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Combined effect of silica fume and steel fibers on the impact resistance and mechanical properties of concrete

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ABSTRACT

This study investigated the impact resistance and mechanical properties of steel fiber-reinforced concrete with water–cement ratios of 0.46 and 0.36, with and without the addition of silica fume. Hooked steel fibers with 60-mm length and an aspect ratio of 80, with three volume fractions of 0%, 0.5%, and 1% were used as the reinforcing material. In pre-determined mixtures, silica fume is used as a cement replacement material at 8% weight of cement. The experimental results show that incorporation steel fibers improve the strength performance of concrete, particularly the splitting tensile and the flexural strengths. A remarkable improvement was observed in impact resistance of the fibrous concretes, as compared with the reference materials. The results demonstrate that when steel fiber is introduced into the specimens including silica fume, the impact resistance and the ductility of the resulting concrete are considerably increased.

1. Introduction

In recent years, demand has continued to grow for high strength concrete for use in infrastructure construction. This construction material is used in high-rise buildings to avoid the use of unacceptably oversized columns on lower floors, to allow large column spacing and more usable floor space, or to increase the overall height of the building without detracting from the aesthetics and function of the lower floors [1]. Furthermore, because of the low permeability characteristics, high strength concrete performs much better under harsh climate conditions and in marine environments, therefore reducing maintenance and repair costs [2]. However, high strength concrete is more brittle than normal concrete and for this reason, utilization of high strength concrete is seriously limited [3–6]. Additionally, it is well understood that silica fume, due to high pozzolanic activity, is a necessary material when producing high strength concrete; however, it also causes the concrete to have a more brittle structure [7]. Therefore, ductility improvement is an important goal in concrete science and must be taken into account by researchers. It is generally accepted that the ductility of high strength concrete can be improved by introducing various types of fibers, especially steel fibers, into the concrete mixtures. Fiber reinforcement allows for crack bridging mixtures, taking advantage of a mechanism that restrains crack opening and enhances the energy absorption of the concrete composites [8–12]. The inclusion of fibers in concrete, mortar, and cement paste can enhance many of the engineering properties, such as flexural strength, fracture toughness, thermal shock strength and resistance under impact and fatigue loadings [13–19]. Concrete is also known to be a strain-rate sensitive material; its properties change with changes in the rate of loading [20]. Its behavior under short duration dynamic loads, such as the impacts from missiles and projectiles, wind gusts, earthquakes, and machine dynamics, is completely different than that displayed under static loads [21,22]. The resistance of concrete under dynamic loadings can be assessed through different types of test procedures, such as the explosive test, drop-weight test, projectile impact test, and constant strain-rate test [23]; of these, the drop-weight test, as reported by the ACI Committee 544 [24] is the simplest. In the present work, the impact resistance and mechanical properties of fibrous and nonfibrous concrete specimens with and without silica fume addition were experimentally assessed.

2. Test program and procedures

In this research, two series of concrete mixtures with water–cement ratios of 0.46 and 0.36, were prepared and labeled as A1 and B1, respectively. Selected specimens were reinforced with 0.5% and 1% (by volume fractions) steel fibers. Silica fume was also added to some specimens as a cement replacement (8% by weight). Compressive strength tests were performed after 7, 28 and 91 days on 100 × 100 × 100-mm cubic specimens and flexural strength

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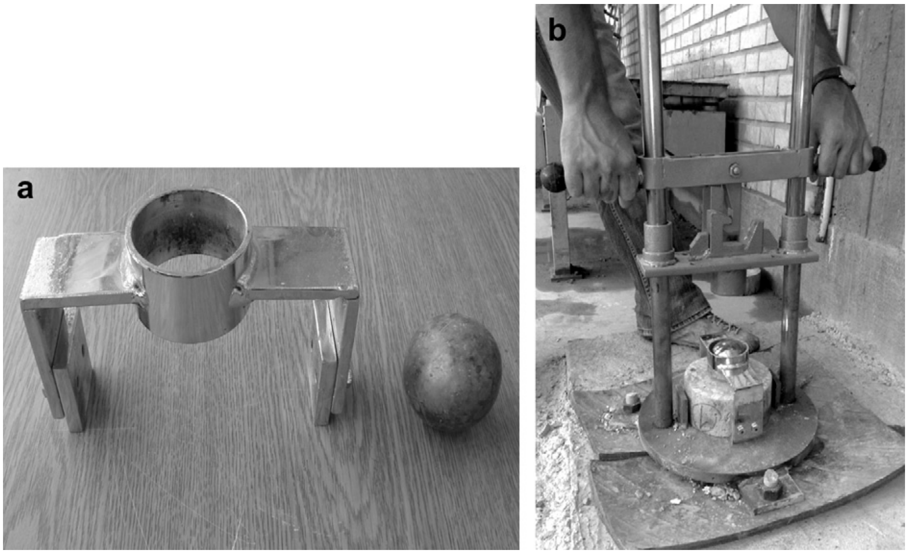

Fig. 1. (a) Base plate within four positioning lugs and subjected to repeated blows, (b) procedure for the impact test.

testing was also performed on 80 × 100 × 400-mm specimens. The splitting tensile strength test was performed at 28 days on 100 × 200-mm cylindrical specimens. The impact resistance of the specimens was also determined in accordance with procedure proposed by ACI Committee 544. For this purpose, six 150 × 64-mm discs cut from 150 × 300-mm cylindrical specimens with a diamond cutter, were prepared and placed on a base plate with four positioning lugs and were then struck with repeated blows. The blows were applied with a 4.45 kg hammer dropped repeatedly from a 45.7-cm height onto a 6.35 cm steel ball, which was located at the center of the top surface of the disc. Fig. 1 shows the specimens, the hardened steel ball, and the impact test apparatus.

In each test, the number of blows (N1) necessary to produce the initial visible crack was recorded as the first-crack strength, and the number of blows (N2) needed to cause complete failure of the disk was recorded as the failure strength.

2.1. Materials and mixing procedure

Ordinary Portland cement (ASTM Type 1), produced by the Hekmatan factory, and silica fume, a by-product of the ferrosilicon Semnan factory, were used in this work. The cement and silica fume properties are given in Table 1. Coarse aggregate with a maximum particle size of 19 mm and fine aggregate with a 3.4 fineness modulus were used in this experiment. The specific gravity and water absorption of the coarse and fine aggregates were 2.69 and 0.56%, and 2.61 and 1.92%, respectively. A high range water reducer agent with the commercial name of carboxylic 110 M (BASF) was used to adjust the workability of the concrete mixtures. Hooked-end steel fibers with a length of 60 mm and a diameter of 0.75 mm were employed in this study. The geometry and the properties of the steel fiber are provided in Fig. 2 and Table 2, respectively. The mixing procedure, which was designed by trial and error, was chosen as follows: the binder and fine aggregate were mixed initially for 1 min, and half of the mixing water and superplasticizer were mixed for 2 min. The coarse aggregate and the rest of the water were added and mixed for 5 min. Finally, fiber was added to

Table 1
Properties of cement and silica fume.

Composition (%)	Cement	Silica fume
SiO_2	21.87	85–95
Al_2O_3	5.39	0.5–1.7
Fe_2O_3	3.85	0.4–2
MgO	1.08	0.1–0.9
Na_2O	–	0.15–0.2
K_2O	0.6	0.15–1.02
CaO	62.81	–
C_3S	51.46	–
C_2S	22.00	–
C_3A	6.42	–
C_4AF	10.35	–
Physical properties		
Specific gravity	3.1	2.21
Specific surface (cm^2/gr)	3000	14,000

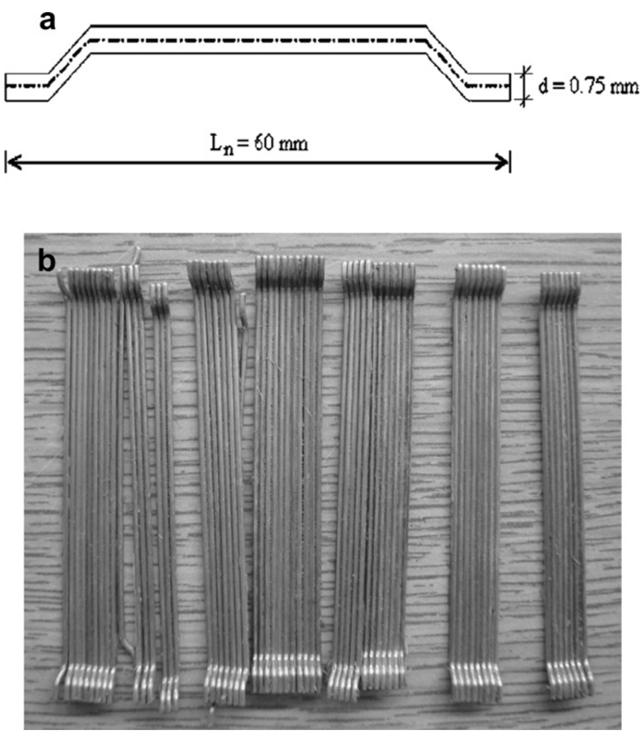

Fig. 2. (a) Shape and dimensions of the steel fibers used in the study, (b) geometry of hooked-end steel fiber.

Table 2
Properties of hooked-end steel fiber.

Length l (mm)	Diameter d (mm)	Aspect ratio l/d	Density (g/cm^3)	Tensile strength (N/mm^2)
60	0.75	80	7.8	1050

the mixtures and mixed for 5 min. Mix proportions are provided in Table 3. The mixing procedure was designed to facilitate dispersion of fibers in the mixtures. The appearance of one mixed batch and a typical flexural section of the fiber-reinforced mixtures, which show the fibers are appropriately dispersed, are shown in Fig. 3(a) and (b), respectively.

2.2. *Specimen molding*

Each type of freshly mixed concrete was cast into cubic (100 mm), cylindrical (100 × 200 mm), prismatic, and cylindrical cutting specimens for compressive, splitting tensile, flexural and impact tests, respectively. Before de-molding all specimens were stored at 23 °C and 100% relative humidity for about 24 h. The concrete specimens were cured in lime-saturated water until testing.

3. Test results and discussion

Compressive, splitting tensile, and flexural strength test results are summarized in Table 4 and graphically illustrated in Figs. 4 through 6.

3.1. *Compressive strength*

The variation in the compressive strength of both water/cement ratio specimens, with and without silica fume, versus fiber volume fractions at 7, 28 and 91 days is shown in Fig. 4. The reference specimens are labeled as W/C = 0.46, and W/C = 0.36, and the silica fume specimens are known as W/C = 0.46-Sf and W/C = 0.36-Sf. The results suggest that, in general, the higher the steel volume fractions in the mixtures, the higher the compressive strength attained. As shown, for 0.46 water–cement ratio specimens, the increase in compressive strength is 14% and 19% at 0.5% and 1% fiber volume fractions, respectively. Addition of silica fume to nonfibrous specimens also improved compressive strength. An increase in compressive strength, up to 23%, can be observed in No. 4 as compared to No. 1. In fibrous specimens, mixes Nos. 5 and 6, with silica fume added to 0.5% and 1% fiber specimens, showed an increase of 27% and 33%, respectively. In series B1, the specimens with a water–cement ratio of 0.36 demonstrated a similar trend in the results. In fibrous concretes without silica fume (Nos. 8 and. 9), an increase of 12% and 14% in compressive strength was attained, respectively, at later material aging. However, in the case of specimens Nos. 11 and 12, when silica fume and steel fibers were added together to the concrete mixtures, an increase of 20% and 25% in compressive strength was observed. Silica fume, as a pozzolan material improves the aggregate-paste bond and leads to an increase in compressive strength of the specimens at later ages. The results also reveal a beneficial advantage in simultaneous use of silica fume and fiber in the mixtures.

Table 3
Mix proportions of the concrete.

Mix No.	Series	W/(C + Sf)	W	Cement	Silica fume	Fine Agg.	Coarse Agg.	V_f	Weight	Sp (%)	Slump (cm)
			(kg/m^3)					(%)	(kg/m^3)		
1	A1	0.46	177	385	–	920	884	–	–	0.60	5.0
2		0.46	177	385	–	914	877	0.5	39	1.00	6.0
3		0.46	177	385	–	907	871	1.0	78	1.20	6.0
4		0.46	177	354.2	30.8	915	878	–	–	0.70	7.0
5		0.46	177	354.2	30.8	908	873	0.5	39	1.10	8.0
6		0.46	177	354.2	30.8	901	866	1.0	78	1.30	10.0
7	B1	0.36	162	450	–	912	877	–	–	1.10	6.5
8		0.36	162	450	–	906	868	0.5	39	1.30	11.0
9		0.36	162	450	–	899	864	1.0	78	1.45	10.0
10		0.36	162	414	36.0	906	870	–	–	1.20	10.0
11		0.36	162	414	36.0	899	864	0.5	39	1.35	10.0
12		0.36	162	414	36.0	893	858	1.0	78	1.40	8.0

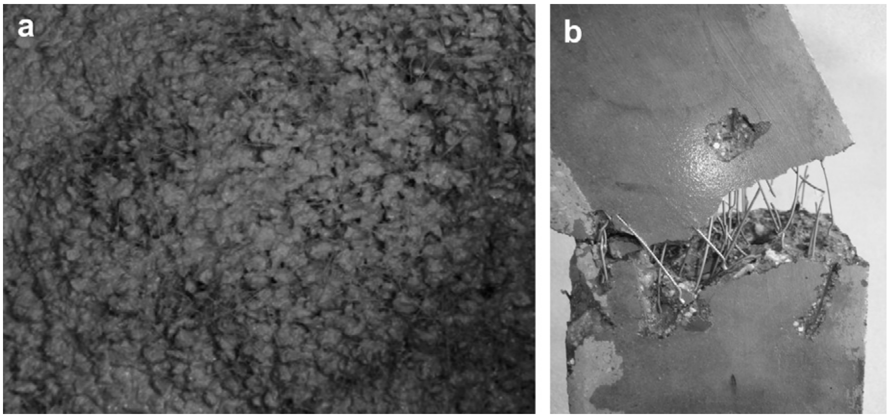

Fig. 3. (a) Appearance of fresh steel fiber-reinforced concrete, (b) dispersion of steel fiber in the hardened flexural section.

Table 4
Mechanical properties of steel fiber-reinforced concrete.

Mix No.	Compressive st. (MPa)			Splitting tensile st. (MPa)			Flexural st. (MPa)
	7 days	28 days	91 days	7 days	28 days	91 days	28 days
1	32.95	41.30	46.65	2.67	3.22	3.89	4.45
2	37.61	46.35	53.19	3.08	3.84	4.39	6.24
3	38.59	47.25	55.46	4.31	5.22	5.39	8.23
4	37.28	49.88	57.44	2.95	3.52	3.97	5.09
5	39.35	53.79	59.50	3.49	4.26	4.71	6.47
6	39.95	55.30	61.77	4.55	5.59	5.87	8.66
7	47.58	55.58	61.01	3.56	4.39	4.74	6.30
8	49.85	58.44	68.27	3.95	4.77	5.67	8.35
9	52.91	60.21	69.33	4.84	5.68	7.08	9.57
10	51.19	63.34	69.48	3.98	4.71	5.52	6.97
11	53.43	66.87	73.00	4.38	5.57	5.87	8.94
12	56.35	69.97	75.93	6.67	7.14	7.86	9.90

3.2. Splitting tensile strength

Fig. 5 shows the splitting tensile strength variation of the concrete mixtures with and without silica fume (W/C = 0.46, W/C = 0.36, W/C = 0.46-Sf, and W/C = 0.36-Sf), versus fiber volume fractions. The results show that splitting tensile strength is increased with increase in the fiber volume fractions. In a typical experiment with series A1, mix No. 3, at 28 days with 1% steel fiber added into the mixtures showed an increase in tensile strength of to 62% as compared with the reference values. Addition of silica fume into nonfibrous specimens had only a slight effect on tensile strength. However, when silica fume is introduced into fibrous specimens, the rate of tensile strength increases. For instance, the tensile strength of 1% fibrous silica fume specimens (mix No. 6) increases up to 70%, 74%, and 51% after 7, 28, and 91 days of aging, respectively as compared to reference values. In the B1 series with a 0.36 water–cement ratio, introduction of 1% steel fiber into the mixtures, with and without silica fume, has a considerable effect on tensile strength improvement. The results indicate that the tensile strength of mix No. 9, increases up to 36%, 29% and 49% after an aging period of 7, 28 and 91 days, respectively. In silica fume fibrous specimens (mix No. 12), the tensile strength reached 87%, 62% and 66% improvement at 7, 28 and 91 days, respectively. These results demonstrate that a high tensile strength concrete can be produced by simultaneous introduction of 1% steel fiber and silica fume into the specimens.

3.3. Flexural strength

Fig. 6 presents the results of flexural strength versus fiber volume fractions testing carried out on twelve different mixtures after 28 days. As expected, a higher flexural strength was obtained as the water–cement ratio was reduced. The introduction of steel fibers into the concrete mixtures led to significant increases in the flexural strength. For instance, the flexural strength increased up to 40–85% and 33–52% for A1 and B1, respectively, when fiber volume fractions were varied from 0.5% to 1%. Although silica

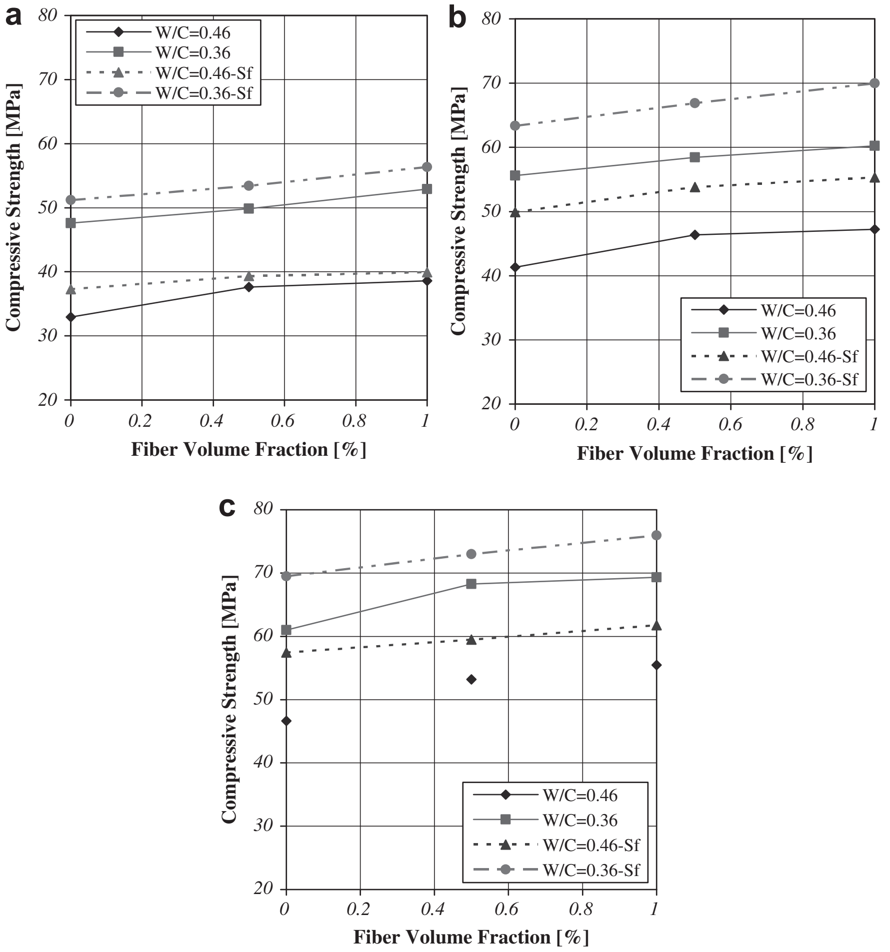

Fig. 4. Compressive strength versus fiber volume fractions at the ages of: (a) 7 days, (b) 28 days, and (c) 91 days.

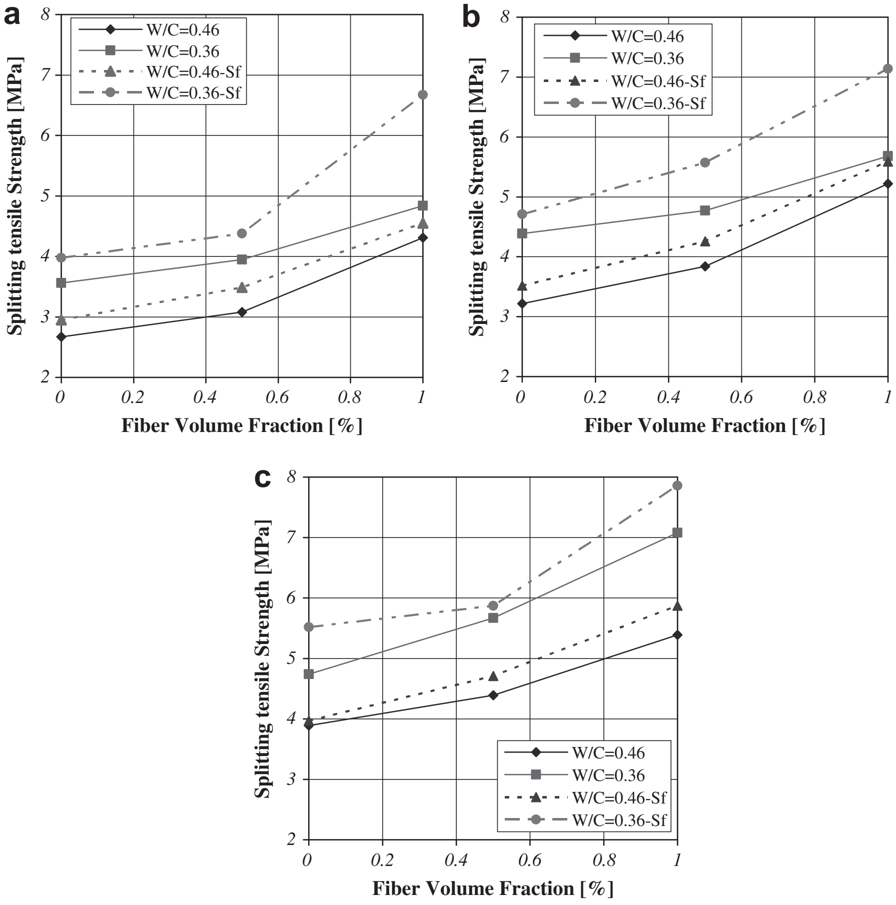

Fig. 5. Splitting tensile strength versus fiber volume fractions at the ages of: (a) 7 days, (b) 28 days, and (c) 91 days.

fume compared with steel fiber has a slight effect on flexural strength, when steel fiber and silica fume are used together, a considerable increase in the flexural strength was observed. It was shown that introduction of steel fiber at 0.5% and 1% volume fractions in the silica fume mixtures led to an increase of 45–95% for A1 and 42–57% for B1 specimens. These results suggest that the combined use of steel fiber and silica fume in concrete produces a significant enhancement in flexural strength for the concrete. This may be attributed to the fact that silica fume enhances the strength of the transition zone in concrete while the steel fibers act as crack arrestors. Therefore, a more significant increase in flexural strength can be obtained when steel fiber and silica fume are used together.

3.4. Impact test

The impact resistance performance of the A1 and B1 of concrete series are given in Table 5 and also shown in Fig. 7. The number of blows resulting in the first visible crack (N1) and the number of blows required for failure (N2) are provided in the results. Table 5

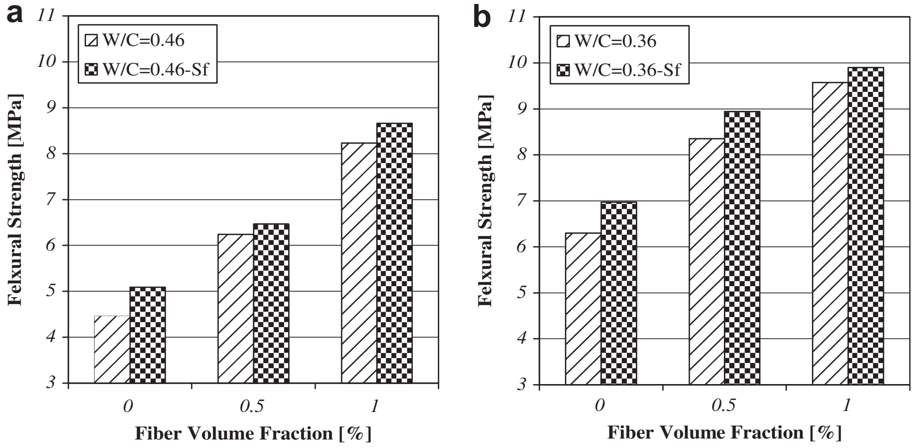

Fig. 6. Flexural strength versus fiber volume fractions at the age of 28 days: (a) W/C = 0.46, (b) W/C = 0.36.

Table 5
Impact test results.

Mix No.	Impact res. (blows)		Impact energy (kN mm)		N2 – N1
	First Crack (N1)	Failure (N2)	First crack	Failure	
1	35	38	712.1	773.1	3
2	270	377	5493.2	7670.1	107
3	344	459	6998.7	9338.4	105
4	243	246	4943.8	5004.9	3
5	398	458	8097.3	9318.0	60
6	825	994	16,784.6	20,222.9	69
7	132	134	2685.5	2726.2	2
8	357	446	7263.2	9073.9	89
9	834	958	16,967.7	19,490.5	124
10	281	284	5716.9	5777.9	3
11	480	599	9765.6	12,186.7	119
12	1289	1456	26,224.7	29,622.3	167

also indicates the calculated impact energy required for the first visible crack and at failure for different specimens in this investigation. The impact energy delivered by the hammer per blow can be calculated as follows:

$$H = \frac{gt^2}{2} \tag{1}$$

$$V = gt \tag{2}$$

$$\text{Impact energy } U = \frac{mV^2}{2} \tag{3}$$

$$m = \frac{W}{g}$$

where U is the impact energy per blows of the hammer, V is the velocity of the hammer at impact, g is acceleration due to gravity, and t is the time required for the hammer to fall a height of 457 mm. H is the height of the fall, m is mass of the hammer, and W is the weight of the hammer.

Substituting the relevant values in Eq. (1) yields:

$$457 = \frac{9810t^2}{2}$$

$t = 0.3052$ s and $V = 9810 \times 0.3052 = 2994.01$ mm/s.

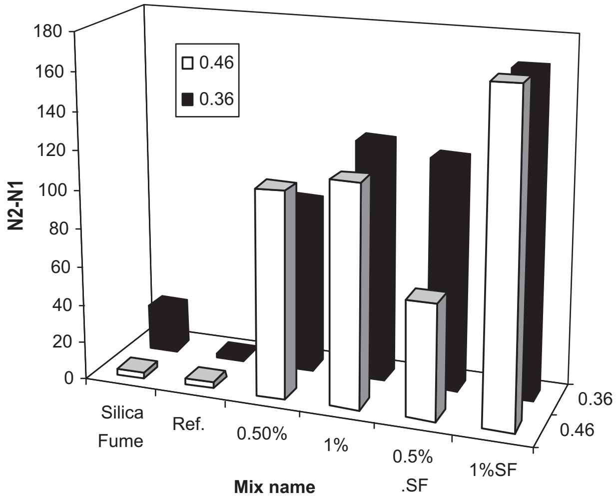

Fig. 8. Variation of (N2 – N1) versus mix type.

The impact energy per blow, U, of the hammer can be obtained by substituting the values in Eq. (3)

$$U = \frac{44.53 \times (2994.01)^2}{2 \times 9810} = 20,345.14 \text{ N mm} \quad \text{or} \quad 20.345 \text{ kN mm}$$

As the results suggest, by incorporating steel fibers into the mixtures, a conclusive increase in the number of blows required for first and final cracking (as compared to reference values) was observed. In contrast, in the case of plain specimens, the increase in post-crack resistance was negligible. In other words, the number of blows required for the first visible crack and final failure are nearly the same, which suggests brittle behavior of nonfibrous concretes. As shown for the A1 series (mix No. 2), which contains 0.5% steel fiber, N1 increases 7.7 times and N2 increases 10 times as compared to values from the No. 1 sample. By increasing the fiber volume fractions to 1% (Mix. No. 3), N1 and N2 increase by 10× and 12×, respectively. When silica fume is introduced to the mixture (No. 4), N1 increases six-fold but no increase in N2 is observed as compared to N1. This result reveals that, although silica fume enhances the impact index of N1, it increases the brittleness of the concrete. However, in silica fume fibrous specimens (Nos. 5 and 6), N1 was increased 10.3 times and 22.6 times, respectively. The values of N2 increased 11× and 25× as

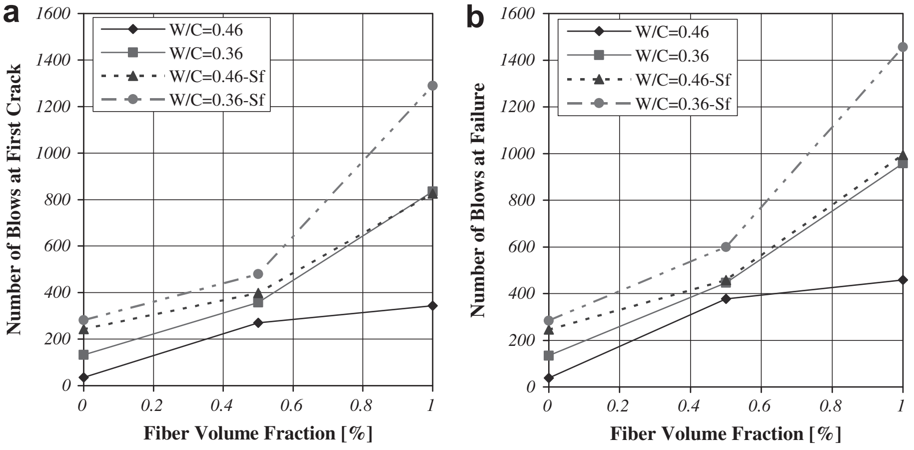

Fig. 7. Impact strength versus percentage of steel fiber volume fractions at: (a) first crack, (b) failure strength.

Fig. 9. Fracture pattern of concrete with different fiber volume fractions under the drop-weight test: (a) plain concrete, (b) 0.5% fiber, and (c) 1% fiber.

compared to the No. 1 specimen, and incorporation of silica fume and steel fiber greatly reduced the brittleness.

As the water–cement ratio was decreased in the B1 mixtures, increased strength and lower ductility of the paste was observed. N1 and N2 were increased as compared to the A1 series. Addition of silica fume led to higher brittleness despite increasing the N1 value. These results are in agreement with the results of other researchers [7,23]. By introducing 0.5% and 1% fiber to the silica fume specimens (Nos. 11 and 12), N1 was increased by 3.6 and 9.7 times, and N2 increased by 4.4 and 10.8 times as compared to the No. 7 specimen. Fig. 8 shows the variations in (N2 − N1) values, or post-peak resistance, for the mixtures. As shown in the figure the highest (N2 − N1) values of 119 and 167 correspond to mixes No. 11 and 12, respectively. These results reveal that simultaneous use of steel fiber and silica fume can exclusively increase post-peak resistance or ductility performance of the concrete.

Fig. 9 shows a comparison of the failure pattern in disk specimens with and without fiber. It can be concluded that, by adding fiber, the failure crack pattern was changed from a single large crack to a group of narrow cracks, which demonstrates the beneficial effects of fiber-reinforced concrete when subjected to impact loading.

4. Conclusions

From the results of the present study the following conclusions can be drawn:

1- Introduction of steel fiber into the mixtures generally increased the compressive strength. The compressive strength of fibrous specimens with 1% fiber at 91 days was increased by 19% and 13.6% in A1 and B1 concretes, respectively.

2- When silica fume was added into the nonfibrous and 1% fiber A1 mixtures, the compressive strength, at 91 days was enhanced by 23% and 32.4%, respectively, while the increase for B1 concretes was 13.9% and 24.5%, respectively.

3- Splitting tensile strength was more greatly affected by steel fiber than silica fume. Splitting tensile strength of the specimens with 1% steel fiber was increased by 62% and 29% for A1 and B1 specimens, respectively. The best performance corresponded to 1% steel fiber silica fume specimens, in which an increase of 74% and 62% were attained for tensile strength of A1 and B1, respectively.

4- As in the tensile strength results, incorporation of 1% steel fiber and silica fume led to the higher flexural strength. Inclusion of 1% steel fiber in the silica fume specimens caused the flexural strength to increase to 1.94 and 1.57 times the reference values in A1 and B1 specimens, respectively.

5- As impact indices, the number of blows at first crack and at failure increased conclusively in fibrous specimens. Addition of 0.5% and 1% steel fibers into the A1 mixtures led to an increase in the number of blows to 7.7× and 10×, respectively, at first crack, and 10× and 12×, respectively, at failure as compared to reference values. In the case of B1 mixtures, inclusion of 0.5% and 1% steel fiber caused the number of blows at first crack to increase by 2.7× and 6.3×, and at failure rose to 3.3× and 7.15×, respectively.

6- Addition of silica fume by itself to the mixtures improved the number of blows at first crack to 6.9× and 2.12× for A1 and B1, respectively, as compared to those of the reference. The number of blows at failure rose to about 6.5× and 2.1× for A1 and B1, respectively. These results reveal that adding silica fume can increase the number of blows required to produce the first crack; however, it also leads to an increase in brittleness.

7- Incorporation of silica fume in fibrous specimens improved the specimens' impact indices (the number of blows at first crack and failure) by considerably more than the addition of silica fume or inclusion of fibers alone.

8- Under impact loading, a ductile failure was observed in fibrous and also silica fume-fibrous specimens. These results show that incorporation of silica fume as a pozzolan material and steel fiber as an arrestor of crack propagation considerably improves the ability of concrete to absorb kinetic energy.

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