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Use of silica fume and recycled steel fibers in self-compacting concrete (SCC)

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HIGHLIGHTS

- Effects of silica fume and the recycled steel fiber experimentally investigated.
- The hardened properties were characterized by using compressive, tensile, flexural, and impact tests.
- The fresh properties were determined by using the slump flow test and V-funnel test.
- Combined effects of silica fume and the recycled steel fiber improved the mechanical properties and impact resistance.

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ABSTRACT

This paper aims to investigate the effects of replacing cement with silica fume in the reinforced self-compacting concrete with recycled steel fiber and study its mechanical properties and impact resistance. To characterize mechanical properties and impact resistance, 144 specimens with different fiber volume fractions of 0.25%, 0.5%, and 0.75% were experimentally tested. Mechanical properties of specimens were characterized with regard of compressive, splitting tensile, and flexural strengths. Concerning the obtained large experimental database, an analytical analysis was performed by using regression analysis to investigate the correlate between the impact and mechanical properties of self-compacting concrete reinforced with recycled steel fibers. In addition, the correlation between the mechanical properties of specimens and the content of the replaced cement with silica fume was also examined.

The results revealed that the combined effects of silica fume and recycled steel fiber improved the mechanical properties and impact resistance of specimens. Moreover, linear equations were also developed to correlate mechanical properties and impact resistance of specimens with a high coefficient of determination.

1. Introduction

Over the last three decades, significant studies have been executed to examine the impact of steel fibers as reinforcing matrix on the mechanical properties and impact resistance. The previous findings revealed that steel fibers significantly improves the mechanical properties and impact resistance of the reinforced concrete. In the last decade, with regard of high cost of steel fiber and environmental friendly issues, using recycled steel fibers as reinforcing matrix in cement-based materials attracted the attention of many researchers.

Many researchers examined the fresh state and hardened properties of the reinforced concrete with recycled steel fibers. Recycled steel fibers obtained from different waste sources such as waste tires and waste formworks were used in these studies. To produce recycled steel fibers from waste materials different recycling methods such as conventional pyrolysis and microwave-induced are used [1]. Aghaee et al. studied about the mechanical properties of structural lightweight concrete reinforced with waste steel wires found in the construction sites [2]. Mechanical properties of mixtures were characterized through execution of compressive, tensile, flexural tests. Furthermore, to attain impact resistance of mixtures, specimens were tested under drop weight impact test. Mixtures were reinforced by different recycled steel fiber volume fractions, including 0.25%, 0.50% and 0.75% [2]. The results showed that the maximum compressive strength recorded for the reinforced mixture was associated with the recycled steel fiber volume 0.5%, however, the maximum splitting tensile strength and flexural strength recorded in the reinforced specimens with the recycled

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steel fiber volume 0.75% [2]. Khaloo et al. investigated the use of polymer fibers recycled from waste car timing belts in reinforcing high performance concrete [3]. Fresh-state of mixtures were assessed by slump flow diameter. In addition, the mechanical properties of the reinforced specimens also were determined through measuring compressive and flexural tests [3]. Different fiber lengths (20 mm and 40 mm) and different volume fractions (0.2%, 0.5%, 1%, and 1.5%) were used to reinforce the mixtures [3]. In their study, it was found that increasing fiber length from 20 to 40 mm leads to achieving a higher efficiency in the flexural strength of the fiber reinforced concrete (3–64% for fiber length 20 mm and 25–125% for fiber length 40 mm) [3]. Khaloo et al. worked on the mechanical properties and rheology of the self-compacting concrete reinforced with steel fibers [4]. Four different steel volume fractions of 0.5%, 1%, 1.5%, and 2% were used in the mixtures. Slump flow diameter, T500, T_V, and L-box tests were carried out to evaluate the rheology of those mixtures. Compressive, splitting tensile, and flexural tests were also performed to estimate the mechanical properties of mixtures at 7, 28, and 91 days [4]. Concerning the results, it was revealed that adding steel fibers reduces the workability of the SCC. More, specifically adding fiber at a volume fraction of more than 2% intensify this reduction [4]. Adding steel fiber also reduced the compressive strength of the material, while splitting tensile strength and flexural strength were improved. Moreover, flexural toughness of the SCC beams increased as the content of steel fibers increased [4]. Nili et al. investigated the combined effects of silica fume and steel fibers on the impact resistance and the mechanical properties of concrete [5]. Hooked steel fibers of 60 mm and the aspect ratio of 80, with three different volume fractions 0%, 0.5%, and 1% were used as reinforcing matrix. Cement was replaced with 8% weight silica fume. The experimental results showed that steel fibers improve the strength performance of concrete, particularly the splitting tensile and the flexural strengths. Furthermore, significant improvement was also observed in the impact resistance of the reinforced specimens, compared to the reference specimen. The results demonstrated that using the steel fiber in the mixtures containing silica fume significantly increase the ductility and impact resistance of the resulting concrete [5]. Dalvand et al. studied the effects of replacing cement with silica fume on the impact resistance and mechanical properties of conventional concrete [6]. Cement was replaced with 7% and 14% weight silica fume. It was observed that increasing the content of silica fume improved both mechanical properties and impact resistance of conventional concrete. Hence, the maximum improvement in the mechanical properties and impact resistance of specimens were recorded for the 14%-cement mixture replaced with silica fume [6].

With respect to the previous studies, adding the silica fume to the fiber reinforced concrete (FRC) with particular shapes, lengths, and diameters of steel fibers improves the impact resistance and the mechanical properties. To the authors' best knowledge there is no study reporting the effects of replacing silica fume on the reinforced self-compacting concrete mixtures with recycled steel fibers presenting different characteristics such as different diameters, lengths, and shapes. In this regard, this study was established to investigate the effects of replacing cement with silica fume on the impact resistance and the mechanical properties behavior of the reinforced self-compacting concrete mixtures with recycled steel fibers.

Different contents of silica fume (7% and 14%) used instead of cement in the mix compositions. Moreover, the mixtures were reinforced by three different levels of fiber volume fractions, including 0.25%, 0.5%, and 0.75%. The effects of replacing cement with silica fume on the rheology were investigated through the use of slump flow test (diameter and time) and V-funnel test. The mechanical properties of mixtures were characterized using compressive, splitting tensile, and flexural tests. Experimental investigations on the hardened properties of mixtures were performed for with 144 specimens divided into four groups, including 36 cubic specimens for compressive tests, 36 cylinders for splitting tensile tests, 36 prismatic beams for flexural tests, and 36 disk specimens for impact resistance tests. Considering the gathered relatively large experimental database, regression analysis was used to analysis the experimental data and some equations were linearly developed to investigate the correlation between the impact and mechanical properties of self-compacting concrete reinforced with recycled steel fibers. In addition, some equations were also presented to indicate the effects of silica fume contents on the impact resistance and the mechanical properties of mixtures.

2. Experimental study

2.1. Materials and concrete mixture design

Concrete mixtures consisted of Portland cement (type II based on ASTM C150 recommendations [7]), silica fume, fine and coarse aggregates, water, and superplasticizer (SP). Cement was replaced with silica fume of 7% and 14% weight. The chemical compositions and physical properties of a used silica fume and cement are listed in Table 1. The coarse and fine aggregates were obtained from the crushed limestone with a specific gravity of 2.63 g/cm^3 and a maximum size of 10 mm. In addition, the fine aggregate provided from

Table 1
Chemical composition and physical properties of cement and silica fume.

Chemical composition	Cement	Silica fume
SiO_2 (%)	21.10	85–95
Al_2O_3 (%)	4.37	0.5–1.7
Fe_2O_3 (%)	3.88	0.4–2.0
MgO (%)	1.56	0.1–0.9
K_2O (%)	0.52	0.15–1.02
Na_2O (%)	0.39	0.15–0.20
CaO (%)	63.33	–
C_3S (%)	51.00	–
C_2S (%)	22.70	–
C_3A (%)	5.10	–
C_4AF (%)	11.90	–
Physical properties		
Specific gravity (g/cm^3)	3.11	2.21
Specific surface (cm^2/g)	3000	14,000

Fig. 1. Used recycled steel fiber.

natural river sand with a specific gravity of 2.60 g/cm^3. The crushed sand used in this study was distributed with an approximate maximum of 4.75 mm grain diameter and the proportion of grains smaller than 0.1 mm was less than 15%. A high range water reducer agent providing a water reduction from 10% to 15% at small dosage rates and achieving a water reduction up to 30% at high dosage rates was used in order to adjust the workability of the self-compacting concrete mixtures. Steel fibers were also used to reinforce self-compacting concretes. They were obtained from tire recycling, containing different characteristics such as different diameters, lengths, and shapes. In this study, the recycled steel fibers were supplied by an Iranian private company. The fibers presented an average length of more than 40 mm, diameter 0.15 ± 0.05 mm, and tensile strength more than 2000 MPa, and density was about 7850 kg/m^3 [8]. Fig. 1 illustrates the fibers used in this work. Mix compositions were reinforced by three different recycled steel fiber volume fractions of 0.25%, 0.5%, and 0.75%. The water/binder ratio was kept constant (equal to 0.44) for all mixtures.

Table 2 lists the mixture designations and material proportions used for the mixtures. Based on the target slump flow, the proportions of materials in Table 2 were determined to be equal or greater than 600 mm for the plain self-compacting concrete.

To batch, the cement and silica fume were mixed with both coarse and fine aggregates for 2 min. Then, the water and superplasticizer were added to the mixtures and mixed for 6–8 min. Finally, the concrete-fibers mixtures were prepared by gradual addition of recycled steel fibers to the fresh self-compacting concrete until the desired fiber/volume ratio was achieved. Fibers were incrementally added to the self-compacting concrete to avoid balling of fibers. Then, the compositions were cast into cubic molds (100 × 100 × 100 mm) [9], cylindrical disk molds (150 × 65 mm) [10,11], prismatic beams (320 × 80 × 60 mm) [12], and cylindrical molds (150 × 300 mm) [13] to be examined by the compressive, impact, flexural, splitting tensile tests, respectively. All specimens were stored at ambient temperature of 20 °C and 75% relative humidity for 24 h. Then, specimens were demolded and cured in water at temperature of 23 °C for 28 days. After 28 days, all specimens were tested and the hardened properties of specimens were characterized by compressive, splitting tensile, flexural, and impact tests.

To evaluate the fresh-state of mixtures, slump flow test (diameter and time) and V-funnel test were carried out based on EFNARC and ACI 237R [14,15]. Nagataki et al. indicated that slump flow time and diameter tests are two common assessment methods to determine the flow characteristics of unobstructed concrete in horizontal surface [16]. Fig. 2 represents the slump flow test for the reinforced self-compacting concrete with 0.5% steel fiber. As indicated in Fig. 2, the recycled steel fibers were distributed homogenously in the composition and there was no segregation observed between steel fibers and paste. The highest packing density of the particle structure could be used to design fresh mix compositions of SCC [21], while a trial-error basis was used to approach a target slump flow equal or greater than 600 mm for plain self-compacting concrete in this study.

Table 2
Mixture designations and used material proportions.

Designation of mixtures	Water/binder*	Silica fume (%, in Wt)	Cement/powder**	Fiber (%, in Vol)	Fine agg./powder	Coarse agg./powder	SP/powder
F0S0 (control)	0.44	0	0.16	0	0.42	0.42	0.0016
F0.25S0	0.44	0	0.16	0.25	0.42	0.42	0.0016
F0.5S0	0.44	0	0.16	0.5	0.42	0.42	0.0016
F0.75S0	0.44	0	0.16	0.75	0.42	0.42	0.0016
F0S7	0.44	7	0.15	0	0.42	0.42	0.0016
F0S14	0.44	14	0.13	0	0.42	0.42	0.0016
F0.25S7	0.44	7	0.15	0.25	0.42	0.42	0.0016
F0.25S14	0.44	14	0.13	0.25	0.42	0.42	0.0016
F0.5S7	0.44	7	0.15	0.5	0.42	0.42	0.0016
F0.5S14	0.44	14	0.13	0.5	0.42	0.42	0.0016
F0.75S7	0.44	7	0.15	0.75	0.42	0.42	0.0016
F0.75S14	0.44	14	0.13	0.75	0.42	0.42	0.0016

Binder*: Cement + silica fume.
Powder**: Fine aggregate + Coarse aggregate + cement + silica fume.

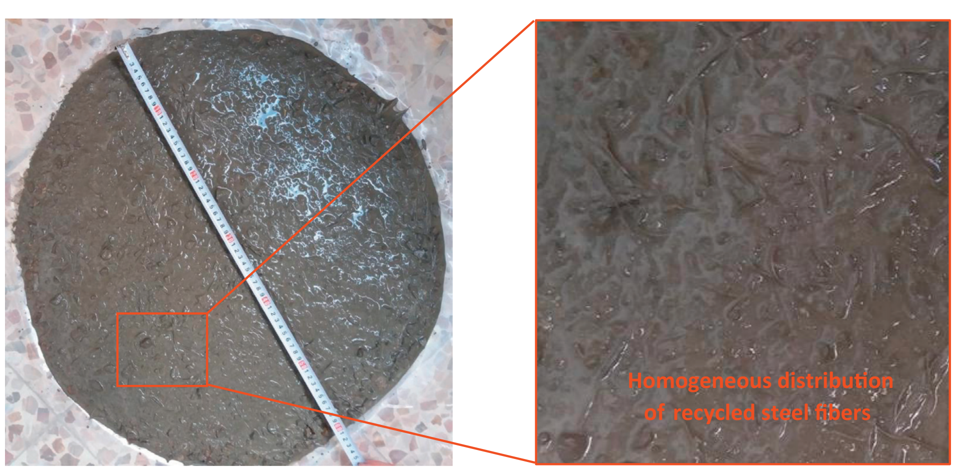

Fig. 2. The slump flow test for reinforced self-compacting concrete with 0.5% recycled steel fiber.

2.2. Test setups and instrumentations

2.2.1. Compressive test

Thirty-six cubic specimens (100 × 100 × 100 mm) were prepared based on the ASTM C39 recommendation and used to assess the compressive strength of different mixtures [9]. To impose the compressive load, a digital standard automatic testing machine with 1000 kN capacity was used. Compressive strength of specimens were recorded under a loading rate of 0.3 MPa/s. For each mix composition, three specimens were tested and the average of the results are presented.

2.2.2. Splitting tensile test

A total of thirty-six cylindrical specimens (150 × 300 mm) were cast and prepared for performing the splitting tensile test according to the ASTM C496 recommendation [13]. Splitting tensile strength of specimens were registered under a load rate of 0.05 MPa/s. Tensile strength of specimens was computed based on the following equation:

$$\sigma_t = \frac{2P}{\pi l d} \tag{1}$$

where, P is the maximum tensile force, l is length of cylinder, and d is diameter of cylinder.

2.2.3. Three point bending test

Thirty-six prismatic beams with dimension of (320 × 80 × 60 mm) were used to carry out three point bending (TPB) test in accordance with the ASTM C78 recommendation [12]. The flexural load was recorded by using a load cell with a capacity of 50 kN, while the mid-span deflection was recorded by using a Linear Variable Differential Transformer (LVDT) of 10 mm stroke. Adopted TPB test setup is depicted in Fig. 3a. TPB test was conducted with a deflection rate of 0.6 mm/min under displacement control. Eq. (2) was used to compute the flexural strength of specimens under TPB test:

$$\sigma_f = \frac{3FL}{2bh^2} \tag{2}$$

where, F is the total flexural load, L is span length, b and h are width (60 mm) and height (80 mm) of beams, respectively.

2.2.4. Impact test

Impact test was carried out for thirty-six cylindrical disks based on ACI Committee 544 [17]. According to the adopted test setup, a steel hammer of 4.45-kg weight was dropped from a 457-mm height on a steel ball of 63.5 mm diameter. The steel ball indicated in Fig. 3b was touching the central surface of specimens. Totally, thirty-six disks of 150 mm diameter and 65 mm height were cast

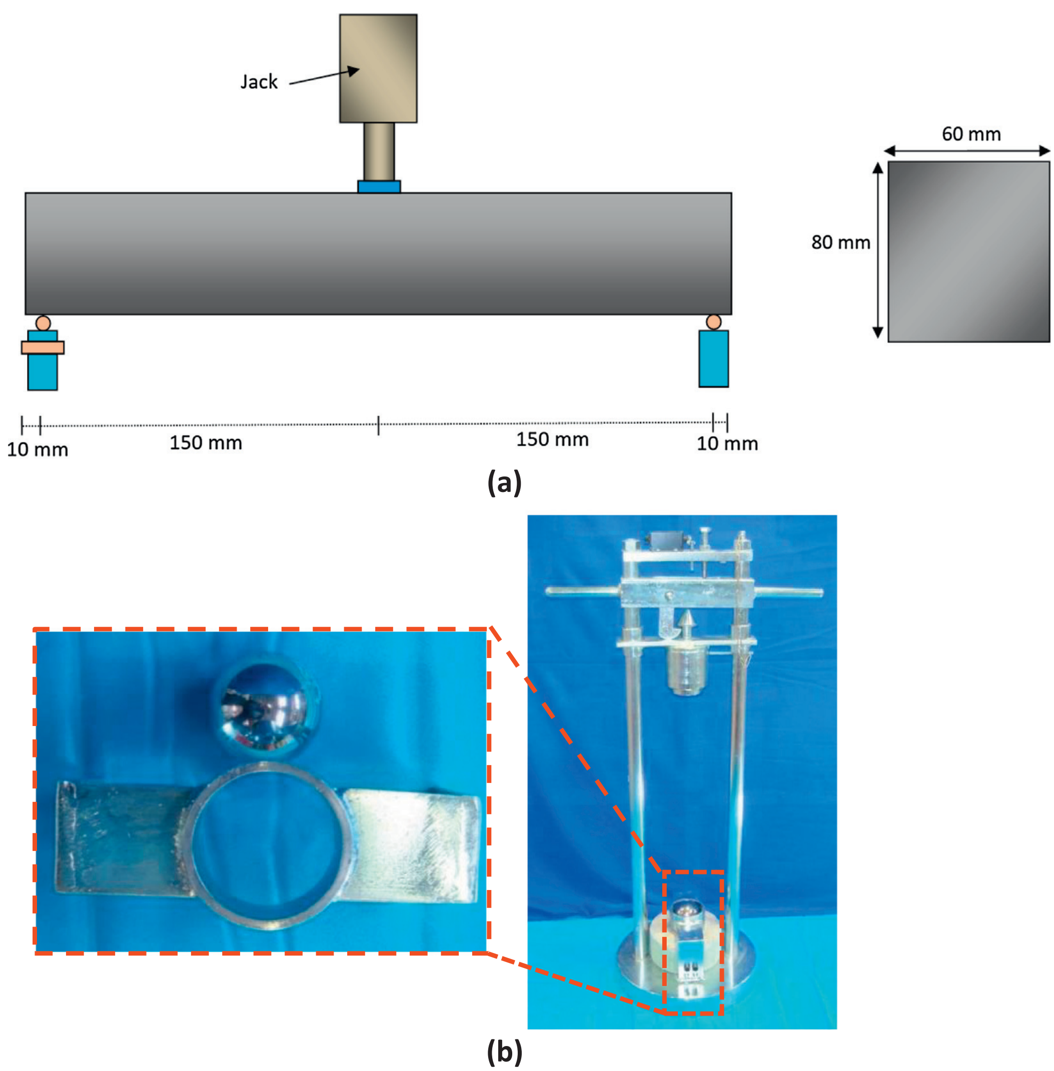

Fig. 3. a) Adopted test setup for flexural test setup; b) used apparatus for implementation of impact test.

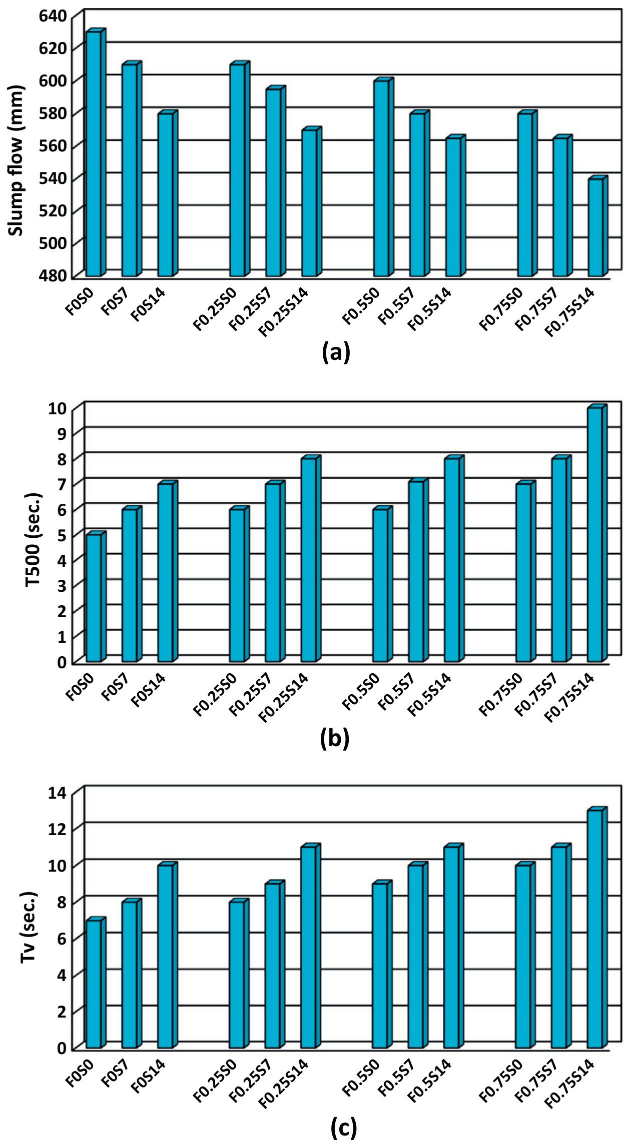

Fig. 4. Effect of silica fume on: a) slump flow; b) T500; c) T_V.

and tested at age of 28 days. To calculate energy absorption the following equation was adopted:

$$E_n = N \times W \times H \quad (3)$$

where, N is number of blows, W is weight of ball, and H is height of fall.

3. Results and discussion

3.1. Properties of fresh self-compacting concrete mixtures

In the first stage of the present study, the fresh-state self-compacting concrete mixtures was assessed by using slump flow test and V-funnel test. The results are indicated in Fig. 4. Concerning the results, increasing the content of silica fume led to reduce the workability, so that the maximum reduction (5%) for the slump flow diameter had been registered for specimen F0S14, compared to F0S7. Moreover, addition of recycle steel fiber intensify this reduction due to increase of self-compacting concrete viscosity [18]. The maximum reduction in slump flow diameter due to addition of simultaneously silica fume and recycled steel fiber was registered about 15% due to replacement of 14% silica fume and adding 0.75% recycled steel fiber compare to control mixture (F0S0).

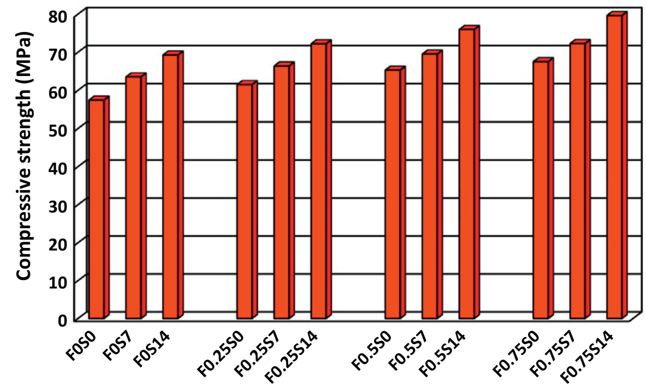

Fig. 5. Effect of silica fume on the compressive strength of mix compositions.

Replacing cement with silica fume resulted in increasing slump flow time (T500) as increasing silica fume content from 7% to 14% in the reinforced self-compacting mixtures with fiber content 0.75% resulted in attaining the maximum increase of T500 (about 25%). Besides, the slump flow time (T500) was also increased by adding both silica fume and recycled steel fiber. In comparison with the control mixture, the maximum increase of T500 attained for specimen F0.75S14 with about two times increase.

The results obtained from the V-funnel test are depicted in Fig. 4c. Replacing cement with silica fume resulted in an increase of T_V, so that increasing the content of silica fume from 7% to 14% in the self-compacting mixtures leads to achieve the maximum increase of T_V (about 25%). Based on the results, adding both silica fume and recycled steel fiber resulted in achieving the maximum increase of T_V with about 85% increase for specimen F0.75S14, compared with the control mixture.

Benaicha et al. investigated the effects of silica fume and viscosity modifying agent on the mechanical and rheological behavior of self-compacting concrete [19]. The rheological tests used in this study consisted of the slump flow, V-funnel, L-Box, and sieve segregation test, as well as yield stress and viscosity measurements [18]. Silica fume in different binder weights 5%, 10%, 15%, 20%, 25%, and 30% was added to the mixture. The results showed that increasing the content of the silica fume reduced the slump flow and increased V-funnel flow time of the mixtures [19].

3.2. Hardened properties of self-compacting concrete

3.2.1. Compressive strength

The compressive strength results represented in Fig. 5. Regarding the results, adding the recycled steel fiber increases the compressive strength as a result of crack arresting capacity of bridging fibers, so that adding 0.75% recycled steel fiber to the plain self-compacting mixtures without presence of silica fume (F0.75S0) increased remarkably the compressive strength (about 18%), compared with the control mixture.

Moreover, replacing cement with silica fume and adding recycled steel fibers to plain self-compacting concrete increases the compressive strength, as shown in Fig. 5. Silica fume as a pozzolanic material improves the aggregate-paste bond and enhances the bond properties at interface between the fiber and the matrix with a dense C-S-H gel in the reinforced self-compacting mixtures. Based on the results presented in Fig. 5, the maximum increase of compressive strength in the mixtures was obtained when the maximum contents of silica fume (14%) and steel fibers (0.75%)

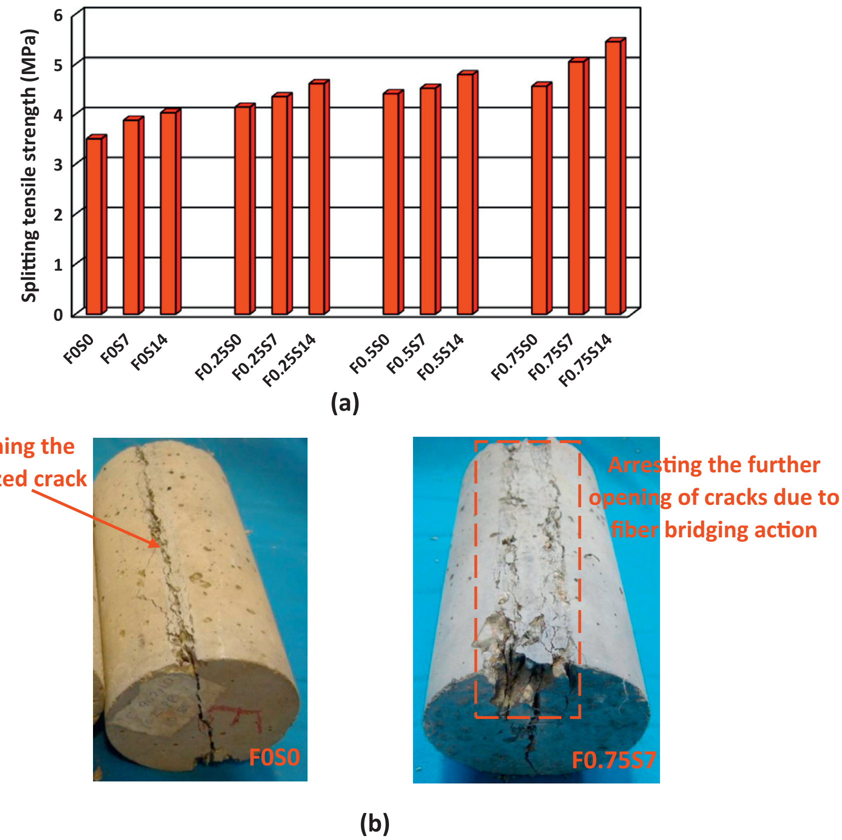

Fig. 6. a) Effect of silica fume on the splitting tensile strength of mix compositions; b) formed crack patterns in the cylindrical concrete specimens under splitting tensile test.

were replaced and added to the mixtures, respectively. The maximum increase of the compressive strength (about 40%) was recorded for specimen F0.75S14, compared to the control mixture.

Simultaneously, adding steel fiber to plain concrete could either increase or decrease the compressive strength [4]. Adding steel fibers increases the porosity of the matrix and reduces its compressive strength. On the contrary, steel fibers effectively limit the crack propagation due to the presence of strong bond between fibers and matrix [22]. Therefore, regardless of virgin or recycled steel fiber, either increasing or decreasing the compressive strength was reported in the previous studies was caused by steel fiber addition. Aslani et al. observed an increase in the compressive strength of the reinforced self-compacting concrete caused by virgin steel fibers of 60 mm length [23], while Khaloo et al. recorded a reduction in the compressive strength of the reinforced self-compacting concrete caused by virgin steel fiber of 20.6 mm length [4].

3.2.2. Splitting tensile strength

The results on splitting tensile strength are depicted in Fig. 6a. Like the results attained for compressive strength, replacement of cement with silica fume (7% or 14%) and addition of recycled steel fiber resulted in an increased splitting tensile strength. Because of the bridging action of steel fibers, increasing fiber content in the reinforced self-compacting concrete mixtures without presence of silica fume increases the splitting tensile strength about 30% for the specimen F0.75S0, compared to the control specimen. Moreover, there is an advantage in simultaneous use of silica fume and fiber in the concrete mixtures: increases splitting tensile strength due to enhancing both the aggregate-paste bond and the bond properties of fiber/matrix. Therefore, based on the results achieved, the maximum increase of splitting tensile strength was recorded for F0.75S14 (about 55%), compared to the control specimen.

Fig. 6b depicts the cracks formed in the cylindrical concrete specimens assessed under the splitting tensile tests. The bridging action of recycled steel fiber arrested the crack from further opening and multiple cracks were consequently formed in the specimens F0.75S7, as shown in Fig. 6b. Since, the cylindrical specimens made with the plain self-compacting concrete (F0S0) failed with forming a localized crack.

Earlier studies also reported the increase of the tensile strength for the reinforced self-compacting concrete caused by steel fibers [22–25]. They also showed that increased tensile strength is associated with an increase in the steel fiber contents [22–25] made by matrix properties as well as by shape, length, and mechanical properties of the steel fiber [26]. Increasing the steel fiber content

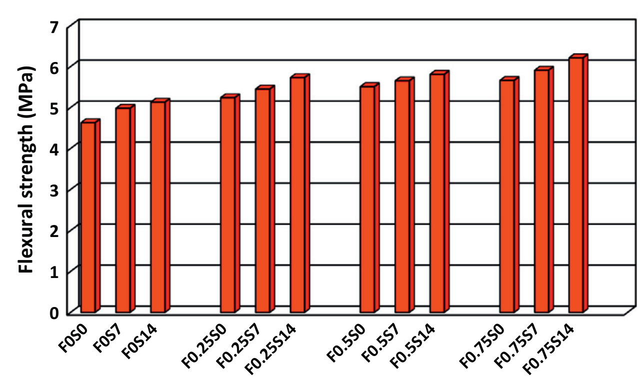

Fig. 7. Effect of silica fume on the flexural strength of mix compositions.

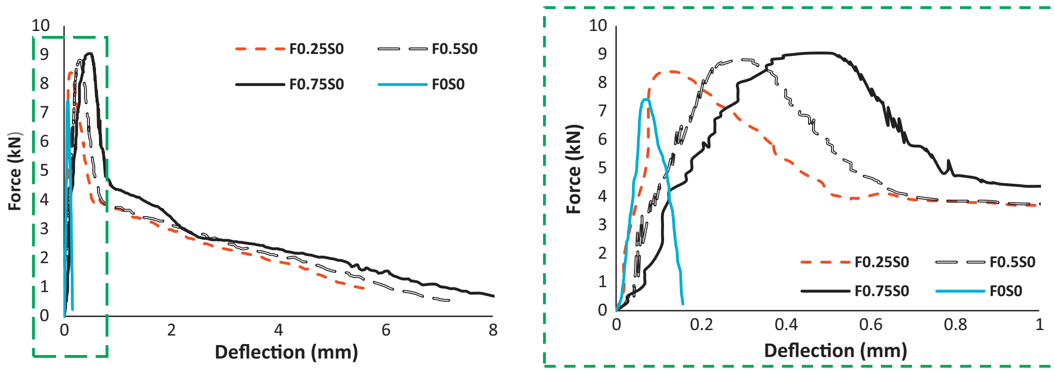

Fig. 8. Effect of addition of recycled steel fiber on the flexural performance of compositions.

results in increasing fiber-bridging actions in the reinforced self-compacting concrete specimens. In this study, the results obtained for the splitting tensile strength were consistent with the findings in [22–25].

3.2.3. Flexural strength

The effects of replacing cement with silica fume on the flexural strength of the plain and reinforced self-compacting mixtures are shown in Fig. 7. The maximum increase of flexural strength in the reinforced self-compacting concrete mixtures without presence of silica fume was detected in specimen F0.75S0 (about 25%), compared to the control specimen. This increase was made by the bridging action of the recycled steel fiber, arresting the cracks from further opening, and forming new cracks in the vicinity [20]. Moreover, regardless of the recycled steel fiber content used to reinforce of the matrix, the flexural strength of mixtures was increased by replacing silica fume due to enhanced interface of aggregate-paste and fiber-matrix. As a results of adding silica fume, the maximum increment was achieved for the specimen F0.75S14 (about 35%), compared to the F0S0.

The effects of adding recycled steel fiber on the flexural performance of the mixtures without presence of silica fume are depicted in Fig. 8. Regarding the results, increasing the fiber content decreases the flexural stiffness, while the ultimate load

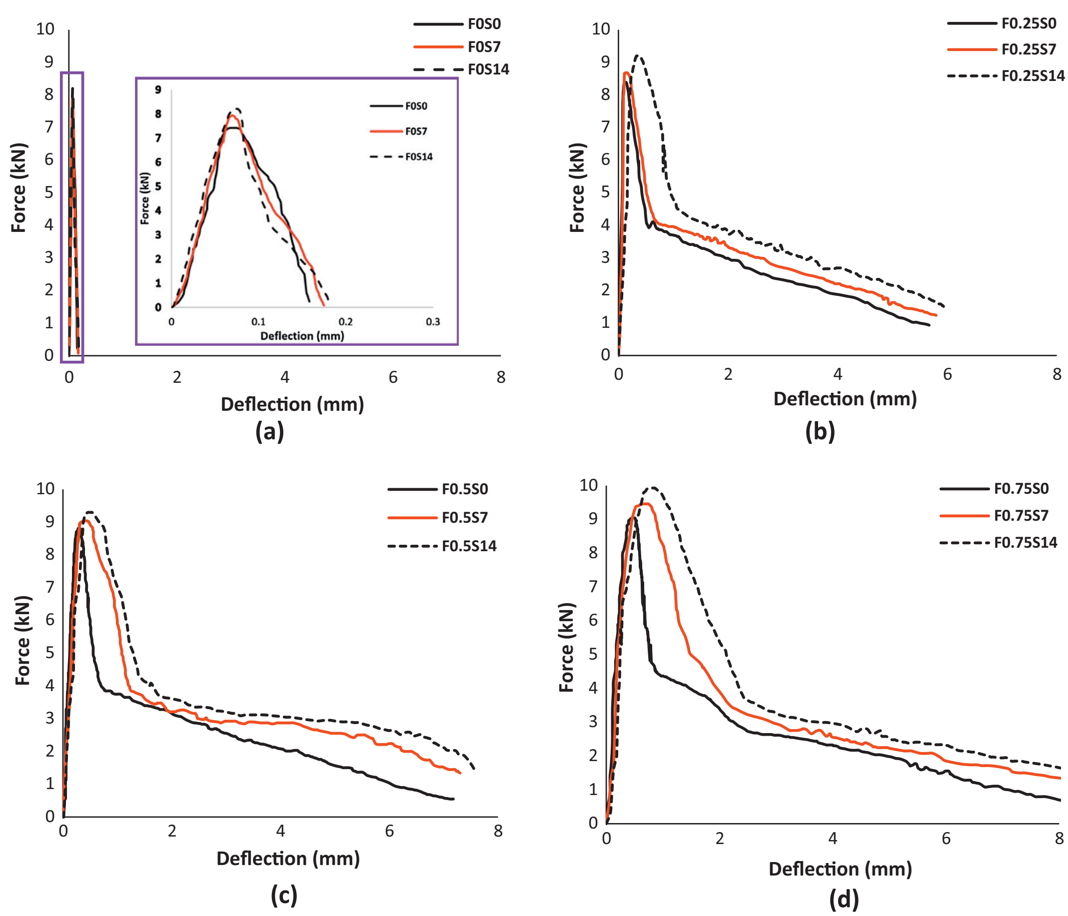

Fig. 9. Effect of silica fume on the force vs. deflection response of mix compositions with: a) 0% recycled steel fiber; b) 0.25% recycled steel fiber; c) 0.5% recycled steel fiber; d) 0.75% recycled steel fiber.

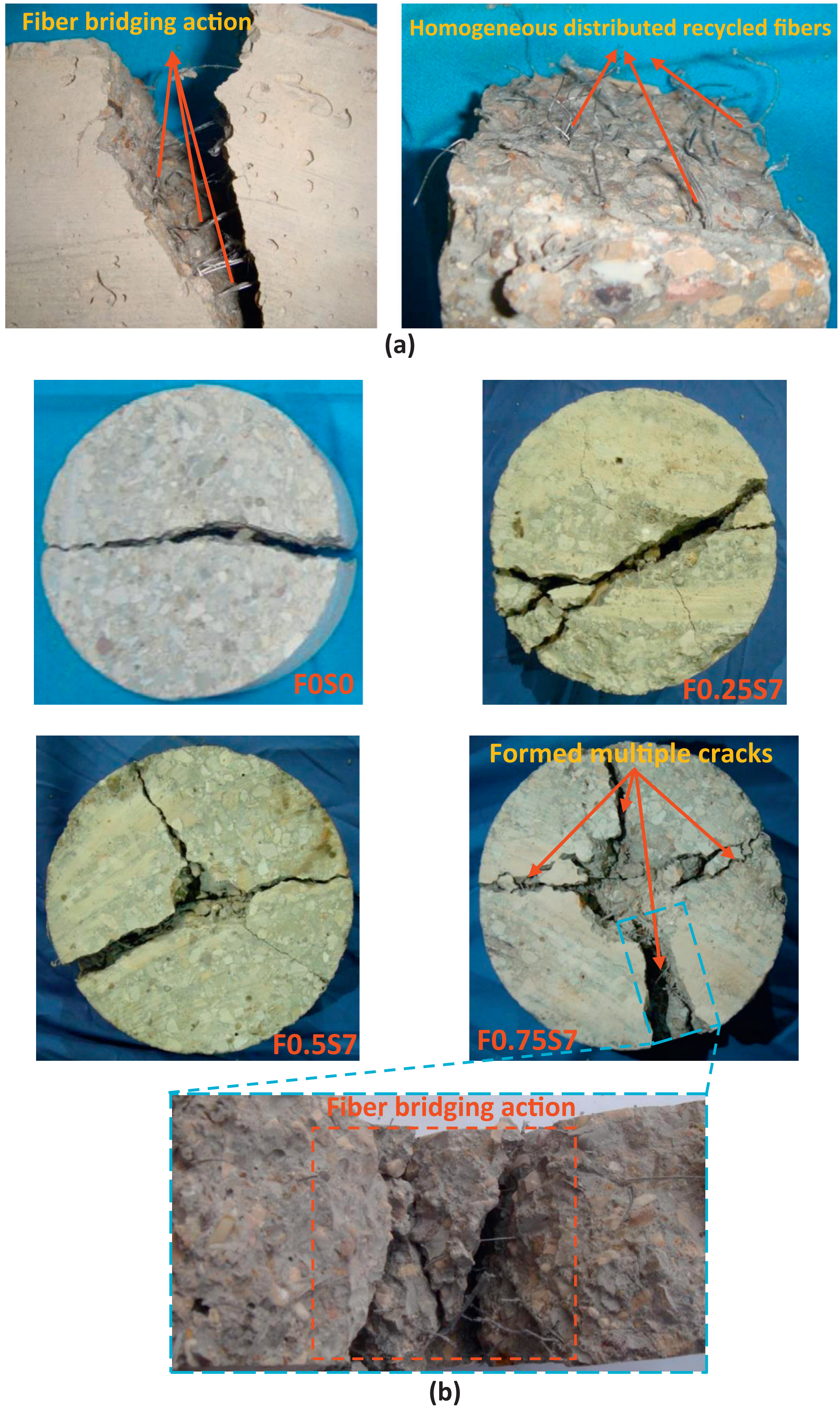

Fig. 10. a) Fracture surface of reinforced specimens; b) effects of recycled steel fiber and silica fume on the formed crack numbers.

carrying capacity and its corresponding deflection increased. Furthermore, the post-cracking residual strength was increased by adding greater contents of recycled steel fiber. The maximum improvement in the load carrying capacity and its corresponding deflection were about 22% and 7 times for the mixture reinforced with recycled steel fiber 0.75%, compared to the control specimen (F0S0).

Ponikiewski et al. investigated on the effects of using steel fibers with different lengths (30 mm and 50 mm) on the flexural performance of the reinforced self-compacting concretes [27]. After assuring the absence of unfavorable effects (e.g. balling) of adding fibers to the mixtures, fibers of longer length are aligned planar, while steel fibers with shorter lengths had a three-dimensional orientation [27,28]. They also found that planar alignment of long steel fibers causes to greater improvement of the reinforced specimen's flexural performance in comparison to the specimens reinforced by three dimensional short steel fibers [27].

The impact of replacing cement with silica fume on the flexural performance of plain and reinforced self-compacting concrete is shown in Fig. 9. The results revealed that replacement of silica fume led to increased load carrying capacity of the plain self-compacting concrete, while no significant increase was observed for the deflection corresponding to the ultimate load carrying capacity (Fig. 9a). In addition, replacing silica fume with plain self-compacting mixtures caused no significant improvement of the post-cracking residual strength.

The results indicated in Fig. 9bd revealed that replacing cement with silica fume results in significant enhancement on the flexural

Table 3
Obtained results from impact test.

Specimen	The first crack impact resistance (blow)	The ultimate crack impact resistance (blow)	INPB (blows)	Absorbed energy (N.mm)
F0S0	17	19	2	379
F0S7	24	27	3	538
F0S14	29	33	4	658
F0.25S0	38	47	9	937
F0.25S7	42	53	11	1057
F0.25S14	44	56	12	1117
F0.5S0	51	70	19	1396
F0.5S7	54	75	21	1496
F0.5S14	57	80	23	1596
F0.75S0	55	81	26	1616
F0.75S7	59	88	29	1755
F0.75S14	63	96	33	1915

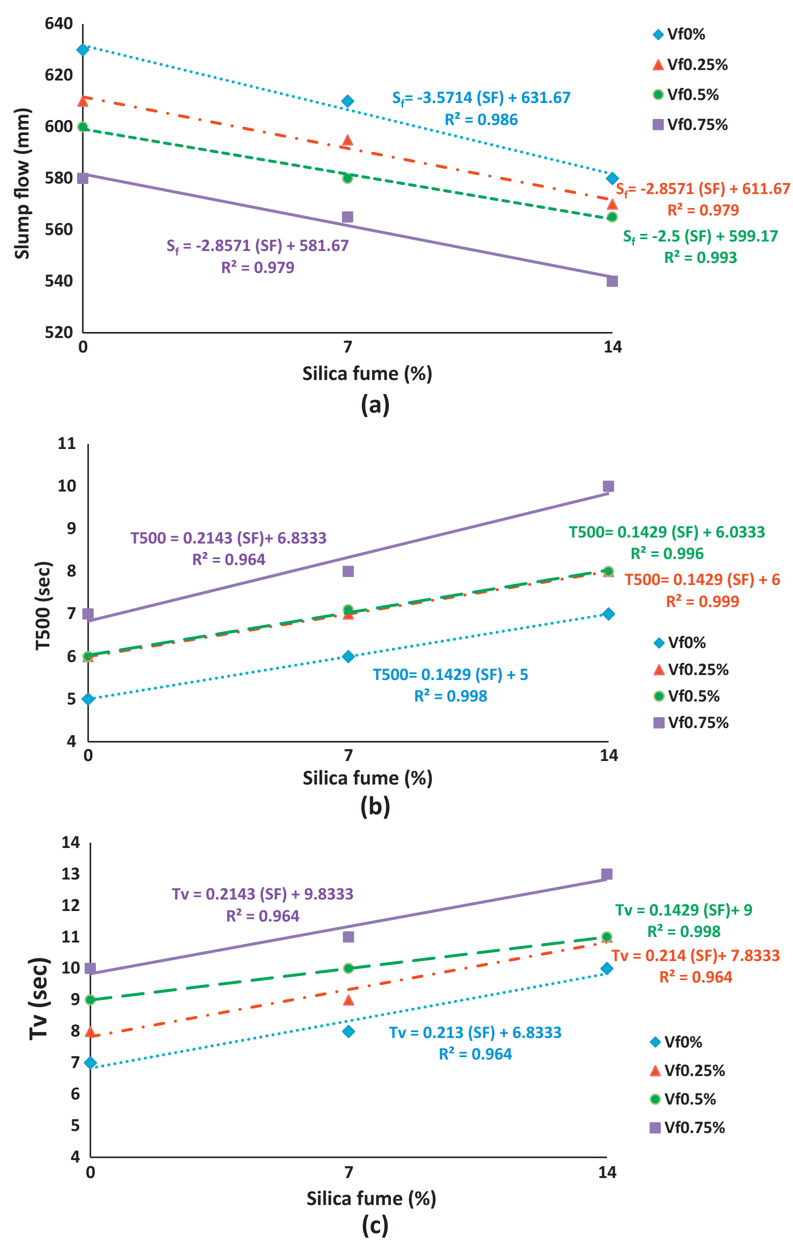

Fig. 11. Silica fume versus: a) slump flow; b) T500; c) T_V.

performance of fiber reinforced self-compacting concrete specimens, including increasing ultimate load carrying capacity, deflection corresponding to the ultimate load, and the post-cracking residual strength. Since, it was shown that replacement of silica fume in the plain and reinforced self-compacting mixtures have no significant effect on the flexural stiffness of specimens.

A fractured surface is shown in Fig. 10a where, parts of recycled steel fibers are marked. Regarding the presented fractured surface, it was revealed that recycled steel fibers are distributed uniformly in the fracture surface and the fiber-bridging action can efficiently improve the mechanical properties of the reinforced mixtures.

3.2.4. Impact resistance

The results on the impact resistance of specimens are summarized in Table 3. Concerning the results, adding recycled steel fiber in the mixture without presence of silica fume improves both the first and ultimate crack impact resistance of specimens; however, further increase was obtained for the ultimate crack impact resistance, compared to the first crack impact resistance. The maximum increase of the first and ultimate crack impact resistance was recorded more than 3 and 4 times for the specimen F0.75S0 comparing to the control mixture. Increased recycled steel fiber content enhances the difference between the blow number of the first crack impact resistance and the blow number of the ultimate crack impact resistance. The use of a recycled steel fiber of 50 mm length resulted in a planar fiber orientation. Mastali et al. demonstrated that three-dimensional orientations of the fibers reduce the impact resistance of the reinforced concrete specimens, while planar fiber orientation enhances it [28].

In this paper, increasing the Number of Post initial crack Blows to failure is labelled as the "INPB" parameter. Increasing steel fiber content from 0.25% to 0.5% and 0.75% increases the number of post-initial crack blows to failure as much as 2.11 and 2.88 times, respectively.

Replacement of silica fume also increased the impact resistance of both plain and reinforced self-compacting concrete mixtures. As a result, compared to the specimen control mixture and due to the replacement of silica fume 14% in the specimens F0S14, the maximum increase of the first and ultimate crack impact resistance was 70.58% and 73.68%, respectively. Nili et al. indicated that adding silica fume to concrete enhances the interfacial transition zone (ITZ) between cement paste and aggregate in concrete [5].

Since, simultaneously use of both silica fume and recycled steel fiber resulted in recording the maximum increment for the first

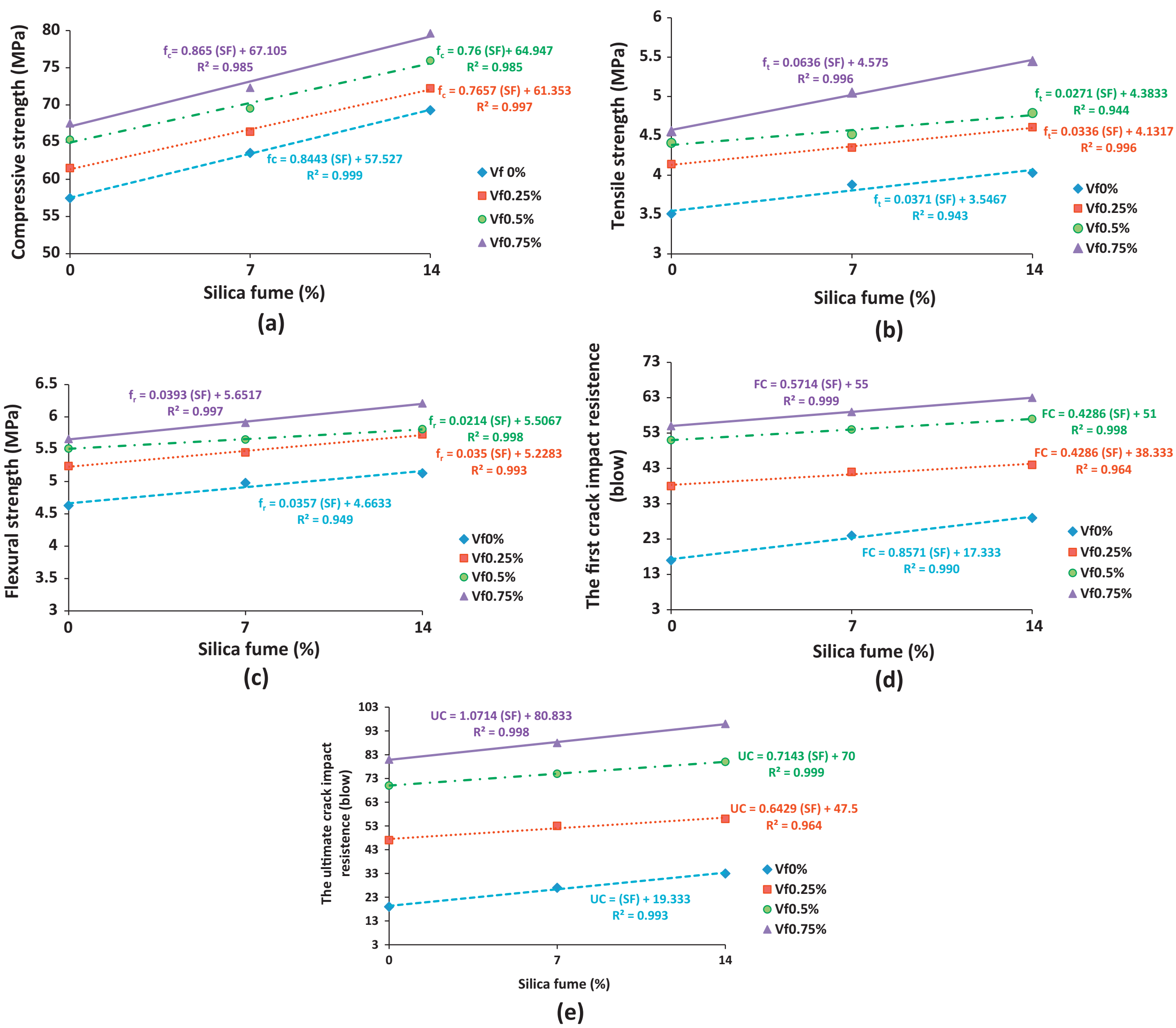

Fig. 12. Silica fume versus: a) compressive strength; b) splitting tensile strength; c) flexural strength; d) the first crack impact resistance; e) the ultimate crack impact resistance.

(about 4 times) and ultimate (about 5 times) crack impact resistance of specimen F0.75S14 compare to control mixture. Moreover, the INPB was increased as much as 16 times for specimen F0.75S14, compared to the control mixture.

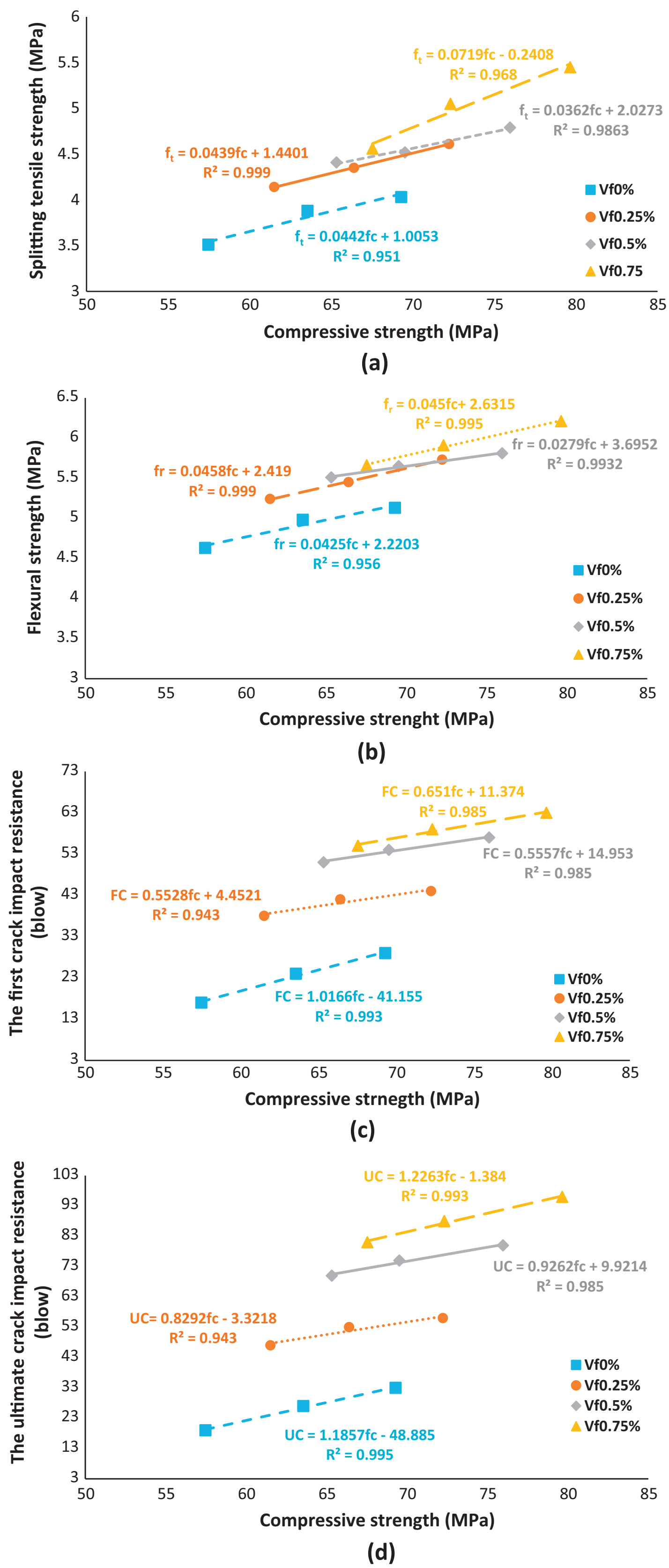

Fig. 13. Compressive strength versus: a) splitting tensile strength; b) flexural strength; c) the first crack impact resistance; d) the ultimate crack impact resistance.

Fig. 10b shows the crack patterns formed on some tested disks, which were plain and reinforced with recycled steel fiber 0.75%. Simultaneously use of both silica fume and recycled steel fiber resulted in forming more cracks on the surface of specimens because of improvements at the interface of aggregate-paste and fiber-matrix and increased fiber bridging action, as shown in Fig. 10b.

4. Analytical analysis

In the first stage of this section, regard of the relatively large gathered experimental database, the fresh and hardened properties of plain and reinforced self-compacting concrete specimens with recycled steel fiber can be correlated with the content of silica fume by empirical equations with high coefficient of determination (R^2). These empirical equations were developed by using regression analysis.

Fig. 11a indicates the linear empirical equations that correlate the slump flow diameter to silica fume content. Based on the developed equations in Fig. 11, fresh-state properties of the plain and reinforced self-compacting concrete mixtures can be linearly correlated to the silica fume content. Concerning these results, increased silica fume content caused the highest reduction rate in slump flow diameter for the plain self-compacting concrete mixtures since the slope of developed equations for the plain self-compacting concrete (V_f 0%) was higher than that for the specimens with fiber contents. Moreover, the maximum rate of increased T500 and T_V was obtained for the reinforced self-compacting concrete with the recycled steel fiber 0.75% as a result of replacing silica fume.where, S_f is slump flow and SF is the content of silica fume in Fig. 11.

Replacing cement with silica fume resulted in the highest rate of gaining compressive strength, splitting tensile strength, and flexural strength for the reinforced self-compacting concrete with recycled steel fiber 0.75%, as indicated in Fig. 12. This is because the maximum rate of increasing the first and ultimate crack impact resistance of the specimens with replacement of silica fume was recorded for the plain self-compacting concrete and the reinforced self-compacting concrete with recycled steel fiber 0.75%, respectively.where, f_c is compressive strength (MPa), f_t is tensile strength (MPa), f_r is flexural strength, FC is the first crack impact resistance, and UC is the ultimate crack impact resistance shown in Fig. 12.

Fig. 13 shows the empirical equations developed on the relationship between the impact resistance and mechanical properties. Accordingly, there was observed a linear relationship between the impact resistance and mechanical properties in each group of mixtures.

By increasing compressive strength, the maximum rate of increasing splitting tensile strength was recorded for reinforced self-compacting concrete mixture with 0.75% recycled steel fiber, while the reinforced specimens with 0.25% recycled steel fiber indicated the highest rate of gaining flexural strength with increase of compressive strength. As indicated in Fig. 13a and b, the developed equations for the reinforced self-compacting concrete mixtures with recycled steel fiber 0.75% and recycled steel fiber 0.25% possess the highest slope in terms of increased splitting tensile strength and flexural strength, respectively.

Moreover, with an increased the compressive strength, the best performance in terms of the first crack and the ultimate crack impact resistance were obtained for plane self-compacting concrete and reinforced self-compacting concrete with recycled steel fiber 0.75%, respectively.

Several methods have been proposed to compute the fracture toughness of the reinforced concrete by using different codes. The present paper employs ASTM C1018 and JCI methods [29,30]. According to ASTM C1018, toughness is computed at four specific deflections, including δ, 3δ, 5.5δ and 10.5δ [29,30]. The elastic or pre-peak toughness is measured at the deflection of δ, however, post peak toughness is recorded at other deflections. Several parameters involved in this method include toughness indices designated by I5, I10, and I20. These indices are defined in Fig. 14a. The residual strengths are also computed based on the average post-peak load at a specific deflection interval. Eqs. (4) and (5) can be used to determine the residual strength values:

$$R_{5,10} = 20(I_{10} - I_5) \tag{4}$$

$$R_{10,20} = 10(I_{20} - I_{10}) \tag{5}$$

Furthermore, the Japanese Concrete Institute (JCI) proposed a method based on measuring the mid-span deflection at span/150 of the beams under flexural test. Flexural toughness factor can be computed through the following equation [31]:

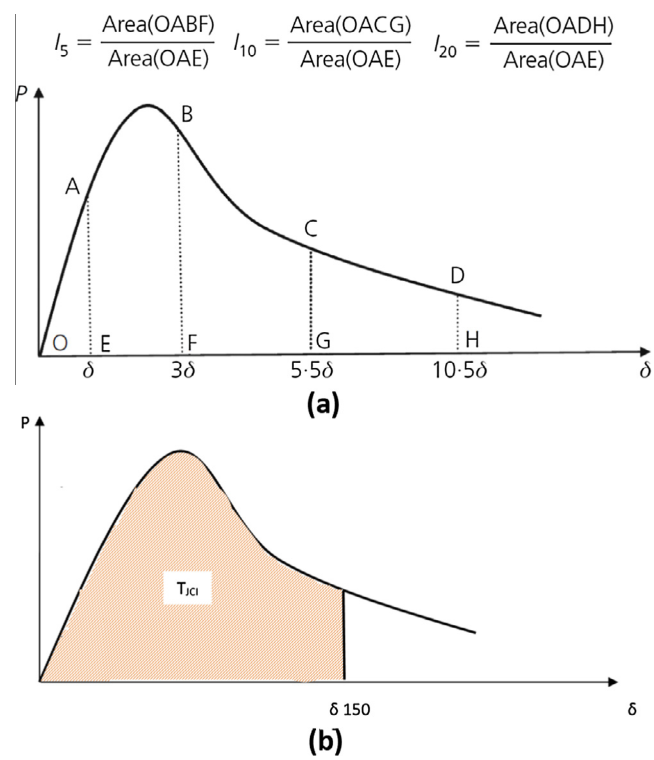

Fig. 14. a) Definition of flexural toughness indices based on ACTM C1018; b) definition of flexural toughness indices based on JCI.

Table 4
Flexural toughness factors and indices of fiber reinforced beams.

Designation of specimens	I_5	I_{10}	I_{20}	I_{10}/I_5	I_{20}/I_{10}	$R_{5,10}$	$R_{10,20}$	σ_b
F0S0	1.00	1.00	1.00	1.00	1.00	0.00	0.00	–
F0S7	1.00	1.00	1.00	1.00	1.00	0.00	0.00	–
F0S14	1.00	1.00	1.00	1.00	1.00	0.00	0.00	–
F0.25S0	5.65	9.07	14.34	1.60	1.58	68.45	52.66	3.32
F0.25S7	8.05	14.87	23.04	1.84	1.55	136.49	81.70	3.52
F0.25S14	5.58	9.16	14.02	1.64	1.53	71.64	48.55	4.27
F0.5S0	4.11	6.36	10.02	1.54	1.57	44.98	36.64	3.45
F0.5S7	4.33	6.39	9.62	1.47	1.50	41.10	32.25	4.30
F0.5S14	4.59	7.02	10.29	1.53	1.46	48.76	32.63	6.92
F0.75S0	3.99	6.29	9.71	1.57	1.54	45.91	34.15	3.95
F0.75S7	3.70	5.33	7.47	1.44	1.40	32.63	21.38	5.15
F0.75S14	3.97	5.70	8.02	1.43	1.40	34.66	23.19	5.85

$$\sigma_b = \frac{\tau_b L}{\delta_{150} b h^2} \quad (6)$$

where, L is span of the beam, δ/150 is mid-span deflection at span/150, is flexural toughness up to the deflection of δ/150, and h and b are height and width of the beam, respectively. As indicated in Fig. 14b, the flexural toughness can be determined through calculating the area under the force-deflection diagram up to δ/150.

Table 4 lists the values of flexural toughness factors, fracture indices and residual strengths of the concrete specimens. With respect to the results listed in Table 4, adding greater fiber content to reinforce the plain concrete resulted in increased flexural toughness, leading to the enhancement of the fracture and impact resistance of the concrete specimens.

Replacing cement with silica fume content increases the flexural toughness factors and the greatest enhancement in the flexural toughness factor was recorded in case of the specimens reinforced with recycled steel fiber 0.5% and the maximum content of cement with silica fume replaced (14%). Moreover, increasing recycled fiber content reduces the flexural toughness indices, presuming constant content of the replaced cement with silica fume.

5. Conclusions

In this paper, the effects of replacing cement with silica fume on mechanical properties and impact resistance of the reinforced self-compacting concrete with recycled steel fibers were experimentally and analytically studied. In this regard, one hundred and forty-four specimens were tested experimentally under compressive test, splitting tensile test, flexural test, and drop weight impact test. The obtained experimental results were comprehensively analysed. Then, based on the relatively large experimental database, analytical analysis was carried out. Concerning the experimental and analytical results, following conclusions can be highlighted:

1. Replacing silica fume and adding recycled steel fiber reduce the workability of the mixtures.
2. The combined effects of silica fume and recycled steel fiber improves the impact resistance and mechanical properties.
3. Replacement of cement with silica fume increases the ultimate load carrying capacity, deflection corresponding to the ultimate load carrying capacity, the post-cracking residual strength of beams under flexural loading, however, no significant effect on the flexural stiffness of specimens is observed.
4. Replacing cement with silica fume in the plain self-compacting concrete mixtures had no significant effect on the post peak response of specimens.
5. Increasing the content of silica fume results the highest rate of reduction in slump flow diameter for the plain self-compacting concrete mixtures. In addition, the maximum rate of increasing T500 and T_V are obtained for the reinforced self-compacting concrete with the recycled steel fiber of 0.75%.
6. Due to replacing cement with silica fume, the highest rate of gaining compressive strength, splitting tensile strength, and flexural strength are obtained for the reinforced self-compacting concrete with recycled steel fiber of 0.75%.
7. Because of the replacement of silica fume, the maximum rate of increasing the first and ultimate crack impact resistance of the disks are reported for the plain self-compacting concrete and the reinforced self-compacting concrete with the recycled steel fiber of 0.75%, respectively.
8. Mechanical properties and impact resistance of specimens are linearly correlated, having high coefficient of determination (R^2).
9. With an increased compressive strength, the reinforced self-compacting concrete mixtures with the recycled steel fiber of 0.75% and the recycled steel fiber 0.25% show the highest rate of gaining splitting tensile strength and flexural strength, respectively.
10. Replacing cement with silica fume content increased the flexural toughness factors.
11. Increasing the content of recycled steel fiber reduces the flexural toughness indices, presuming constant content of the replaced cement with silica fume.

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