CHALLENGE JOURNAL OF STRUCTURAL MECHANICS 5 (1) (2019) 29–34

Challenge Journal of Structural Mechanics

Research Article

Research on effect of the quantity and aspect ratio of steel fibers on compressive and flexural strength of SIFCON

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ABSTRACT

SIFCON (Slurry Infiltrated Fiber Reinforced Concrete) is a composite which occur hardening of the matrix phase, consists of cement, water, mineral additives, fine sand, water reducing plasticizer, and reinforced with high volume fiber (5–20%). The main difference from the high strength concrete (HSC) is the ductile behaviour at failure. However, the brittleness increases with the strength increase in HSC, SIFCON has a ductile behaviour because of the high volume fiber content, low permeability, high durability. Despite fiber content is 2-3% in fiber reinforced concrete, fiber content may be ten times more in SIFCON and ductility is gained. This concrete is suggested to be used in military buildings against explosion, industrial grounds, airports, and bridge feet. In this study, in order to investigate the compressive and flexural strengths of SIFCON, the aspect ratio and fiber volume of steel fibers were chosen as variable and the effects of these parameters on compressive and flexural strengths were investigated. In the study, steel fibers with aspect ratio of 40, 55, 65, and 80 were used in 0, 4, 8 and 12% ratios. The water/binder ratio was kept constant at 0.35. Silica fume is used 10% and water-reducing plasticizer is used 1.5% of cement by weight. 7 and 28 days cured samples were subjected to compressive and flexural tests and the results were compared. As a result of the tests carried out, increases in both the compressive and flexural strengths of SIFCON specimens were determined with increasing fiber volume up to 8%. Strength reductions were observed at higher ratios. In cases where the fiber volume is too high, it has been seen that the strengths were decreased. The reason of strength reduction can be explained by the difficulty of passing ability of mortar between the fibers. The highest strengths were obtained from fibers with the aspect ratio of 80. Increase in the aspect ratio as well as increases in compressive and flexural strengths have been found.

ARTICLE INFO

Article history:
Received 12 December 2018
Revised 4 February 2019
Accepted 11 February 2019

Keywords:
SIFCON
Steel fiber
Aspect ratio
Compressive strength
Flexural strength

1. Introduction

Concrete is an important building material which is obtained by mixing the aggregate (fine and coarse aggregate), water, cement and if necessary, the mineral admixtures according to the desired property and strengthening the initial plastic consistency over time.

Technical features can be developed by adding different materials to the concrete in order to improve and strengthen the weak properties of concrete (Topçu and Boğa, 2005). In order to achieve the desired performance in concrete, special concretes have been developed by producing concrete suitable for different applications. One of the special concrete types is fiber concrete. Fibers; glass, steel, plastic, different types of materials, such as aspect ratio and different sizes are produced. Such fibers are used in concretes by different volumes to improve the properties of the concrete, in particular the energy absorption capacity and flexural strength. For this purpose, mineral, metallic, polymer or natural materials having a certain ratio (size / diameter) of specificity mixed with different methods of fresh concrete are

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ISSN: 2149-8024 / DOI: https://doi.org/10.20528/cjsmec.2019.01.004

called fiber. The American Concrete Institute (ACI) committee is considered the best parameter for defining the fiber-to-fiber volume, which is the ratio of the length of the fiber to the equivalent fiber diameter. Equivalent fiber diameter; is defined as the diameter of a circle equal to the cross-sectional area of the fiber. The tensile stress and geometric structure of the fiber are the other parameters that define the fiber (Ünal et al., 2007).

SIFCON (Slurry Infiltrated Fiber Concrete) is a cement-based, high-engineering, high-density fiber-reinforced mixture of cement, superplasticizer, very fine sand and silica fume. SIFCON's high compressive strength, flexural strength and toughness make this special concrete type superior to traditional concretes. Due to these advantages of SIFCON, it is recommended to be used in building explosion-proof structures, bridge piers exposed to high deformation and/or industrial floors (Alcan and Bingöl, 2019).

The most important feature that distinguishes SIFCON from high strength concrete is that it exhibits ductile behaviour during breakage. The increase in strength is also the most important problem in high strength concrete. SIFCON, with its high durability, low permeability, strength and ductility properties, is a building material with fibers up to 20% by volume. Fiber content of fiber concretes is between 2% and 3%. In parallel with the fiber content used in SIFCON, the order of material ductility is about 10 times higher (Taşdemir and Bayramov, 2007).

SIFCON allows the use of high rates of fiber with the advantage of production technique (Arslan and Aydın, 1999). SIFCON was first produced in 1979 by the Lankard Materials Laboratory in the United States with the aim of creating a highly dense fiber system, by placing high volume of steel fibers into the mold (Lankard, 1984). The fiber matrix of SIFCON contributes significantly to the strength of concrete as similar to fibrous concrete. Since the fibers in normal fibrous concrete are mixed together with the mixing matrix, the mixing of the fibers with the matrix is limited. This limit may be 1% or 2% depending on the fiber type and workability in the mixture. The fiber volume in SIFCON can range from 5% to 30% (Lankard, 1984; Homrich and Naaman, 1987).

Fiber volume to be used in SIFCON depends on the type, length, diameter of the fiber and the vibration applied to ensure the full filling of the mixture matrix. By prolonging the vibration time, shorter fibers can be placed in a denser and higher volume than long fibers (Gilani, 2007). The fibers to be used when preparing SIFCON are randomly stacked in a desired pattern, area or plate etc. at the desired volume. The array can be made by hand to the sample mold, or by large-scale applications with machines capable of fiber distribution. As previously mentioned, the amount of fiber; fiber diameter, in particular the aspect ratio (l/d), fiber geometry and placement technique. In addition, vibration can be applied when placing the fibers. Strong vibration should be applied to achieve high fiber volumes. One of the most important factors in SIFCON manufacturing is fiber orientation. Direction is mainly perpendicular to gravity and is in two dimensions. Direction effect is more effective in some fiber types than others are. Fiber orientation is a phenomenon that should be considered when designing in laboratory or wide field applications. The preparation of SIFCON test samples should be determined based on need, avoiding uneven fiber distributions. The fiber density at the edge of the mold may be much less than inside. In addition, a number of fibers can be aligned vertically (parallel to the axis of the cylinder) along the outer surface (Lankard, 1985).

The aim of this study is to investigate the effects of fiber volume on the mechanical properties of SIFCON. Within the scope of the study, in addition to the steel fiber-free control group, 13 separate groups of SIFCON samples were produced by using 4%, 8% and 12% steel fibers in volume and with 40, 55, 65 and 80 aspect ratio.

2. Material and Methods

In this study, the Portland cement CEM II 42.5 produced by Aşkale Cement Plant was used. The physical, mechanical and chemical analysis results of this cement obtained from the producer factory are given in Tables 1 and 2.

Table 1. Physical and mechanical properties of cement.

Specific Mass (g/mL)		3.13
Litres mass (g/L)		1110
Setting time (hour)		2.10
Final set (hour)		3.15
Volume expansion. (mm)		3
	2 days	23.5
Compressive strength (MPa)	7 days	35.3
	28 days	47.0
	2 days	5.0
Flexural strength (MPa)	7 days	6.2
	28 days	7.7

Table 2. Chemical properties of cement.

Chemical Composition	Ratio (%)
SiO_2	19.94
Al_2O_3	5.28
Fe_2O_3	3.45
CaO	62.62
MgO	2.62
SO_3	2.46
Glow Loss	1.99
Na_2O	0.23
K_2O	0.83
Cl	0.0107
Unacceptable	0.08
Total	100
Free CaO	0.51
Insoluble Residue	0.70
Fe_2O_3	3.45

The MasterGlenium® ACE 450 product, produced by BASF, was used as a plasticizer additive. This product is a super plasticizing additive which increases the strength of the concrete by increasing the water content of the concrete with high amount of water with the same amount of water. 1.5% of the weight of the cement is added to the mixture. It is effective against frost and permeability. It reduces water used in the mixture by more than 20% depending on dosage. Some properties of superplasticizer additive are given in Table 3.

Table 3. Super plasticizing additive properties.

Name	BASF MasterGlenium® ACE 450
Type	Polycarboxylic Ether Based
Colour	Brown, homogeneous and liquid
Density (kg/m^3)	1 089±20
pH Value	About 5-7
Alkali Content	≤ 3.00
Chlorine Ion Content %	≤ 0.10

In this study, Silica Fume obtained from Silica Ferrochrome plant in Antalya Electrometallurgy Plant was used. The chemical composition of Silica Fume is given in Table 4. 10% of the weight of cement was used in the mixtures.

Table 4. Chemical composition of silica fume and sieve analysis.

Chemical Composition		Sieve Analysis	
Material	Amount (%)	mm	Remain (%)
Cr_2O_3		+0.250	0.3 – 1
SiO_2	85–95	+0.125	0.8 – 2.5
Fe_2O_3	0,5–1,0	+0.074	0.5 – 2.5
Al_2O_3	1.0–3.0	+0.044	1.0 – 7.5
MgO	1.0–2.0	+0.038	3.0 – 7.0
CaO	0.8–1.2	-0.038	92 – 80
C	0.5–1.0		
S	0.1–0.3		
Glow Loss	0.5–1.0		

KMX 40/30 BG, KMX 55/30 BG, KMX 65/35 BG and KMX 80/60 BG type, cold drawn steel fibers were used from Kemerli Metal Industry and Trade Joint Stock Company. The technical properties of the steel fiber used are shown in Table 5.

Table 5. Technical properties of the steel fiber.

Fiber Type	KMX 40/30 BG	KMX 55/30 BG	KMX 65/35 BG	KMX 80/60 BG
Length (mm)	30	30	35	60
Diameter (mm)	0.75	0.55	0.55	0.75
Aspect ratio (l/d)	40	55	65	80
Min. Tensile strength (N/mm^2)	1200	1500	1500	1200
Unit Quantity (fiber/kg)	9000	16750	14530	4580

In this study, natural sand is used which obtained from Erzurum Beton A.Ş. Within the scope of the study, in addition to the steel fiber-free control group, 13 separate groups of SIFCON samples were produced by using steel fibers with 40, 55, 65 and 80 aspect ratio in volume of 4%, 8% and 12%. The amount of material entering into the mixture is given in Table 6.

Compressive strengths of concretes are determined on cubic samples with 15 cm dimensions. Both 7 and 28 days strengths are calculated. Because the concrete is a material that shows deformation depending on time, the loading speed is an effective parameter on the compressive strength of the concrete (Baradan et al., 2007). Therefore, all samples were tested under a constant loading rate. For TS EN 12390-3 (2010) this value should be between 0.2 MPa/s and 1.0 MPa/s. The process of breaking the concrete samples was done by selecting the loading speed of 0.4 MPa/s.

Determination of the flexural strength of concrete according to TS EN 12390-5 (2002) and TS 10515 (1992) standards, fiber and fiberless concrete samples were made by simple beam method loaded from the midpoint of the opening in this test method. For the determination of the flexural strength, 70x70x280 mm beam samples were produced. Flexural strength is calculated using the equation given below:

$$F = 3PL/2bd^2 \quad (1)$$

where F is flexural strength (MPa), P is maximum load (N), L is clearance between abutments (mm) b and d are cross-section dimensions of the sample (mm).

The effects of fiber on compressive and flexural strength of the samples were investigated in the samples produced at different fiber volume and aspect ratios.

3. Research Results

3.1. Compressive strength test

The results of the compressive strength of SIFCON samples obtained by using fiber of different volumes and fiber of different aspect ratio with the control group for 7 days and 28 days cure application are presented in Tables 6 and 7.

Table 6. Material quantities for SIFCON (for 1 m^3 concrete).

Group \ Material	Cement (kg)	Aggregate (kg)	Silica Fume (kg)	Water (kg)	Water/Binder	Plasticiser (kg)	Amount of Fiber (kg)
N0 - L0	800	950	80	308	0.35	13.2	0
N40 – L4	800	950	80	308	0.35	13.2	320
N55 – L4	800	950	80	308	0.35	13.2	320
N65 – L4	800	950	80	308	0.35	13.2	320
N80 – L4	800	950	80	308	0.35	13.2	320
N40 – L8	800	950	80	308	0.35	13.2	640
N55 – L8	800	950	80	308	0.35	13.2	640
N65 – L8	800	950	80	308	0.35	13.2	640
N80 – L8	800	950	80	308	0.35	13.2	640
N40 – L12	800	950	80	308	0.35	13.2	960
N55 – L12	800	950	80	308	0.35	13.2	960
N65 – L12	800	950	80	308	0.35	13.2	960
N80 – L12	800	950	80	308	0.35	13.2	960

Table 7. Compressive strength of 7-day samples.

Sample Code	Load (kgf)	Strength (MPa)	Percent Change by Control Sample (%)
N0 - L0 (Control Sample)	111200	48.47	0
N40 – L4	114122	49.74	2.63
N55 – L4	116691	50.86	4.94
N65 – L4	119835	52.23	7.76
N80 – L4	122200	53.26	9.89
N40 – L8	126534	55.15	13.79
N55 – L8	128943	56.20	15.96
N65 – L8	133417	58.15	19.98
N80 – L8	135872	59.22	22.19
N40 – L12	90100	39.27	-18.98
N55 – L12	95331	41.55	-14.27
N65 – L12	96478	42.05	-13.24
N80 – L12	98841	43.08	-11.12

Table 8. Compressive strength of 28-day samples.

Sample Code	Load (kgf)	Strength (MPa)	Percent Change by Control Sample (%)
N0 - L0 (Control Sample)	140415	61.20	0
N40 – L4	154525	67.35	10.05
N55 – L4	160399	69.91	14.23
N65 – L4	171136	74.59	21.88
N80 – L4	174601	76.10	24.35
N40 – L8	164689	71.78	17.29
N55 – L8	168085	73.26	19.71
N65 – L8	175404	76.45	24.92
N80 – L8	183824	80.12	30.92
N40 – L12	124630	54.32	-11.24
N55 – L12	127681	55.65	-9.07
N65 – L12	130366	56.82	-7.16
N80 – L12	134105	58.45	-4.49

3.2. Flexural strength test

The results of the 3-point flexural strength for 7-days and 28 days cure applied SIFCON samples are presented in Tables 9 and 10.

4. Conclusions

The most important outcomes of this study are listed below.

- The maximum compressive strength of 7 days cure was obtained in the N80- L8 sample group with 80 aspect ratio and 8% fiber content with 59.22 MPa. According to the control sample, an increase of 22% in compressive strength was observed.
- The maximum compressive strength of 28 days cured specimen was 80.12 MPa which is obtained from the N80-L8 group. According to the control sample, an increase in compressive strength of approximately 30% was observed.
- According to the results obtained from the experiments, it was determined that there was an increase in the compressive strength values as the aspect ratio increased.
- Increasing the fiber volume showed an increase in compressive strengths up to 8% fiber content for each aspect ratio. Over the 8% fiber volume, it became more difficult to place the matrix between the fibers, resulting in a reduction in the compressive strength.
- In the 7-day samples, the maximum flexural strength was obtained in the N80- L8 sample group with 80 aspect ratio and 8% fiber content with the value of 33.92 MPa. Flexural strength was increased by about 13 times compared to the control sample.

Table 9. Flexural strength of 7-day samples.

Sample Code	Load (kgf)	Strength (MPa)	Percent Change by Control Sample (%)
N0 - L0 (Control Sample)	284	2.44	0.00
N40 – L4	1670	14.32	487.86
N55 – L4	2163	18.55	661.51
N65 – L4	2217	19.02	680.99
N80 – L4	2482	21.29	773.94
N40 – L8	2698	23.14	849.94
N55 – L8	3125	26.80	1000.35
N65 – L8	3530	30.28	1142.96
N80 – L8	3955	33.92	1292.61
N40 – L12	2645	22.69	831.47
N55 – L12	2607	22.36	817.92
N65 – L12	3252	27.89	1045.07
N80 – L12	3580	30.71	1160.56

Table 10. Flexural strength of 28-day samples.

Sample Code	Load (kgf)	Strength (MPa)	Percent Change by Control Sample (%)
N0 - L0 (Control Sample)	402	3.45	0
N40 – L4	1888	16.19	369.53
N55 – L4	2333	20.01	480.22
N65 – L4	2656	22.78	560.66
N80 – L4	2966	25.44	637.81
N40 – L8	3380	28.99	740.80
N55 – L8	3500	30.02	770.77
N65 – L8	3669	31.47	812.56
N80 – L8	4180	35.85	939.68
N40 – L12	2824	24.22	602.43
N55 – L12	2957	25.36	635.49
N65 – L12	3422	29.35	751.21
N80 – L12	3784	32.46	841.40

- The maximum flexural strength of 28 days samples was obtained in the N80- L8 sample group with the value of 35.85 MPa. 9-fold increase in flexural strength was observed compared to the control sample. This results are similar with literaute (Farnam et al., 2010). They indicated that SIFCON's fracture energy can achieve 300-fold of fracture energy of traditional concrete while its tensile strength can achieve 7–15-fold of tensile strength of traditional concrete. These mechanical features indicate that SIFCON is a concrete with superior qualities.
- According to the results obtained from the experiments, it was found that the increase in the aspect ratio increases the flexural strength values as well as the compressive strength. However, these increases were more pronounced.
- With increasing fiber volume, increase on flexural strengths up to 8% fiber volume have been observed for each aspect ratio. After the fiber volume of 8%, it is difficult to settle between the fibers.
- As a conclusion of the experimental results, it is seen that increase on the flexural strength was more meaningful according to compressive strength for SIFCON.
- When the test results of samples with a fiber volume of 12% were examined, the aggregate used could not be infiltrated by the dense fiber network of the matrix due to the maximum diameter of 1 mm. As a result, compressive strengths decreased compared to other fiber volumes, but the flexural strengths showed decreases compared to only 8% fiber content. So it was determined that 1 mm aggregate diameter was not suitable for high fiber content.

As a conclusion of this study; the results showed that fiber addition improves the properties of concrete and high volume fiber concrete SIFCON has superior mechanical properties. Similarly, Shah and Ribakov (2011), indicated that; addition of fibers to high-strength concrete improves its mechanical properties and makes the material very attractive for applications in construction.

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