strength	Adding steel fiber to SCC significantly improves flexural strength, while the first crack load only slightly rises, but flexural strength is reduced when fiber content is increased more than optimum percentages. Also, the beams' flexural toughness improved as the amount of steel fiber increased.
11	Durability	The rate of chloride ion diffusion is low because of very low porosity of the cementitious matrix. The durability of SCC improved with the addition of steel fiber due to prevention of shrinkage cracks. Therefore, penetration of harmful chemical solutions causing degradation is reduced and consequently durability increased.