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Impact resistance, microstructures and digital image processing on self-compacting concrete with hooked end and crimped steel fiber

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HIGHLIGHTS

- This current research paper is focused on the toughness and impact resistance of hybrid fiber reinforced self-compacting concrete.
- Compressive strength made this suitable for structural elements.
- Using SEM images, the SCC's failure mechanisms were assessed and fibre-aggregate interface was evaluated.
- In digital image processing, the cross sections inspected and fiber segregation coefficient values were evaluated.

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ABSTRACT

This research paper presents the results of extensive experimental investigations and analytical results on the fresh and hardened properties of self-compacting concrete reinforced with hybrid hooked end fiber (HF) and crimped steel fiber (CF) in different fiber volume fractions. In this present investigation, the mixes were reinforced with different fiber combinations of hooked end fiber (0.25, 0.5 and 0.75%) and crimped fiber (0.25 and 0.5%). The fresh state properties of the mixes were characterized by using slump flow diameter, T_{50cm}, and V-funnel test. The hardened properties of self-compacting concrete (SCC) mixes were assessed by using compressive strength, flexural strength and impact resistance test. Regression analysis was carried out in order to correlate the fresh and hardened state on the extensively large volume of collected experimental data. The results reported that adding hybrid hooked end-crimped steel fiber significantly improves the compressive strength, flexural strength and impact resistance. Addition of hooked end steel fiber led to improve the compressive strength when compared to crimped end fiber. Moreover, increasing the crimped fiber content decreased the effect of hooked end steel fiber in flexural strength improvement.

1. Introduction

In last two decades, the major research projects have focused on steel fiber reinforced concrete (FRC) for the construction of tunnels, airport runways, hydraulic structures, railway sleepers, underground works, earthquake resistance structures and highway projects like bridges [31]. The study of the fresh and hardened properties of FRC Akcay and Tesdemir [3] reported that length, diameter and shapes of fiber were extensively most important parameters that significantly affect the reinforcing capacity and toughening behavior of steel fiber reinforced concrete. Many Foreign researchers have manufactured fiber reinforced concretes by adding different geometries or shapes of single steel fiber. They produced concretes with better reinforcing capacity, compressive strength, flexural strength, toughness and fracture energy absorption capacity than single-fiber-reinforced concrete.

Main drawback of concrete with fibers is its very low ductility property. Moreover, these plain concrete has low tensile characteristics, flexural strength and corresponding properties. Incorporation of steel fibers is a very effective way of producing plain concrete with enhanced hardened properties such as compressive, flexural strength properties and impact resistance. This method of adding steel fiber has proved to improve the ductility properties, toughness and post-cracking strength of steel fiber reinforced concrete by enhancing the fiber-bridging and interfacial bonds of fiber matrix. The enhancement of fiber-bridging mainly influences the hardened properties of concretes [10,15,22,17]), toughness properties, [9,16], ductility behavior [21,20]), torsion [27,29], impact resistance of concrete[4,24]. Addition of hybrid macrofibers – microfibers mainly enhances the steel fiber reinforced concrete

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in terms of post-crack performance of concrete under flexural strength test (Sorelli et al., 2003, [23].

Khaloo et al. [19] reported fresh and hardened properties of steel fiber reinforced self-compacting concrete. In their test, they used four different volume fractions of steel fibers (0.5, 1, 1.5, and 2%) to enhance fiber bridging of steel fiber reinforced mix compositions. The rheological properties were evaluated by slump flow test, T_{50cm}, L-box test and V-funnel tests. Moreover, it was proved that the characteristics of fresh and hardened concrete were evaluated through compresstive, flexural and splitting tensile strength test. They proved that incorporation of steel fiber decreased the fresh properties of steel fiber reinforced concrete mixtures. Additionally, it was proved that incorporation of steel fiber enhances splitting tensile, flexural strength and toughness behavior but decreasing compressive strength of concrete [19,8].

Banthia et al. investigated an extensive experimental investigation in order to evaluate the flexural toughness with larger diameter mixed with smaller diameter of crimped fibers. The experiment results revealed that hybridization of steel fiber in concrete is a very promising method and substituting large diameters with smaller diameter of crimped fibers led to enhance significantly the flexural toughness behavior [7]. Sun et al. revealed that the high-performance fiber reinforced concrete incorporated with hybrid fibers, i.e., polyvinyl alcohol fiber (PVA), steel fibers, and polypropylene (PP) fiber. In their rest, it was proved that the hybridization of fibers with different types, sizes and shapes may decrease the propagation of crack and its width, size and amount [30]. Dawood and Ramli studied the high strength concrete characteristics with hybrid fibers such as palm fibers, steel fibers and synthetic fibers (2% of volume fraction). The experiment results revealed that the hybrid fiber improves the toughness and tensile characteristics. Incorporation of hybrid fibers led to enhance the impact resistance and post-crack performance [12].

One of the major issues associated with plain cement concrete is the brittleness. When a structure is subjected to earthquake loads, the brittleness of the plain cement concrete magnifies. Moreover, in regions with high seismic intensity and unspecified standards building codes, RC structures have established into a death trap for many individuals. However, a common approach regarding the issue correlated with the brittleness of concrete is incorporation of steel reinforcement. Still, this may be very expensive, greatly dependent on labor's skillfulness, and also mainly dependent on the quality of steel. A solution recommended in this research work consists of introducing steel fibers to the SCC.

The main contribution of this paper, however, lies in the determination of fresh and hardened properties of SCC's incorporating hooked end and crimped steel with various levels and most primarily, the determination of total number of fibers in cross section using digital image processing and evaluation of ITZ of SCC. The outcome of this research project provides toughness, flexural strength and ductility behaviour of SCC with hybrid steel fiber.

To the best of author's knowledge, no experimental/analytical investigations have yet been reported on impact resistance, SEM analysis and Digital image processing of SCC with hybrid fibers. This research work seeks mainly to address the large gap in the current existing literature by inspecting the fresh and mechanical characteristics of SCCs incorporating hooked end and crimped steel fibers. However, many research projects were depending upon plain concrete, and there is very minimum number of studies on mechanical characteristics of concrete with hybridization of steel fibers. Additionally, an experimental investigation was carried on mechanical characteristics of high strength concrete with hooked end steel and deformed steel fiber [6]. Yet, that investigation has not reported any experimental, analytical studies, micro-structural analysis (SEM) and Digital image processing parameters of the SCC with hybrid fibers.

In this current investigation research, the fresh properties of hybrid steel fiber reinforced self-compacting concrete were assessed by performing slump flow test, T_{50cm} and V-funnel test. Moreover, the hardened properties and impact resistance of SCC specimens were characterized by using 120 hardened specimens. Hardened properties were revealed through performing compressive and flexural tests. Additionally, some analytical studies, micro-structural analysis (SEM) and Digital image processing were also carried out with extensive large volume of gathered results in order to assess and correlate the fresh and mechanical properties of SCC specimens.

2. Experimental program

2.1. Materials and mix designs

The mix compositions of present investigation contain portland cement, coarse and fine aggregates, water, mineral additives (Silica fume) and superplasticizer (SP). Table 1 depicts the physical and chemical properties of the cement and silica fume used for this study. The mix proportions of used materials are listed in Table 2, which represents that the contents acquired from a target flow diameter more than or equal to 650 mm in slump flow test for SCC as per EFNARC guidelines. The notations used for each specimen were represented in Table 2. They are as follow the notation H means hooked end fiber, the number after H means the hooked end fiber volume fraction, C means crimped fiber, and the number after C means the crimped fiber volume fraction.

As represented in Table 2, totally 12 mixtures with different fiber volume fraction were prepared, cast in moulds, cured and tested to evaluate the fresh, mechanical characteristics properties and impact resistance behavior of hybrid steel fiber reinforced self-compacting concrete with hooked end – crimped steel fiber. The fiber volume fractions of CF fiber ranged from 0, 0.25% and 0.5%, and the fiber volume fractions of HF varied from 0 to 0.25%, 0.5, and 0.75%. Moreover, a highrange water reducer (HRWR) super plasticizer agent was used. The super plasticizer used was a polycarboxylic-ether based admixture, commercially branded as Glenium Master Sky 8233 in order to adjust the workability of SCC mixes. Steel fibers were used to reinforce self-compacting concretes. The HFs had a length of 70 mm, diameter of 0.7 mm, and tensile strength 2100 MPa. Density of fibers was approximately 7850 kg/m^3. The hooked end fiber and crimped fiber used in this study are shown in Fig. 1. Moreover, to produce hybrid fiber combinations, crimped fiber with a length of 70 mm, diameter of 0.7 mm, tensile strength of 2100 MPa, was added to mixtures. For batching, Coarse aggregate, fine aggregate, cement, mineral additives were mixed in concrete mixer for 5 min. Then, superplasti-

Table 1
Chemical Composition and Physical Properties of Portland Cement and silica fume.

Items	Cement	Silica fume
SiO_2	25.6	36.85
Al_2O_3	6.8	12.65
Fe_2O_3	2.96	0.92
CaO	63.02	41.4
MgO	1.62	7.86
SO_3	–	–
P_2O_3	–	–
Na_2O	–	0.68
K_2O	–	–
LOI	–	–
	Compounds	
C_3S	52.5	–
C_2F	21.0	–
C_3A	6.4	–
C_4AF	10.5	–

Table 2
Proportions of the Materials Used in the Mix Compositions (kg/m^3).

Specimen	Cement	Silica fume	Fine aggregate	Coarse aggregate	SP (%)	W/C	Hooked end Fibre (volume %)	Crimped Fiber (Volume %)
0% HF – 0% CF	500	31	919	843	7.5	0.32	0	0
0.25% HF – 0% CF							0.25	0
0.5% HF – 0% CF							0.5	0
0.75% HF – 0% CF							0.75	0
0% HF – 0.25% CF							0	0.25
0.25% HF – 0.25% CF							0.25	0.25
0.5% HF – 0.25% CF							0.5	0.25
0.75% HF – 0.25% CF							0.75	0.25
0% HF – 0.5% CF							0	0.5
0.25% HF – 0.5% CF							0.25	0.5
0.5% HF – 0.5% CF							0.5	0.5
0.75% HF – 0.5% CF							0.75	0.5

Note: W/C = water to cement

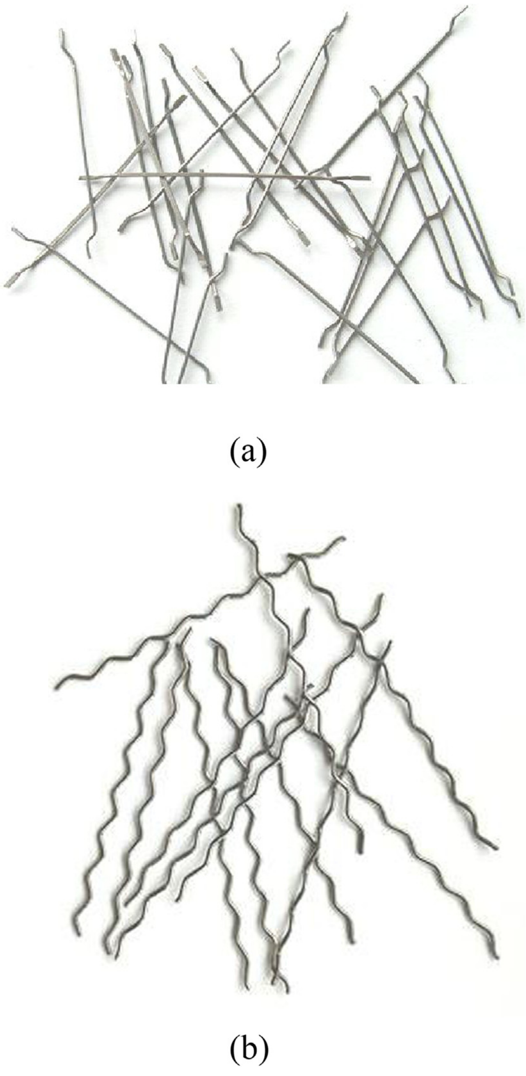


Fig. 1. (a) Hooked end steel fiber; (b) Crimped Steel fiber.

cizer with water was added and mixed in the concrete mixer for 6–8 min. The concrete–fiber mix compositions were prepared by adding hybrid hooked end and crimped steel fibers to the fresh SCC mixes while incorporating enough HF and CF fibers to the mixes in order to obtain desired fiber volume fraction was acquired. Steel fibers were added gradually and slowly to SCC mixes to avoid balling effect due to fiber content. Afterward, the SCC mixes were then cast into respective molds. For compression test, cube molds of 100 mm dimensions were used. For flexural strength test, the prismatic beams of size 500 × 100 × 100 mm were utilized. Finally, cylindrical disk molds of size 150 × 65 mm were used for impact test [28,14].

All the cast moulds were kept at 24 °C temperature for 24 h. Then, those specimens were demolded and kept it for curing in water with temperature of 20 °C for 28 days. After 28 days of curing, totally 120 SCC specimens were taken for performing test so as to assess the characteristics such as impact resistance, compression, flexural properties, SEM analysis and Digital impage processing. Table 3 represents the investigation revealed in this current paper. Slump test and V-funnel tests were performed as per the guidelines given by EFNARC [13] in order to evaluate the fresh properties of SCC mixes. Slump flow and V-funnel test are common way to assess the flowability, passing ability of SCC [26] on horizontal surface. Fig. 2 depicts the slump flow test and slump flow diameter for the Hybrid steel fiber reinforced SCC with 0.75% hooked end steel fiber and 0.25% crimped fiber. Hybrid hooked end and crimped steel fibers were distributed homogenously in the mixture compositions. No segregations were occurred between cement and fibers, as shown in Fig. 2. However, using HF with a length of 70 mm led to some difficulties for evaluating the fresh properties of hybrid steel fiber reinforced SCC. Therefore, slump flow and T_{50cm} test was performed based on EFNARC [13] to overcome the difficulties in obtaining the fresh properties of hybrid steel fiber reinforced SCC containing large amounts of HFs and CFs.

Additionally, Prismatic beams were utilized for assessing the flexural strength of hybrid steel fiber reinforced SCC mixes with hooked end and crimped fiber with length of 70 mm could provide the fibers a planar orientation. Furthermore, this planar orientation of fibers considerably influences the flexural characteristics of prismatic beams [24]. Therefore, the influences of planar fiber orientation are considered into account for assessing the hardened properties of hybrid steel fiber reinforced SCC mixes containing

Table 3
Considered Specimens for the Experimental Program.

Specimen	Compressive test (28 days)	Four point bending test(28 days)	Impact test (28 days)
0% HF – 0% CF	3	3	4
0.25% HF – 0% CF	3	3	4
0.5% HF – 0% CF	3	3	4
0.75% HF – 0% CF	3	3	4
0% HF – 0.25% CF	3	3	4
0.25% HF – 0.25% CF	3	3	4
0.5% HF – 0.25% CF	3	3	4
0.75% HF – 0.25% CF	3	3	4
0% HF – 0.5% CF	3	3	4
0.25% HF – 0.5% CF	3	3	4
0.5% HF – 0.5% CF	3	3	4
0.75% HF – 0.5% CF	3	3	4

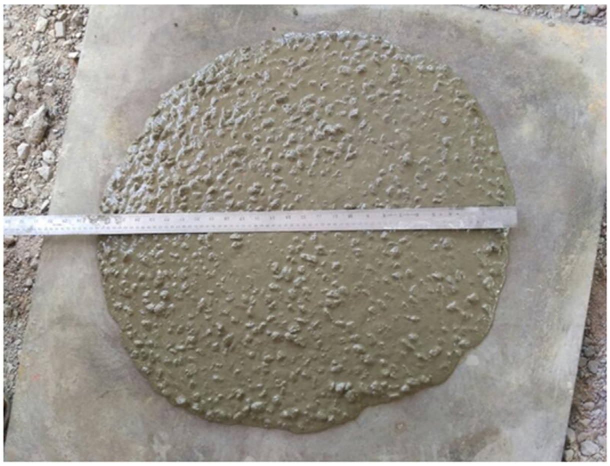


Fig. 2. Slump flow test.

large volume of HF, the compressive strength, flexural strength and impact resistance were acquired by utilizing specimens with cubic specimens (100 mm), prism specimens (500 × 100 × 100 mm) and cylindrical disks (150 × 65 mm) respectively.

3. Test setups and test procedures

3.1. Compressive test

Totally, 36 cubical specimens (Size of 100 mm) were used to perform the compression test and test were preformed based on Indian Standard for evaluating compressive strength behavior of hybrid steel fiber reinforced SCC. For each SCC mixes, 3 cubical specimens used to perform compression test and the average of 3 test results was taken into account. A standard compression testing machine with maximum capacity of 3000kN utilized to apply load on cubes. In this present investigation, about 40 MPa was considered as minimum compressive strength for hybrid steel fiber reinforced SCC mixes.

3.2. Four-point bending test

Totally, 36 prisms were used to evaluate the flexural strength. The prismatic beams of size 100 × 100 × 500 mm were used. Moreover, the flexural test was performed as per Indian standards and their recommendation. For each SCC mixes, the flexural strength were calculated by taking average of three specimens. The capacity of flexural testing machine was 50kN. In which the deflection at point ‘a’ (distance between the supporting and loading pins) were measured using LVDT with 50 mm stroke. Fig. 3 illustrates the test setup adopted for four point bending test. Eq. (1) depicts the flexural strength of SCC specimens under FPB test

$$\sigma_f = \frac{3Fa}{bd^2} \tag{1}$$

where F = total flexural load; **a** - distance between the supporting and loading pins; and b and h = width (equal to 100 mm) and height (equal to 100 mm) of beams, respectively.

3.3. Impact drop weight test

Totally, 48 cylindrical disks were used to evaluate the impact resistance of hybrid steel fiber reinforced SCC mixes. It was carried out on cylindrical disks of size 150 mm diameter and 65 mm of height. For SCC mixes, the first crack and ultimate crack load and number of blows for impact resistances were acquired by taking

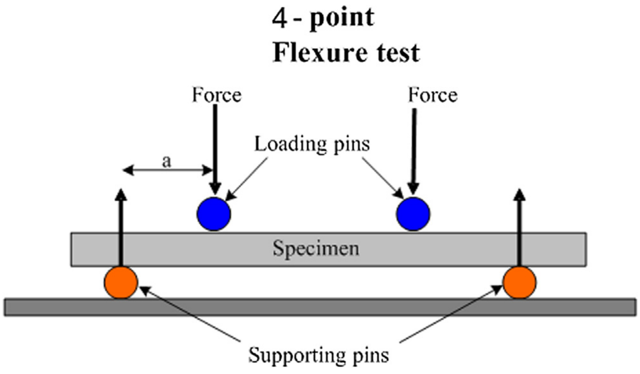


Fig. 3. Adopted flexural test setup.

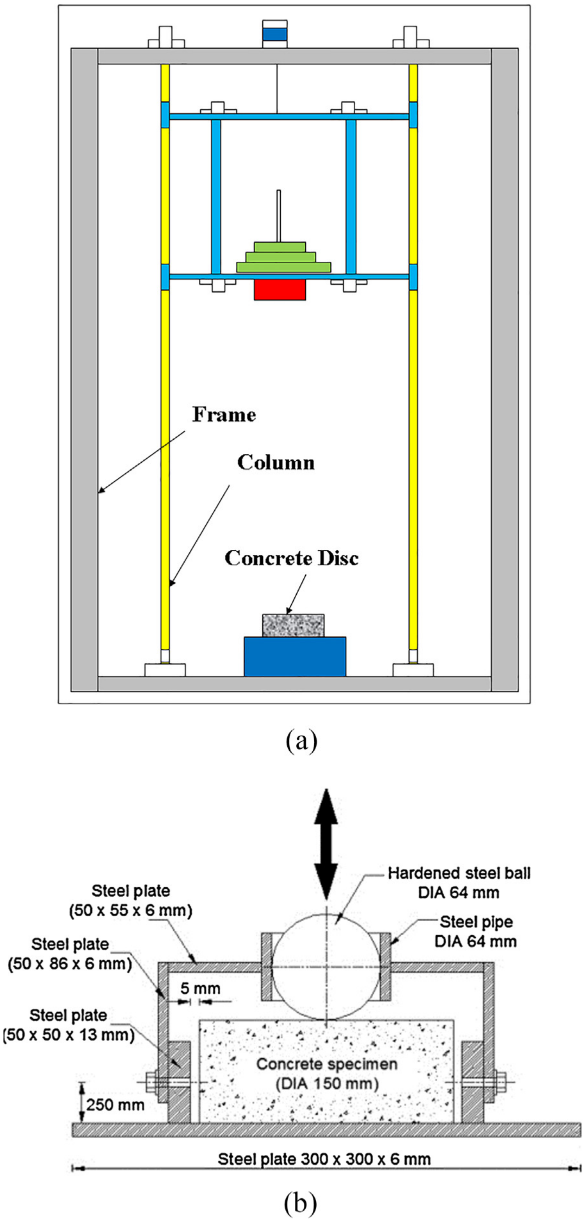


Fig. 4. Schematic diagram (a) Drop-weight impact machine; (b) Impact test - Specimen setup.

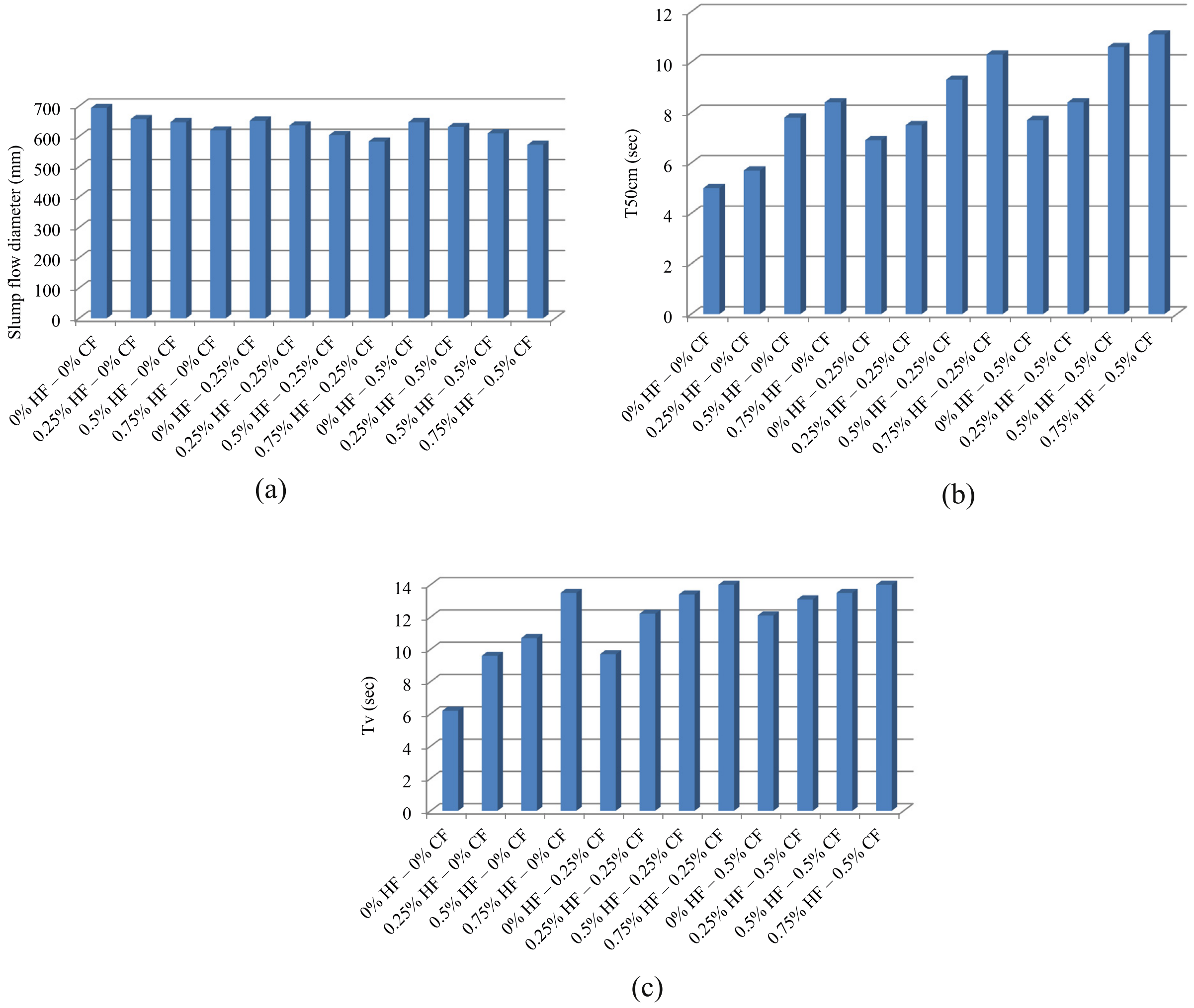


Fig. 5. Recorded results for (a) slump flow diameter; (b) T_{50cm}; (c) Tv.

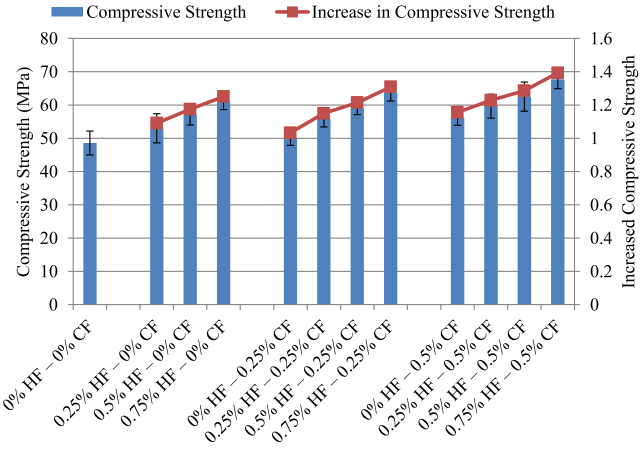


Fig. 6. Effects of fiber on the average of compressive strength.

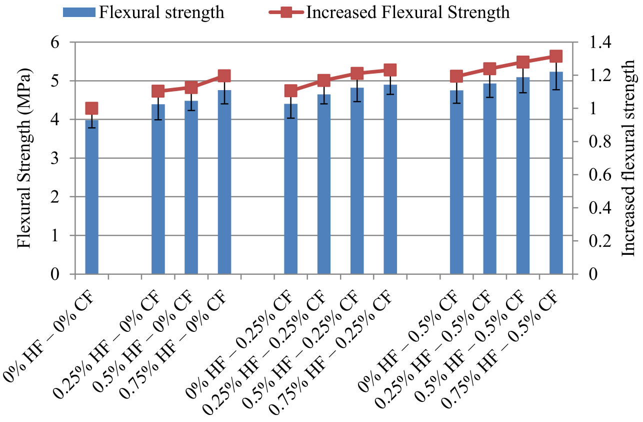


Fig. 7. Effects of fiber on the average of flexural strength;

average of four cylindrical replicated disks of SCC mixes. The test setup consists of a free-fall drop with instrumented hammer ball above the center of the disks (Fig. 4(a)). Impact drop weight impact test was performed on SCC specimen in the laboratory based on guidelines of ACI committee [2]. The impact testing machine included of a 4.5 kg ball hammer on center of disks falling from the height of 450 mm on a hardened SCC specimen of 65 mm height (Fig. 4(b)).

3.4. Digital image analysis using ImageJ software

For digital image process, SCC specimens were performed on test prisms after four point flexural test. Afterward, saw cutting was done for FPB tested specimen. Exposed surface of SCC specimen was wetted and polished in order to give better reflection of fibers and visibility of fibers. Camera with high resolution was utilized to ensure good quality images of prepared specimen

[300 dpi]. Furthermore, the following steps were carried out: (i) spectral transforming (grayscale); (2) forming a binary image (3) applying filters to remove interference and other small noise, Then separating HF/CF fibers from cementing materials touching each other; and (4) selecting an elliptical orientation in order to evaluate the total number of fibers in cross section.

3.5. Micro-structural analysis (SEM analysis)

The microstructure of the SCC specimen was carried out by using SEM – Scanning Electron Microscopic machine (ZEISS make) at EHT 20 kV. The microscope testing was evaluated on 1 cm square pieces from tested SCC concrete samples. Moreover, on the surface of square specimen, a layer of gold was applied as coating.

4. Results and discussion

4.1. Fresh mix properties

As discussed before, the fresh characteristics of hybrid steel fiber reinforced self-compacting concrete were obtained by slump and V-funnel test. The obtained results were cross checked with EFNARC guidelines. The results of hybrid steel fiber reinforced self-compacting concrete were illustrated in Fig. 5(a)–(c). The results revealed that the incorporation of fiber content decreases workability. The maximum reduction in the flow diameter was obtained nearly 20% for SCC Specimen 0.75% HF – 0.5% CF when compared to that of 0% HF – 0% CF. Further, increase in fiber content led to increase viscosity of SCC in fresh state, which led to reduction in SCC's workability. Additionally, the maximum increase of T_{50cm} and T_V (V funnel test) were 2.16 and 2 times for Specimen 0.75% HF – 0.5% CF when compare to Specimen 0% HF – 0% CF, respectively.

Incorporation of fiber content, the flow diameter of SCC mixes decreases considerably; this reduction in workability was may be because of increasing of the SCC's viscosity and moreover, the fiber's large surface area, which needed more amount of cement mortar around it. Additionally, it was proved that incorporating more CF fiber led to a high amount of reduction in flow diameter when compare to increase the amount of HF fiber. Khaloo et al. [19] investigated on the fresh and hardened properties of SCC reinforced with steel fibers of four different volume fractions (0.5, 1, 1.5, and 2%) were utilized in their mixes. The experimental results

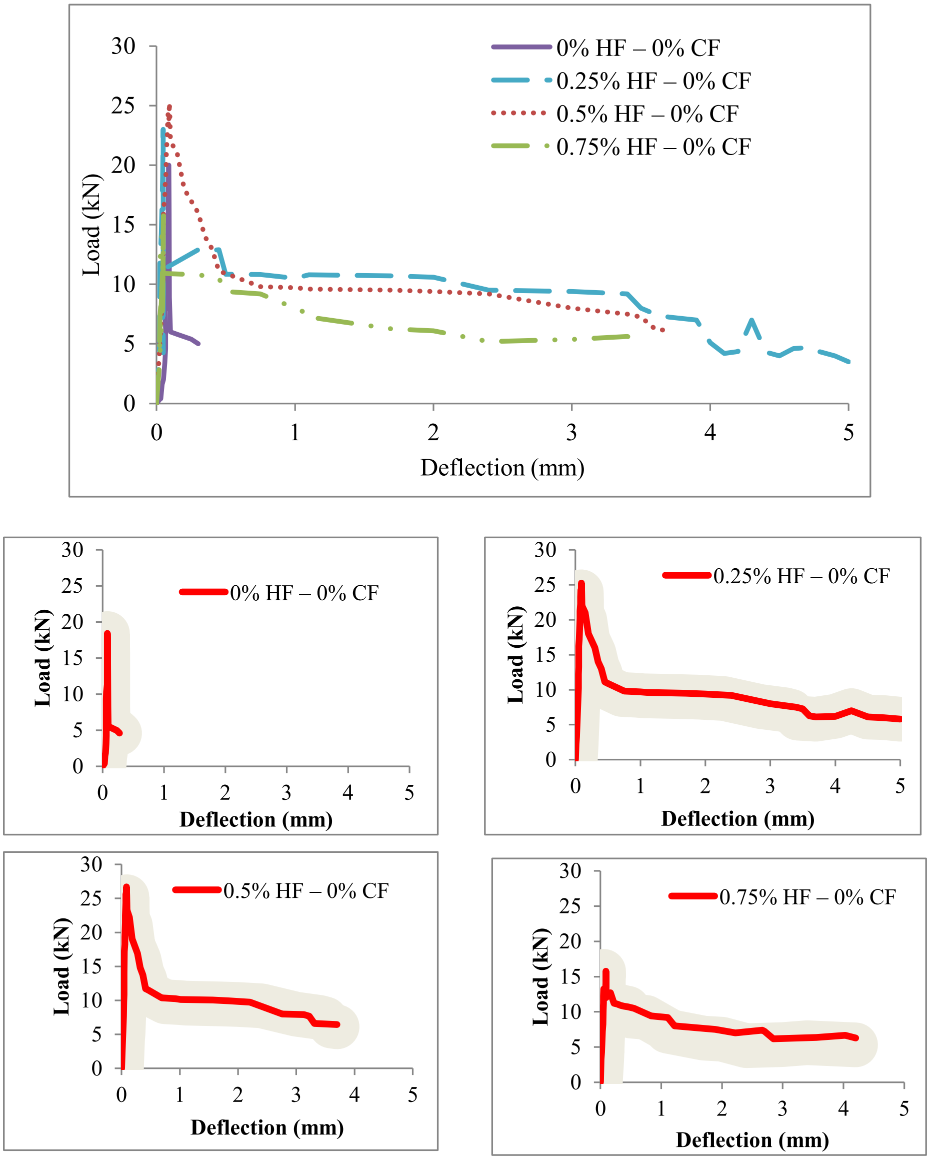


Fig. 8. Force versus deflection response of reinforced beams under FPB test with (a) 0% CF; (b) 0.25% CF; (c) 0.5% CF.

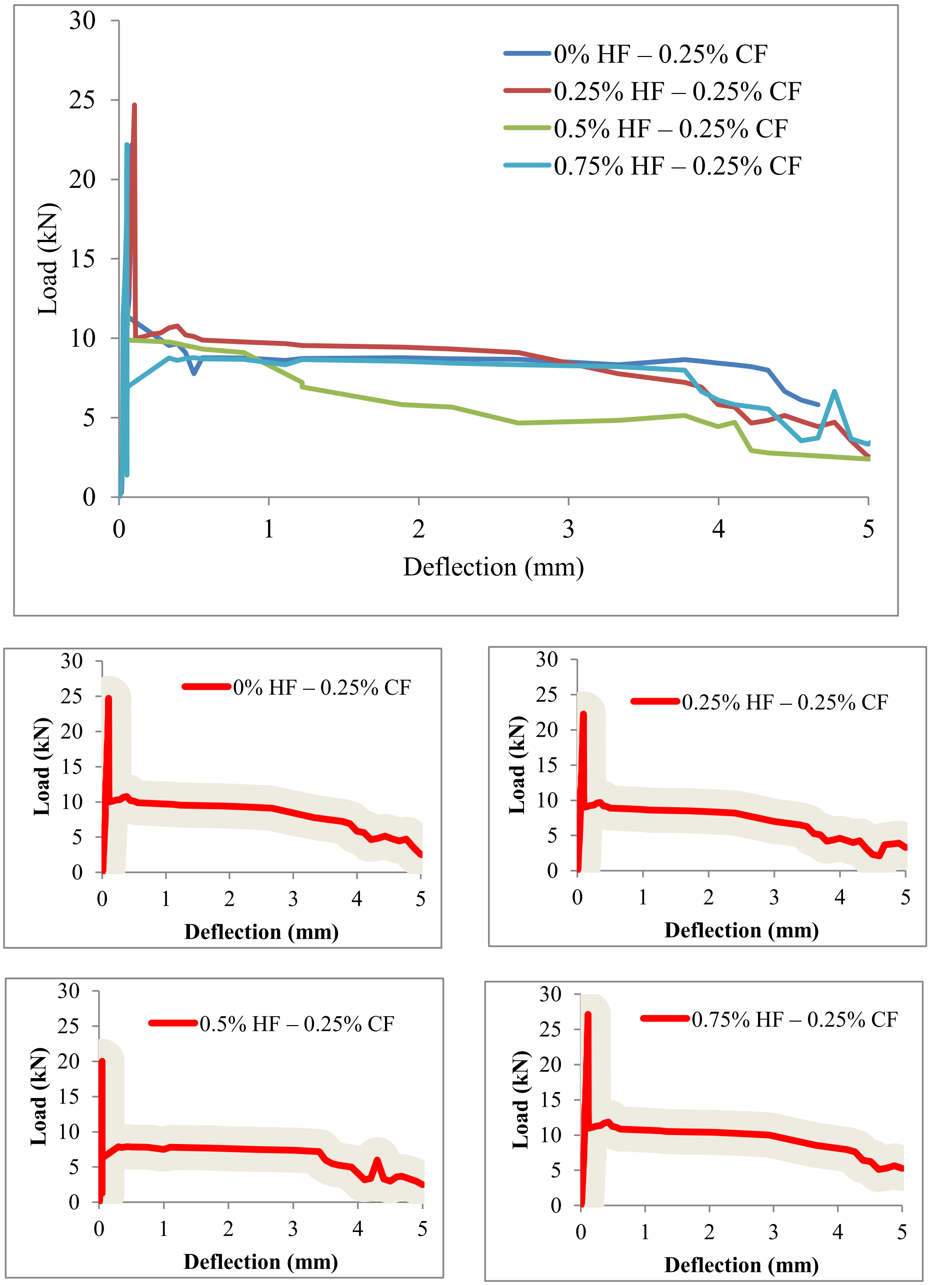


Fig. 8 (*continued*)

reported that incorporating steel fiber decreased the fresh state characteristics of fiber reinforced self-compacting concrete [19].

4.2. Hardened properties

4.2.1. Compressive strength

The incorporation of steel fiber to plain SCC mixes may increase significant porosity in it and correspondingly compressive strength will be reduced. However, fiber reinforced SCC may reduce or atleast limit the propagation of crack effectively. Hence, Incorporating steel fiber to SCC mixes has 2 influences on compressive strength opposite to each other, in which the addition of fiber, either improve or reduce the mechanical properties. Fig. 6 illustrates the average of compressive strength calculated for different SCC mixes. By considering these effects, incorporating steel fiber significantly improves the compressive strength of all SCC mixes, which reflects that the incorporation of fiber for reinforcing was very effective by improving the fiber's crack-arresting behavior, when compared to improve in porosity.

Improvement of compressive strength is considerably influenced by type, geometry and volume fraction of fiber. As a outcome of incorporation of HF, higher increment of compressive strength was obtained. Substitution of 0.5% HF to the plain SCC mixes enhanced the compressive strength value by nearly 18% when compared to SCC plain mixes, Mean while incorporating thee equal amount of CF fiber (i.e., 0.5% vol. fraction) led to a 16% enhancement.

These results can be due to the fiber's bridging capacity and higher crack-arresting behavior in hooked end fiber compared to crimped fiber. The deformed surface of crimped fibers provides more porosity at the fiber/matrix interface, compared to hooked end fibers. According to the obtained results, simultaneous incorporation of 0.75% HF and 0.5% CF to plain SCC mixes resulted in the maximum compressive strength (about 58 MPa) and maxi-

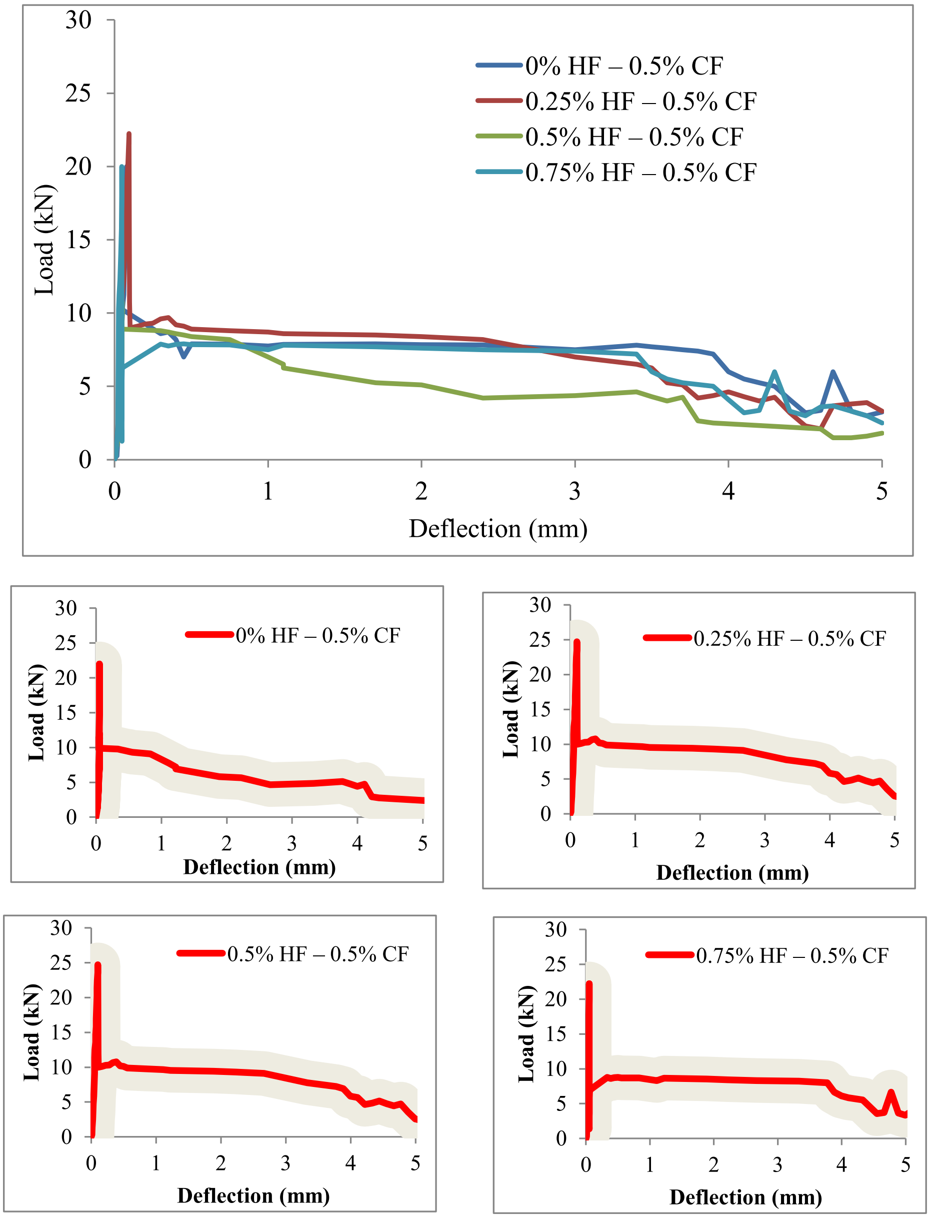


Fig. 8 (*continued*)

mum enhancement of compressive strength (about 40%) in hybrid steel fiber reinforced self-compacting concrete.

4.2.2. Flexural strength

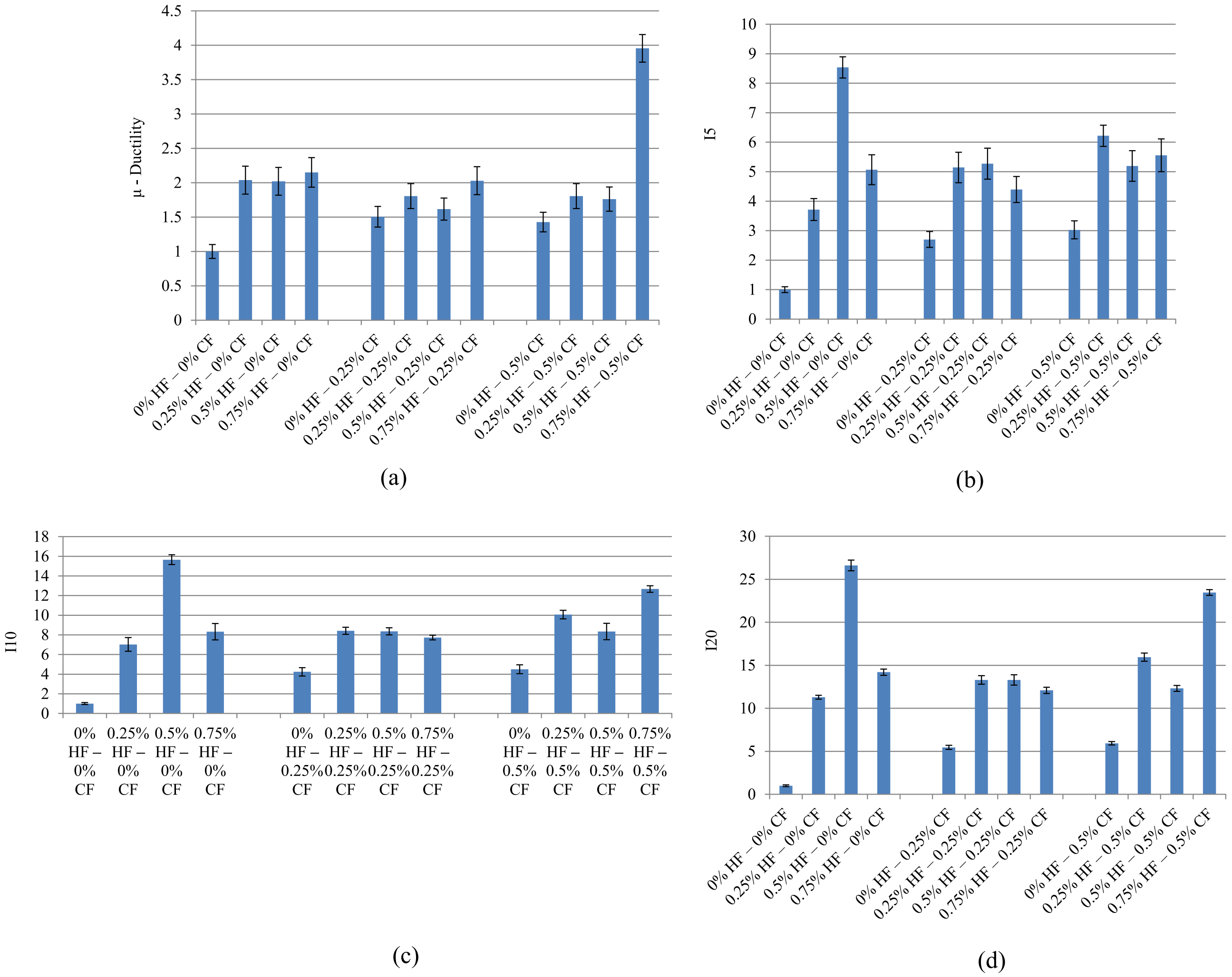
The results obtained from flexural strength test were illustrated in Fig. 7 which exhibits the influences of incorporating CF and HF fiber on the flexural strengths of SCC mixes. Fig. 7 shows the average flexural strength for each SCC mixes. With respect to the obtained flexural strength results, regardless of shape, volume fraction and type of fiber, incorporating fiber for reinforcing the SCC plain mixes enhanced its flexural strength behavior.

The highest flexural strength was nearly 4.5 MPa for SCC mixes 0.75% HF – 0.5% CF (nearly about a 32% increase). The improvement in flexural strength capacity of the SCC mixes because of fibers' capacity to arrest crack propagations, which reduces the formation of new cracks in close locality [24]. As depicted in Fig. 7, influence of hooked end fiber (HF) on improving flexural strength is decreased by adding crimped fiber (CF) content. Hence, adding the amount of HF from 0 up to 0.75% in SCC mixes without CF fiber results in 20% of increment in flexural strength of SCC mixes [Fig. 7]; On the other hand incorporating more amount of HF in the SCC mixes with 0.25 and 0.5% CF fiber enhanced flexural strength nearly 13% of SCC mixes [Fig. 7] and similarly about 12% (Fig. 7), respectively. According to the fractured surface of SCC specimen represents that HF and CF fibers are uniformly distributed in the surface and the bridging capacity of fiber may efficiently increase the flexural properties of hybrid fiber reinforced self-compacting concrete.

The obtained load Vs deflection curves of SCC specimens under FPB tests are depicted in Fig. 8(a)–(c), the relationship curves which show to the average three prismatic beams. Load-deflection curves are illustrated for individual cases by showing the scattering of the results (with a grey area) during the pre-crack and post-cracking regimes. According to the gathered results, incorporating fiber content may lead to SCC mixes having maximum flexural toughness, deflection (due to flexural properties),

Table 4
Flexural Toughness and Indices of Fiber-Reinforced Beams.

Specimen	μ	I_5	I_{10}	I_{20}	I_{10}/I_5	I_{20}/I_{10}	$R_{5,10}$	$R_{10,20}$	Flexural bending
0% HF – 0% CF	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	–
0.25% HF – 0% CF	2.04	3.72	7.03	11.29	1.63	1.38	66.22	42.66	5.85
0.5% HF – 0% CF	2.02	8.54	15.65	26.61	1.58	1.46	142.24	109.56	6.72
0.75% HF – 0% CF	2.15	5.07	8.32	14.21	1.41	1.47	65.19	58.82	8.20
0% HF – 0.25% CF	1.51	2.70	4.24	5.46	1.35	1.11	30.79	12.21	4.00
0.25% HF – 0.25% CF	1.81	5.14	8.41	13.30	1.41	1.36	65.36	48.85	6.11
0.5% HF – 0.25% CF	1.62	5.27	8.36	13.30	1.36	1.37	61.75	49.45	7.15
0.75% HF – 0.25% CF	2.03	4.39	7.72	12.09	1.51	1.35	66.56	43.69	8.58
0% HF – 0.5% CF	1.43	3.03	4.50	5.93	1.28	1.13	29.41	14.36	4.75
0.25% HF – 0.5% CF	1.81	6.22	10.06	15.94	1.39	1.36	76.88	58.82	6.60
0.5% HF – 0.5% CF	1.76	5.19	8.34	12.32	1.38	1.27	62.95	39.82	8.16
0.75% HF – 0.5% CF	3.96	5.56	12.67	23.47	1.96	1.59	142.24	108.02	9.47



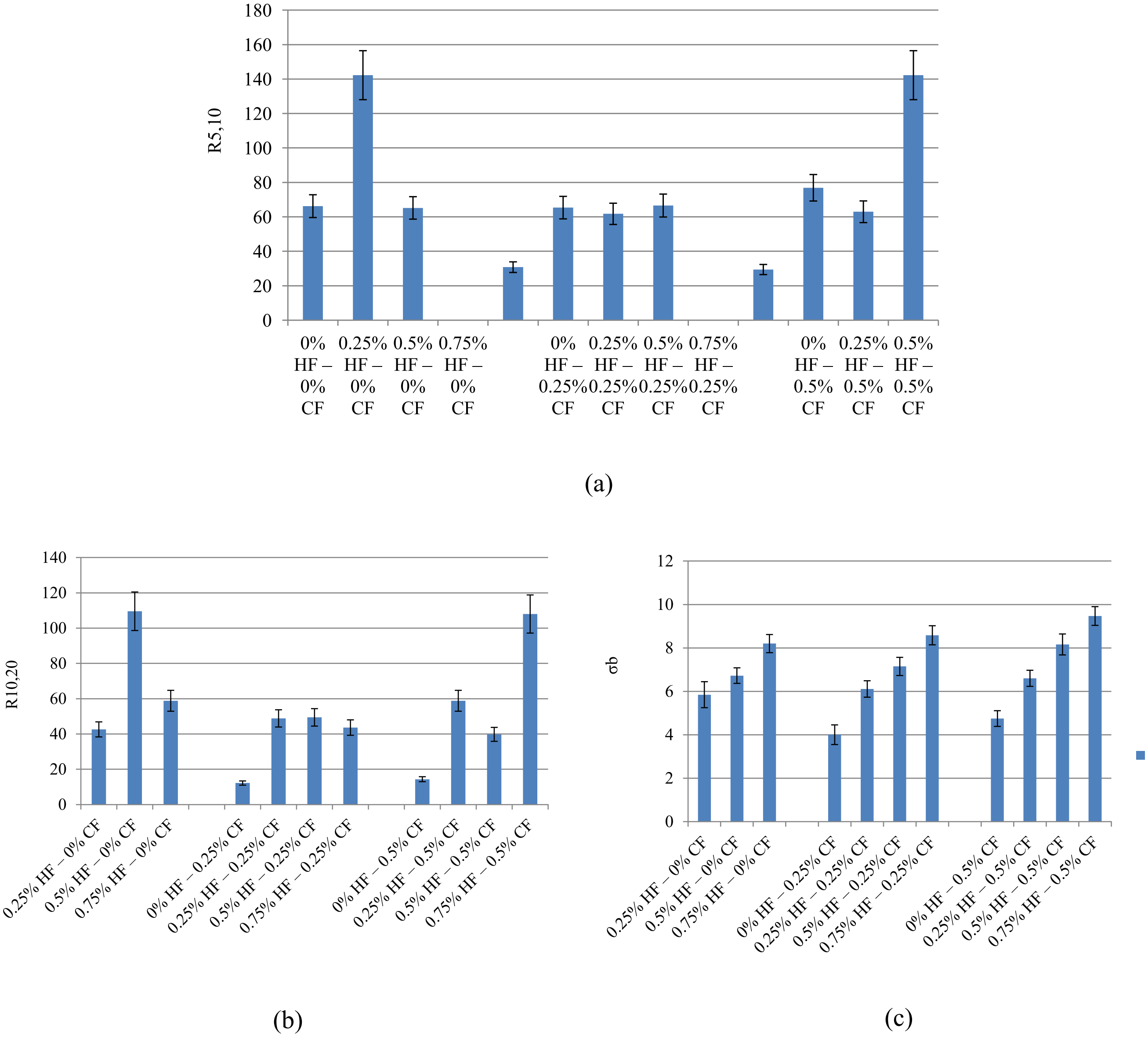
(a) (b) (c) (d)

Fig. 9. (a) Ductility; (b) toughness index of I5; (c) toughness index of I10; (d) toughness index of I20;

absorbed energy, ductility, flexural strength and post-peak residual strength, in while the flexural stiffness (initial) of the SCC mixes was decreased as increasing the steel fiber content.

Numerous concepts have been exited to calculate the flexural toughness of fiber reinforced concrete. Current paper incorporates ASTM C1018 and JCI-Japanese Concrete Institute methods. With respect to ASTMC1018, flexural toughness is evaluated at 4 different specific deflection locations, which are δ, 3δ, 5.5δ, and 10.5δ. With respect to the ASTM C1018 guidelines, δ is the deflection according to the first-crack propagation [ASTM C1018 [5,18]]. The pre-peak flexural toughness is calculated at δ, while for other (3δ, 5.5δ, and 10.5δ) deflections, post-peak flexural toughness is evaluated. Flexural toughness indices (I_5, I_{10}, and I_{20}) are incorporated in this method. Additionally, the pre-peak residual strengths are calculated depending up on average post-peak strength in particular interval of deflection. The residual strength values are calculated with following equations; Eqs. (2) and (3).

$$R_{5,10} = 20(I_{10} - I_5) \quad (2)$$



(a)

(b)

(c)

Fig. 10. (a) Residual strength of R510; (b) residual strength of R1020; (c) flexural toughness factor.

Table 5
Summarized Experimental Results (Percentage increase or decrease in strength with respect to 0% HF – 0% CF).

Mix ID	Compressive Strength (MPa)		Flexural Strength (MPa)		Impact Energy (J)	
					First Crack	Ultimate failure
0% HF – 0% CF	42.06 ± 3.6		3.45 ± 0.6		1152.2 ± 48	1291.2 ± 43
0.25% HF – 0% CF	45.85 ± 4.4	(9.05%)	3.80 ± 0.4	(10.3%)	1629.0 ± 52	1887.2 ± 69
0.5% HF – 0% CF	49.38 ± 3.1	(17.49%)	3.88 ± 1.6	(12.56%)	2105.7 ± 64	2463.3 ± 26
0.75% HF – 0% CF	52.65 ± 2.2	(25.10%)	4.12 ± 0.9	(19.6%)	3933.3 ± 52	4350.5 ± 48
0% HF – 0.25% CF	43.43 ± 2.3	(3.29%)	3.81 ± 0.7	(10.55%)	933.7 ± 24	1052.9 ± 72
0.25% HF – 0.25% CF	48.42 ± 2.5	(15.02%)	4.02 ± 0.5	(16.83%)	1370.7 ± 62	1549.5 ± 68
0.5% HF – 0.25% CF	51.07 ± 1.9	(21.40%)	4.18 ± 0.9	(21.11%)	1728.3 ± 74	2026.3 ± 85
0.75% HF – 0.25% CF	55.03 ± 2.4	(30.86%)	4.25 ± 0.4	(23.12%)	2880.5 ± 26	3317.5 ± 22
0% HF – 0.5% CF	48.61 ± 2.3	(15.64%)	4.11 ± 1.3	(19.35%)	774.7 ± 38	874.1 ± 65
0.25% HF – 0.5% CF	51.66 ± 3.6	(22.84%)	4.26 ± 0.6	(23.87%)	953.5 ± 53	1112.5 ± 75
0.5% HF – 0.5% CF	54.13 ± 4.4	(28.6%)	4.41 ± 0.4	(27.89%)	1291.2 ± 65	1509.8 ± 47
0.75% HF – 0.5% CF	58.58 ± 2.8	(39.3%)	4.53 ± 1.2	(31.42%)	1768.0 ± 45	2105.7 ± 29

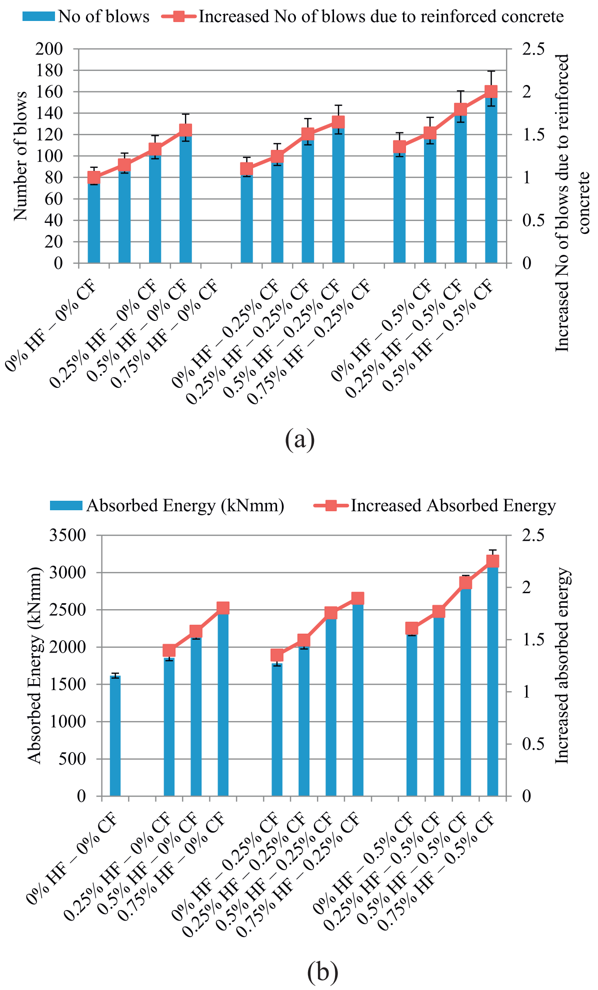


Fig. 11. Effects of fiber on (a) the number of blows; (b) absorbed impact energy.

$$R_{10,20} = 10(I_{20} - I_{10}) \tag{3}$$

Additionally, JCI recommends another concept depending up on deflection measurement at span/150 of the prismatic concrete beams under flexural loading. The toughness parameter may be evaluated through following eqn. Eq. (4): [25]:

$$\boldsymbol{\sigma_b} = \frac{\boldsymbol{T_b L}}{\delta_{150}\boldsymbol{bd}^2} \tag{4}$$

where L = span of the prismatic beam (500 mm); δ_{150} = deflection at span/150; T_b = Toughness up to the specific deflection at δ_{150}; and h = height (100 mm) and b = width (100 mm), respectively. Toughness can be evaluated through evaluation of the area under load–deflection curve diagram up to δ/150. The flexural toughness, residual strength and fracture indices are calculated and exhibited in Table 4 and Fig. 9 for all SCC specimens reinforced with hooked end and crimped fiber and different volume fractions of fiber. Table 4 illustrated the mean value of three prismatic beams. Moreover, Eq. (5) was utilized for evaluating ductility parameter.

$$\mu = \frac{D_u}{D_y} \tag{5}$$

Where D_U = deflection when the crack forms and load initiates to decrease at point B and

D_Y = Maximum deflection while curve behaves linearly behavior at point A

Ductility of the steel fiber reinforced SCC mixes is calculated as reported in Fig. 9(a) and Table 4. Flexural toughness indices (I_5, I_{10}, and I_{20}) were calculated and reported in Fig. 9(b–d) respectively. Residual strength of R5,10; R10,20 and flexural toughness factor are represented in Fig. 10(a–c) respectively. According to the results mentioned in Table 4, incorporation of more fiber content for reinforcing SCC plain concrete which results in improving toughness. This improvement of toughness value led to increase in the impact, fatigue and toughness parameters of hybrid reinforced SCC.

The maximum increase in toughness parameter was obtained for specimens reinforced with 0.5% CF and 0.75% HF. The highest recorded flexural toughness parameter was given for SCC's Specimen 0.75% HF – 0.5% CF. The highest ductility of SCC (nearly about 3.96) was also acquired in Specimen 0.75% HF – 0.5% CF.

4.2.3. Impact resistance

SCC's impact resistance for different volume fraction of fiber was recorded in terms of numbers of blows required for first visible crack propagation (N_1) and number of blows for ultimate failure (N_2) for all SCC mixes. Steel ball placed at centre of cylindrical disks and this disk was located on base plate of impact testing machine and within lugs of positioning. Hammer ball was allowed to fall repeatedly, dropped. The recorded values of N_1 and N_2 were denoted as initial and ultimate crack resistance parameter respectively.

The initial potential energy was calculated before rebound, E_i with equation Eqs. (6)

$$E_i = N_1 mgh \tag{6}$$

Table 6
Impact resistance results for fiber reinforced self-compacting concrete.

Mix	N_1			N_2			N_2 - N_1	Impact Energy (J)		N_2/N_1
	Mean	SD	COV (%)	Mean	SD	COV (%)		First Crack	Ultimate failure	
0% HF – 0% CF	74	5.29	10.17	81	3.61	5.23	7	1479	1618	1.09
0.25% HF – 0% CF	80	9.64	13.58	93	2.65	2.82	13	1597	1855	1.16
0.5% HF – 0% CF	90	6.93	6.79	108	7	5.88	18	1793	2151	1.20
0.75% HF – 0% CF	105	9.64	5.16	126	23.39	9.51	21	2094	2511	1.20
0% HF – 0.25% CF	84	1.73	3.53	90	2	3.64	6	1664	1783	1.07
0.25% HF – 0.25% CF	92	6.08	9.81	101	5.29	7.35	9	1836	2015	1.10
0.5% HF – 0.25% CF	108	9.54	12.55	123	7.81	8.4	15	2139	2437	1.14
0.75% HF – 0.25% CF	112	11.53	8.73	134	10.82	6.98	22	2226	2663	1.20
0% HF – 0.5% CF	106	3.61	9.03	111	2.65	6.46	5	2099	2198	1.05
0.25% HF – 0.5% CF	116	3.61	7.68	124	5.29	10.17	8	2299	2458	1.07
0.5% HF – 0.5% CF	135	1.73	2.75	146	2.65	3.63	11	2685	2904	1.08
0.75% HF – 0.5% CF	146	9.64	12.36	163	7.94	8.19	17	2900	3238	1.12

SD – Standard Deviation; COV – Coefficient of Variation

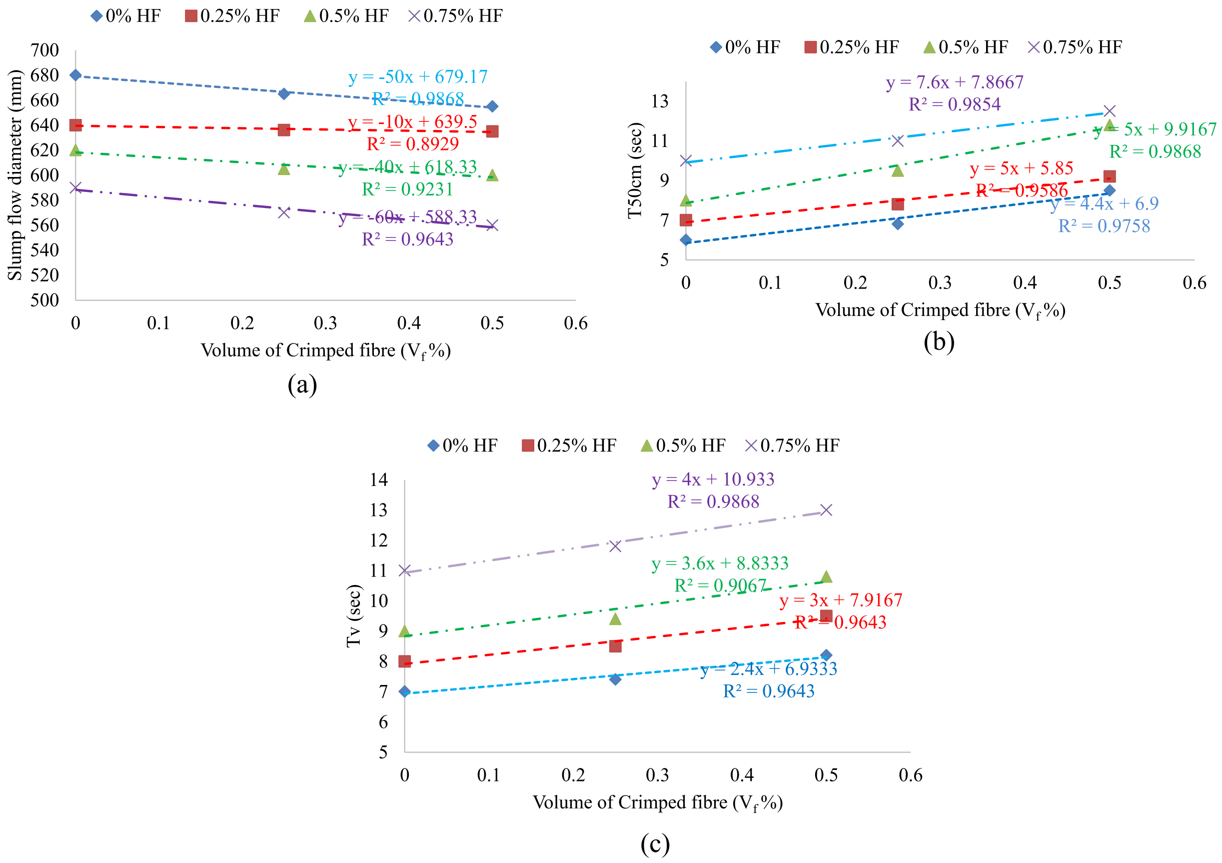


Fig. 12. Developed equations to correlate the volume of CF fiber with (a) slump flow diameter; (b) T_{50cm}; (c) Tv.

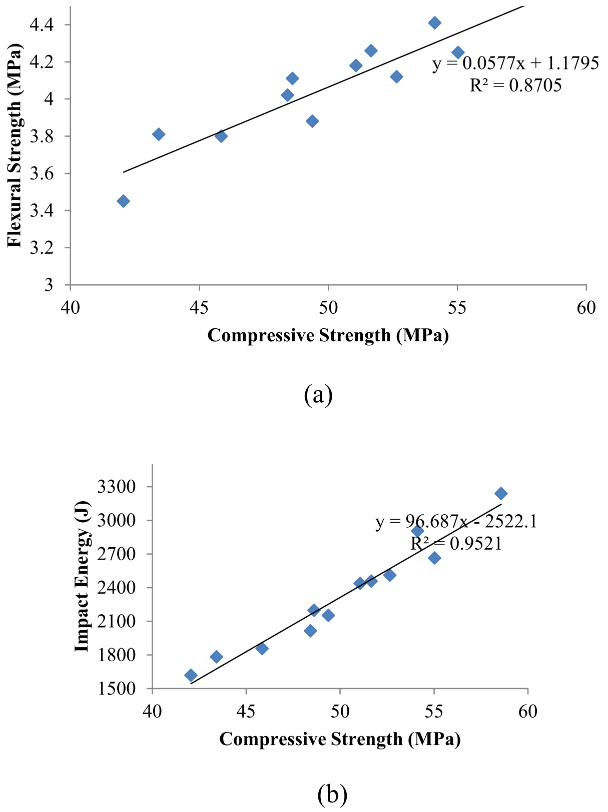


Fig. 13. Correlation between compressive strength and (a) flexural strength; (b) maximum impact energy.

Final potential energy was calculated after rebound, E_f using equations Eqs. (7):

$$E_f = N_2 mgh \tag{7}$$

where m – mass of steel ball (4.5 kg), h – initial height of steel ball (450 mm).

The energy absorption of SCC's mixes, E_p evaluated as the difference in the initial (E_i) and final (E_f) potential energy ($E_p = E_i - E_f$). Loss because of atmospheric air was eliminated.

The experimental results obtained from compression test, flexural test and impact test was summarized in Table 5. Fig. 11(a) and (b) depict the influence of incorporating HF and CF fibers on the number of blows, impact energy of the disks. The summarized results illustrated in Fig. 11 showed that the average of four cylindrical disks. By considering the gathered results, incorporation of 0.5% volume CF fiber has led to maximum increase in number of blows of SCC reinforced with HF (nearly about 163 Nos. for Specimen 0.75% HF – 0.5% CF). This maximum value represents nearly about 100% enhancement of impact strength compared to highest energy recorded for cylindrical disks manufactured from plain SCC concrete. Additionally, increasing CF fiber volume fraction content increased the number of blows (Table 6). The damages due to hammer on plain SCC concrete influences very rapidly propagate, while incorporating fiber led to increase the bridging capacity of fiber between microcrack which are created due to the hammer [24]. As illustrated in Fig. 11(b), an uninterrupted enhancement of absorbed impact energy observed, corresponding to HF fiber content increment. The highest absorbed impact energy (nearly 2500 J) was observed for SCC's Specimen 0.75% HF – 0% CF. This highest amount of absorbed energy represents nearly 55% enhancement, compared to absorbed impact energy of the cylin-

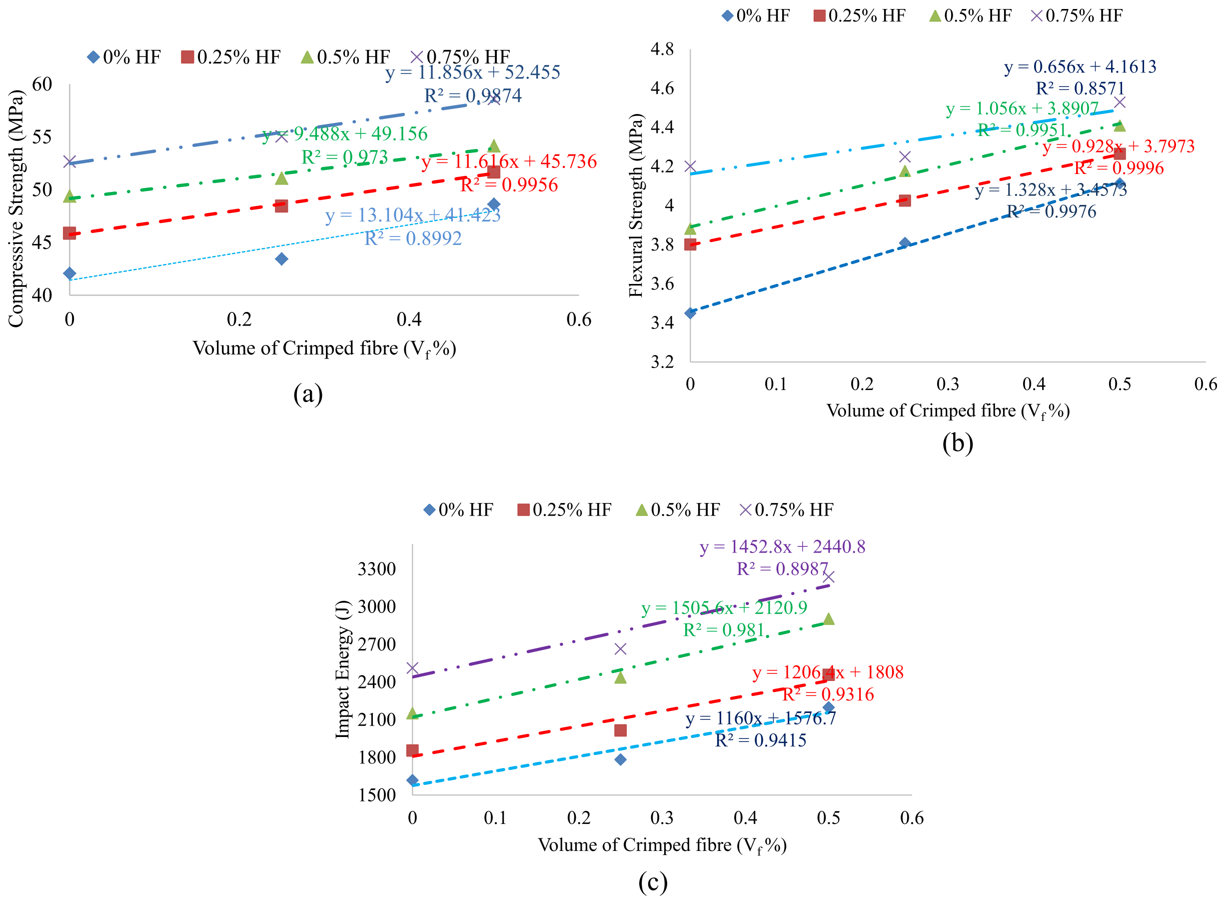


Fig. 14. Developed equations to correlate the volume of CF fiber with (a) compressive strength; (b) flexural strength; (c) maximum impact energy.

drical disks manufactured with plain SCC concrete. However, there is no specific trend between increasing the hooked end-crimped steel fiber and absorbed impact energy of the SCC's specimens. The highest absorbed impact energy (nearly 3200 J) was observed for Specimen 0.75% HF – 0.5% CF. The highest increase in absorbed impact energy (nearly 100% increment compared to SCC's Specimen 0% HF – 0% CF) was also calculated for Specimen 0.75% HF – 0.5% CF.

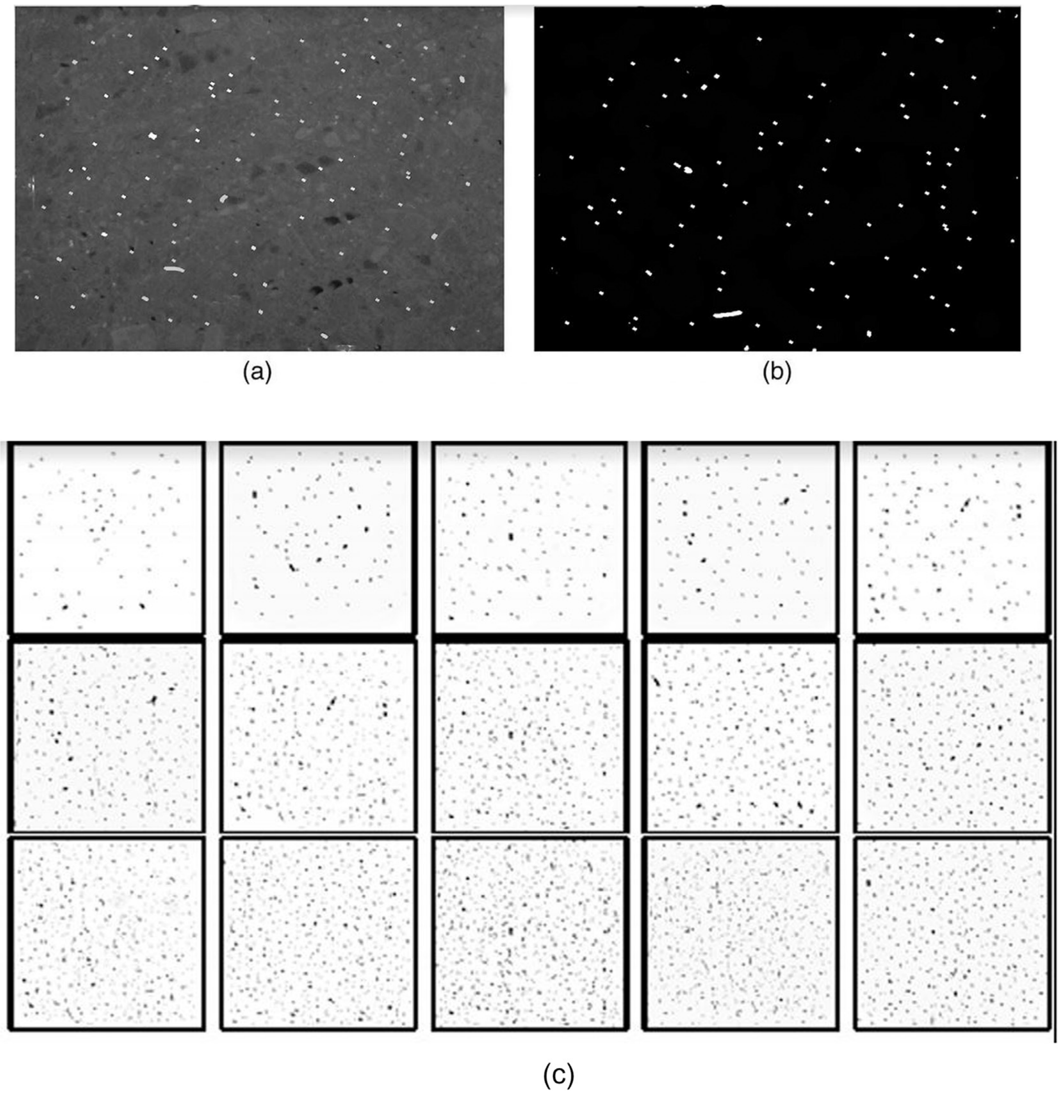
4.2.4. Analytical analysis

With respect to observed experimental data gathered in the experiments, behavior of the steel fiber reinforced SCC specimens in fresh state and hardened state properties may be correlated to type, geometry and volume fraction of fiber content through analytical and empirical relationship. In order to obtain this specific goal, analytical regression analysis employed and some of linear empirical equations evaluated with coefficient of determination (R^2). Omary et al. (2016) and Mastali et al. [24] reported that fresh state, hardened properties and impact energy of the steel fiber reinforced SCC specimens may be correlated. As illustrated in Fig. 12, empirical equations are formed related with CF fiber content to fresh properties of SCC mixes reinforced with HF. Empirical equations were shown that the flow diameter, T_{50cm}, and T_V may be correlated with linear relationship related to CF fiber content of each SCC specimen group of steel fiber reinforced SCC specimens. According to the results illustrated in Fig. 12(a), highest decrement in equation's slope value was obtained in SCC mixtures which did not contain HF (H0), i.e., incorporation of CF fiber with no HF resulted in highest decrement in flow diameter. Additionally, the maximum rates of improvement for T_{50cm} and T_V were observed (Fig. 12(b and c)) in specimens with CF fiber together with 0.75 and 0.5% HF, respectively.

According to the Fig. 13(a) and b, obtained results depict the empirical equations which relate to flexural strength and highest absorbed impact energy value to compressive strength value. According to the empirical equations developed, both values of flexural strength value and highest impact energy may be linearly correlated to compressive strength values with maximum coefficient of determination ($R^2 \geq 0.87$). As illustrated in Fig. 14(a)–(c), empirical equations also evaluated which correlate with hardening characteristics of fiber steel reinforced SCC specimens to CF fiber content. According to the results illustrated in Fig. 14(a), incorporation of CF fiber may lead to the highest increase in compressive strength values and flexural strength values in SCC mixes with no HF (H0), while the maximum incremental rate of absorbed impact energy obtained in SCC mixes reinforced with 0.5% volume fraction of HF fiber. It is most worthy representing that the obtained results utilized in this portion for calculating empirical equation and correlating the values of compressive, flexural, and impact strength values represented to the mean value of three cubes, three prisms and four cylindrical disks, respectively.

4.2.5. Digital image processing

4.2.5.1. Number of fibers and distribution of fibers in a cross section. The characteristics of hooked end and crimped steel fiber reinforced SCC specimens are based on fiber distribution and fiber segregation coefficient. Uneven distribution of steel fibers in SCC specimen may extensively affects the properties of SCC mixes. Moreover, Digital image processing confirmed the fresh and hardened properties which are evaluated already in this present paper.


(a)

(b)

(c)

Fig. 15. Digital image analysis: (a) transforming the image in the grayscale; (b) creating a binary image. (c) Distribution of fibers in cross section for selected specimens.

By evaluating the value of fiber segregation coefficient for each mix (ξ_{seg}), thereby, the ability or capacity to distribution of fibers may be easily evaluated. Coefficient of Segregation of fiber calculated by following equation Eq. (8) Abrishambaf et al. (2013:

$$\xi_{seg} = \frac{1}{hN_T^f}\sum_{i=1}^{N_T^f} y \tag{8}$$

where y is the coordinate of fiber with respect to gravity center; h - height of specimen and ξ_{seg} – coefficient of segregation of fiber ranges;

The fiber distribution is generally accounted as 0.5. Coefficient of Fiber segregation calculated together for both hooked end and crimped fibers. Although hooked end and crimped fibers have different volume fraction, this parameters has not been taken into account in digital image processing analysis. Distribution of steel fibers of specimen of SCC was shown in Fig. 15(a–c). Based on the inspection of cross sections of selected specimen and evaluated values for the ξ_{seg}, the uniform distribution of hooked end (HF) and crimped fiber (CF) is evaluated and justified for all SCC mixtures (Table 7). This explains clearly, small scattering of the results even between different batches.

4.2.6. Micro structural analysis

Scanning Electronic Micrograph (SEM) analysis of for fiber matrix with cement paste interaction and interfacial transition zone (ITZ) between coarse aggregate, fine aggregate and cement is shown in Fig. 16(a). Aggregate-paste (Popovics (1987)) interface are found to be very dense microstructure Fig. 16(a). This is attributed to self compacting behaviour of SCC mixes. While in normal plain vibrated concrete, it has been well known and recognized

Table 7
Fiber Distribution Parameters.

Fibre Content	N_f (fibers/m^2)	ξ_{seg}
0% HF – 0% CF	485	0.43
0.25% HF – 0% CF	1323	0.5
0.5% HF – 0% CF	852	0.49
0.75% HF – 0% CF	471	0.47
0% HF – 0.25% CF	1233	0.5
0.25% HF – 0.25% CF	768	0.49
0.5% HF – 0.25% CF	386	0.43
0.75% HF – 0.25% CF	1034	0.5
0% HF – 0.5% CF	726	0.49
0.25% HF – 0.5% CF	521	0.47
0.5% HF – 0.5% CF	1254	0.5
0.75% HF – 0.5% CF	682	0.48

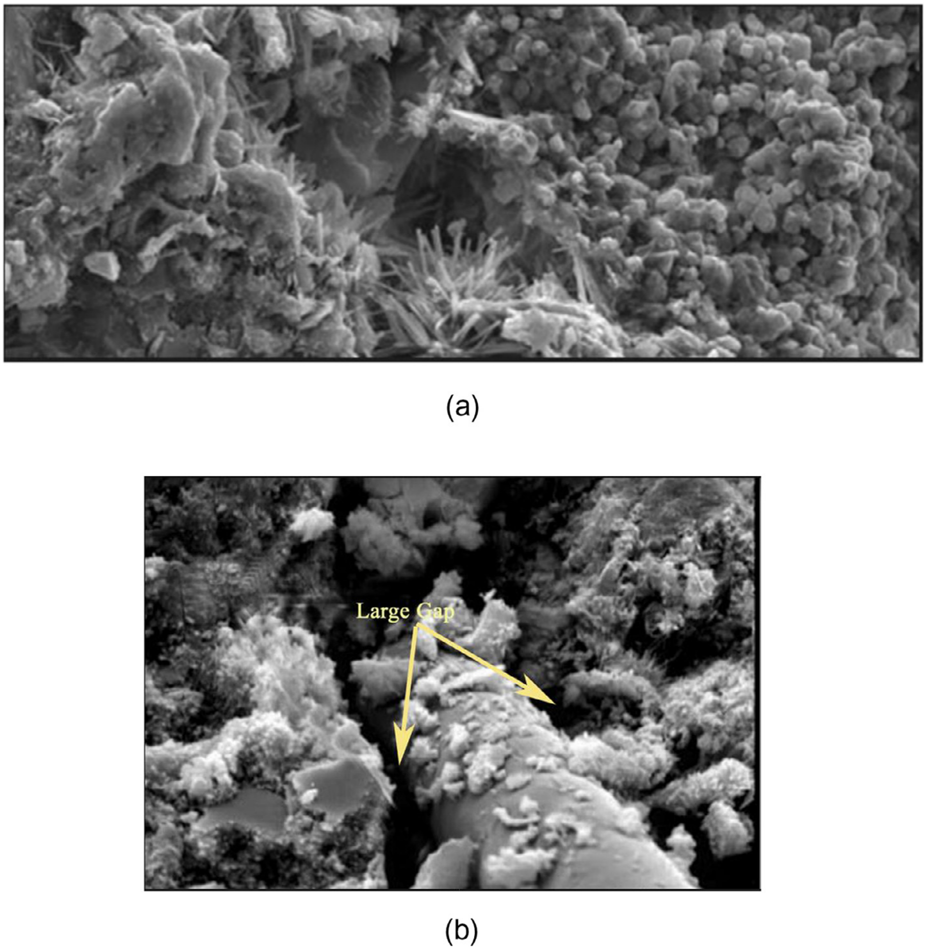


Fig. 16. (a) SEM image of samples (b) SEM image of samples incorporating steel fibers.

that pathetic link could be ITZ between coarse aggregates and cement matrix Cwirzen and Penttala (2005. SEM analysis of SCC containing hybrid steel fiber is shown in Fig. 16(b). More number of micro-cracks and cavities were recorded in the cement matrix of SCC mixes as shown in Fig. 16(a), results implies reduction in the strength of SCC. Cavities are observed and recorded in the interface of cement paste and steel fiber in Fig. 16(b) which reflecting a very weak interaction between steel fibers and cement paste. The SEM analysis further represent that the fiber particles have irregular shapes. It illustrated that interfacial (ITZ) bonding between steel fiber and cement mortar is very weak, which results in the development of cracking in SCC specimen at the interface. The interface cracking exhibits in the decrease in mechanical behavior of the SCC mixes.

5. Conclusion

This current research paper shows the results of experimental, analytical studies, SEM analysis and Digital image processing on fresh and hardened characteristics of steel fiber reinforced SCC with hybrid hooked end-crimped steel fiber. SCC mixes were reinforced with hybrid hooked end steel fiber (0.25, 0.5 and 0.75%) and CF fiber (0.25 and 0.5%). In order to obtain the fresh properties of SCC mixes, flow diameter, T_{50cm}, and T_V were used.

Considering different volume fraction of fiber and combinations of hybrid fiber, the mechanical properties of various SCC mixes were evaluated using 36 cubic specimens (100 mm) for compressive strength test, 36 prisms (100 × 100 × 500 mm) for flexural strength test, and 48 number of cylindrical disks (150 × 65 mm) for impact resistance test. Further, analytical studies conducted on the extensively large volume of gathered data. The conclusions were summarized and highlighted as follows:

- Incorporating the content of hybrid hooked end-crimped steel fiber results in reduction in flow diameter, however linear increases in other fresh properties such as T_{50cm} and T_V;
- The lowest reductions in flow diameter were recorded in SCC mixes reinforced with both CF fiber (0.25 and 0.5%) and HF (0.75%);
- According to the developed empirical equations, the highest rate of increase in fresh properties such as T_{50cm} and T_V observed for SCC mixes reinforced with CF fiber (0.25 and 0.5%) and HF (0.75 and 0.5%), respectively;
- Addition of hybrid hooked end-crimped steel fiber results in further increment of mechanical characteristics and impact resistance of SCC specimens, which results in highest compressive, flexural, and impact strength of SCC were observed in SCC's Specimen 0.75% HF – 0.5% CF;
- Compared to incorporation of CF fiber, adding HF provided a maximum impact in enhancing compressive strength behavior of SCC mixes;
- The better flexural strength behavior caused by incorporation of HF is decreased when CF fiber content is added;
- Absorbed impact energy and flexural properties correlated linearly with compressive strength and maximum coefficient of determination (R^2) was observed as 0.87;
- Due to incorporation of CF fiber, the maximum increase in impact resistance observed in SCC's specimens with 0.5% HF;

- Due to incorporation of CF fiber, the maximum increase in flexural strength and compressive strength behavior observed in SCC's specimens which did not contain HF (0% HF).
- Using SEM images, the SCC's failure mechanisms were assessed, which represents that reduction in internal friction between cement and aggregate particles may lead to reduction of mechanical behavior of SCC mixes. Increasing hybrid hooked end- crimped steel fiber may lead to increase the basic hardened properties such as compression, flexural and impact resistance of SCC mixes.
- In digital image processing, the cross sections inspected and fiber segregation coefficient values were evaluated, which indicates the uniform distribution of hooked end fibers and crimped fibers were established and confirmed within all specimens.
- For future work, the behaviour of beam-column joint, prototype beam, column, slab can be also investigated with high strength SCC and high performance SCC.
- For further studies such as fire resistance, freeze–thaw resistance and corrosion of steel fibers with various levels of steel fibers and silica fume replacement level could be studied for different engineering applications such as highway and dam construction.

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