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RESEARCH PAPER

Examining SIFCON's Mechanical Behaviors According to Different Fiber and Matrix Phase

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Abstract

Slurry infiltrated fiber concrete (SIFCON) is a cement-based composite material produced from various fibers. SIFCON contains fiber at a ratio of 5–30% by volume. Thanks to the high fiber ratio of it, SIFCON shows high performance with respect to mechanical features like compressive strength, flexural strength, tensile strength and toughness. This new generation special concrete is recommended to be used in explosion-proof military buildings, industrial floors and bridge piers, especially due to its features of high toughness and flexural strength. SIFCON consists of three different phases: slurry phase, fiber phase and interface. In the present study, 10% of steel and woolen polypropylene fiber by volume to observe effect of the change of fiber phase on SIFCON's mechanical properties. Furthermore, silica fume, equal to 5, 10 and 15% of cement by weight, and fly ash, which is equal to 20, 40 and 60% of cement by weight, were added to examine how mineral additives, which were added into the slurry phase, influence SIFCON's mechanical features. According to the results of compressive, flexural and toughness tests performed, steel fiber SIFCON specimens were observed to have better mechanical properties than woolen polypropylene fiber samples. On the other hand, the results showed that 15% silica fume added samples and 20% fly ash added samples gave better results.

Keywords SIFCON · Steel fiber · Woolen polypropylene fiber · Silica fume · Fly ash

1 Introduction

It is known that the post-peak decrease is sharp in the stress–strain curve created under the load to which the concrete is exposed. This indicates that the concrete is brittle (Lankard and Newell 1984). It was proposed that fibers of steel, glass, woolen polypropylene, basalt be added to solve the problem of brittleness, which emerged in the course of time. Thus, fiber concretes were formed. Fibers at ratios of 1–3% by volume were added to produce fiber-reinforced concretes. This fibrous content of concrete improves features of concrete, especially flexural, ductility and energy absorption capacities. The reason why mechanical features improve in fiber concretes is the fact that the fiber content compensates the stresses that it encounters and transfers them to the tough portions of the matrix. The fiber content behaves like a bridge inside the concrete, and thus, it retards crack formation, prevents the crack from spreading and prevents crack propagation (Shah and Ribakov 2011).

This type of concrete sometimes cannot satisfy what is expected because fiber content does not exceed 3% by volume. It was seen that the increase in reinforcement amount caused problems in workability and settlement in fiber concretes. SIFCON technology was developed to eliminate these negative effects and to increase reinforcement ratio.

SIFCON includes 5–30% fiber. This is equal to tenfold of that taking place in fiber-reinforced concretes. Due to such high fiber content, SIFCON's manufacturing type and ingredients are different from those of other concrete types (Schneider 1992). In fiber-reinforced concrete technology, fibers are added to concrete while fibers are placed into molds before slurry is added onto fibers in SIFCON. Fibers to be used are placed horizontally or vertically depending on direction of the force to be applied. Quite fine materials are used to produce a slurry phase, which can embrace the fibers properly and fill the mold completely, due to the mentioned fiber intensity (Homrich and Naaman 1987). Slurry

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preparation includes cement, mineral additives (fly ash, silica fume, blast furnace slag), powder as aggregate (silica sand, quartz sand, basalt) and chemical additives for fluidity. Although there is no specification or standard relating to SIFCON production, according to the studies that have been conducted until now, the highest material size is 600 micron so that the produced slurry infiltrated between the fibers to ensure adherence (Yazıcı et al. 2006).

Due to small size of the materials that are used in SIFCON, gaps are filled to maximum level so that the resulting concrete contains gap at minimum level. Furthermore, due to the rich fiber content, high-performance concretes are produced with respect to flexural and toughness strengths. SIFCON is recommended to be used in shelters or military structures that should be protected from explosion and fire due to such advantages of it. Furthermore, it can be used in other structures like reinforced concrete beams, strengthening structures, industrial floors and bridges (Schneider et al. 1988). 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 (Farnam et al. 2010).

Features of matrix phase and fibers have an effect on SIFCON's mechanical behavior. The aim of this study is to examine the effect of different fiber types and mineral additives on the mechanical properties of SIFCON. For this reason, different mortar phases and different fiber types are used. Specific value of this study is that effect of different fiber types and mineral additives on SIFCON's mechanical features were examined to test the effect of both slurry phase and fibers. Two types of fiber were used in the experiments: steel and woolen polypropylene fiber. Furthermore, silica fume and fly ash, which are among the useable mineral additives in SIFCON slurry, were added to the mixture at different ratios.

2 Experimental Study

2.1 Materials in the Use

Cement Portland cement satisfying the standards of TS EN 197-1:2012 (EN 2012) was used for the experiments. This material was supplied by Aşkale Cement Plant, and its class is CEM I 42.5 R. This cement type's chemical, physical and mechanical features provided by the manufacturer are given in Tables 1 and 2.

Silica fume Silica fume is a material containing minimum 93% of silicon dioxide (SiO_2) with a maximum particle size of 0.5 µm. It is formed by reduction in quartz to silicon or during silicon manufacturing in electrical arc furnaces. The whole silica fume material used in the experiments was supplied by Dost Kimya, and physical and chemical features of the material provided by the manufacturer are given in Tables 1 and 2.

Table 1 Chemical features of CEM I 42.5 R type cement, silica fume and fly ash

Component (%)	Cement	Silica fume	Fly ash
CaO	63.65	0.50	20.47
SiO_2	18.10	96	47.15
Al_2O_3	4.48	0.70	20.42
Fe_2O_3	3.09	0.25	4.15
MgO	2.50	0.60	1.51
Na_2O	0.21	0.25	0.59
K_2O	0.62	0.85	1.36
SO_3	2.84	0.50	2.08
Ignition loss	3.90	1.50	0.97
Free CaO	0.44	–	–

Table 2 Physical and mechanical features of CEM I 42.5 R type cement, silica fume and fly ash

Physical features		Cement's compressive strength (MPa)
Cement		3-day
Specific area (cm^2/g)	3690	27.90
Specific weight	3.12	
Silica fume		7-day
Specific area (cm^2/g)	210,400	44.80
Specific weight	2.20	
Fly ash		28-day
Specific area (cm^2/g)	2986	58.00
Specific weight	2.20	

Fly ash Fly ash is a material produced by collecting wastes from coal burned in coal mines on electro-filters. This material's color is dark gray, and its grain size is very small (Aruntaş 2006). Fly ash material used in the experiments was supplied by Ares Çimento from Orhaneli Thermal Power Plant, and its class is F according to ASTM (2003). Density of the material is 2.2 g/cm^3, while its maximum grain size is 100 µm. Physical and chemical features of the material provided by Ares Cement Plant are given in Tables 1 and 2.

Quartz sand Quartz sand is produced by grinding quartz stone, which is one of the most abundant minerals on earth to the required size. Quartz is a material having high purity containing 99% of silica. Quartz sand was preferred in this study because it is used in high-performance concretes frequently as aggregate due to its higher compressive strength, compared to compressive strength of aggregates used in

Table 3 Steel fiber's physical features

Length (mm)	Diameter (mm)	Aspect ratio (L/day)	Tensile strength (MPa)
35	0.70	50	1100

traditional concretes, up to 180 MPa, its higher hardness degree and its higher abrasive strength. Quartz sand used in the experiments is the material having largest grain size in SIFCON manufacturing. Its grain size is 100–400 µm, and its density is 2.65 g/cm^3.

Fiber Two types of fibers were used in the experiments: steel and woolen polypropylene fiber. Fibers were supplied by Atlas1 Company. Features of steel fiber and woolen polypropylene fiber are given in Tables 3 and 4, respectively.

Chemical additive Daracem 200, which is a hyper fluidizer, was used to obtain the required workability during the experiments. This additive was produced from poly naphthalene sulfates.

Water Atatürk University potable well water was used in the experiments.

2.2 Production and the conducted Experiments

Sizes of the cubic molds used in this study are 15 cm × 15 cm × 15 cm, while sizes of the prism molds used in this study are 7 cm × 7 cm × 28. Samples produced by using cubic molds were used in calculation of compressive strength and toughness, while those produced by using prism molds were used in calculation of flexural strength. It was calculated that 2.65 kg of steel fiber was required for cubic SIFCON samples, while the samples produced in prism molds required 1.07 kg of steel fiber. For the SIFCON samples containing woolen polypropylene fiber, 303.75 g of woolen polypropylene fiber was used in cubic samples, while 123.48 of woolen polypropylene fiber was used in prism samples to ensure 10% of fiber content by volume.

During production of steel and woolen polypropylene fiber SIFCON samples, molding process consisted of three stages to ensure a homogeneous fiber distribution in every point of the mold. This three-stage molding process was chosen because it had yielded the best result in the previously produced test samples. At the first stage, one-third of the mold was filled with slurry and one-third of the fiber was added to it. Then, the mold was shaken by hand to ensure that the slurry was infiltrated between the fibers properly. Then, the abovementioned stage was repeated twice for the remaining parts of one-third until the molds were full. This process was repeated for each fiber type and for each mold (Fig. 1). Because the SIFCON slurry was fluid, no surface correction process was required after molding. The prepared SIFCON samples were left 1 day for strengthening. Then, they were extracted from the molds and left for curing for 28 days (Fig. 2).

Table 4 Physical and chemical features of woolen polypropylene fibers

Length (mm)	Cross section	Diameter (µm)	Density (g/cm^3)	Tensile strength (MPa)	Elasticity Module (MPa)	Melting point (°C)	Fire point (°C)
19	Circular	18–20	0.91	450–700	3000–3500	162	593

Fig. 1 SIFCON molding

Fig. 2 Samples in the curing pool

Fig. 3 Flexural test apparatus and loading status

For the experiments, seven groups were formed. First of them was CNTRL, which was the slurry not containing fiber and mineral additives (no silica fume and fly ash). The groups containing silica fume 5, 10 and 15% of cement instead of cement were titled as SF5, SF10 and SF15, respectively. Maximum silica fume ratio allowing addition to concrete is 15% by mass, and when the ratio is exceeded, it affects the concrete (Demir 2009). According to the studies relating to fly ash content of concretes, the optimum value is 30% by mass in traditional concretes, while it can be added to special concretes up to 60% by mass (Bouzoubaa and Lachemi 2001). The samples containing fly ash at the ratios of 20, 40 and 60% of cement amount instead of cement were labeled as FA20, FA40 and FA60. Table 5 shows concrete slurry's mixture ratios.

Flexural strength test was conducted according to TS EN 12390-5 (BSI 2009) on SIFCON samples to find their flexural strength. Working principle of the conducted test is the same with that of the flexural strength calculation for traditional concretes. Load was applied to one point on the prism samples as seen in Fig. 3. Attention was paid to make loading precisely in the middle of the beams to obtain accurate results. Loading rate was adjusted as 5 kg f/cm^2 (50 N/cm^2).

Compressive strength test was conducted according to TS EN 12390-3 (EN 2003). Cubic samples were placed in the test apparatus and exposed to loading at a rate of 0.5 MPa/s. The same apparatus was used in determination of toughness. LVDTs were placed at both sides of the cubic sample (Fig. 4) to measure deformation versus to a certain strain from the beginning of loading until fracture, and the obtained data were used in drawing the $\sigma-\varepsilon$ curve. The area below this curve was calculated to find toughness in N.m. (ASTM 2002).

3 Results and Discussion

Tables 6, 7 and 8 show compressive strength, flexural strength and toughness values, respectively, based on the findings from the conducted tests.

According to the tables, it is seen that fiber content has positive effect on concrete's compressive strength, flexural strength and toughness. The reason is that the fiber content compensates the stresses that it encounters and transfers them to the tough portions of the matrix. The fiber content behaves like a bridge inside the concrete, and thus, it retards crack formation, prevents the crack from spreading and prevents crack propagation. This bridging behavior of the fibers is seen in Fig. 5 symbolically. Favorable increase in the test results is higher in steel fiber SIFCON samples because steel fibers' tensile strength is higher than that of woolen polypropylene fibers. Woolen polypropylene fibers also compensate this stress, but after a while, they rupture

Table 5 Concrete slurry's mixture ratios (for 1 m^3 of concrete)

	CNTRL	SF5	SF10	SF15	FA20	FA40	FA60
Cement (kg/m^3)	800	760	720	680	640	480	320
Water (kg/m^3)	320	320	320	320	320	320	320
Silica fume (kg/m^3)	0	40	80	120	0	0	0
Fly ash (kg/m^3)	0	0	0	0	160	320	480
Quartz sand(kg/m^3)	1083	1072	1056	1043	1029	972	915
Additive (kg/m^3)	16	16	16	16	16	16	16
Water/binder	0.40	0.40	0.40	0.40	0.40	0.40	0.40

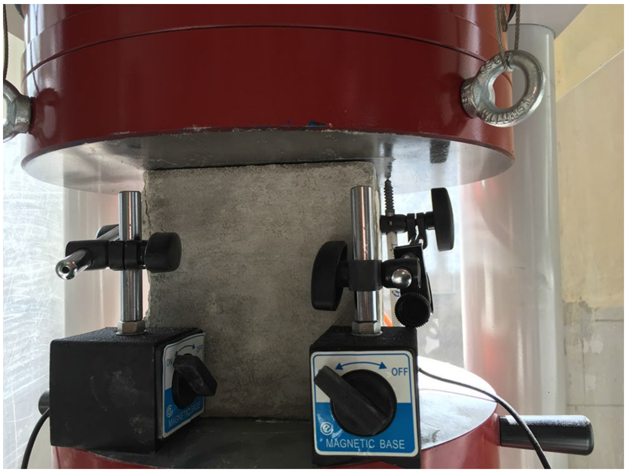

Fig. 4 LVDTs placed at both sides of the cubic sample

Table 6 Compressive strength (MPa) results

	Without fiber	Steel fiber	Woolen polypropylene fiber
CNTRL	57.19	128.50	62.00
SF5	61.00	131.73	65.67
SF10	63.57	135.46	68.18
SF15	65.24	139.20	73.81
FA20	64.65	137.17	71.39
FA40	52.72	125.33	52.14
FA60	43.38	118.00	*

*No data were obtained from woolen polypropylene fiber FA60 samples

Table 7 Flexural strength (MPa) results

	Without fiber	Steel fiber	Woolen polypropylene fiber
CNTRL	2.68	30.86	10.38
SF5	2.90	31.16	11.44
SF10	3.11	35.61	13.57
SF15	3.49	38.64	15.95
FA20	3.24	36.23	14.62
FA40	2.46	28.00	8.20
FA60	2.17	22.17	*

*No data were obtained from woolen polypropylene fiber FA60 samples

in the stress area and fracture occurs in these samples. In case of steel fibers, fracture occurs when fibers get free from slurry. Furthermore, it is believed that better adherence of steel fibers to slurry compared to woolen polypropylene fibers may have a role in this result.

Table 8 Toughness (N.m.) results

	Without fiber	Steel fiber	Woolen polypropylene fiber
CNTRL	1057.10	10,467.40	5312.40
SF5	975.43	10,760.85	6044.42
SF10	886.79	11,671.26	6953.48
SF15	847.55	13,002.98	7549.20
FA20	724.60	12,588.35	7237.63
FA40	417.93	10,280.46	4485.50
FA60	195.18	9675.73	*

*No data were obtained from woolen polypropylene fiber FA60 samples

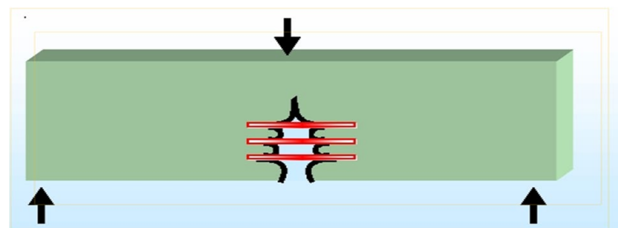

Fig. 5 Fiber's bridging feature

Considering mineral additives' effect on the results, it was seen that better results were obtained in the samples containing silica fume at a ratio of 15% by mass and fly ash at a ratio of 20% by mass. It is believed that the reason is the fact that the fine material bonds with free CH to increase CSH amount in the internal structure and furthermore, it reduces gaps in the concrete. However, in the cases in which 40% by mass of fly ash is used, the values measured in the without fiber, steel or woolen polypropylene fiber SIFCON samples, are lower than those of samples without mineral additive, with fly ash of 20% and silica fume. In case of the samples containing fly ash of 60%, test results decreased significantly, and in SIFCON samples with woolen polypropylene fiber, no result could be obtained at this fly ash ratio. The reason may be the fact that because too much mineral additive was used in preparation of slurry, pozzolanic effect was not seen in early age. In the woolen polypropylene fiber samples containing fly ash of 60%, it is assumed that these samples cannot be strengthened because very large surface area of woolen polypropylene fibers cannot be embraced by the fine material, which is too much in amount. It is believed that woolen polypropylene fibers in the FA60 group samples act as a gap inside the concrete.

The area below the stress–strain curve ($\sigma - \varepsilon$) taken from the test apparatus was calculated to fine toughness value. Because the LVDTs used in the tests can read deformation up to 10 mm, deformation value in the graphics is restricted by 10 mm in SIFCON samples. It is estimated that if the LVDTs used in the tests had higher reading capacity, magnitude of deformation would exceed 10 mm in the SIFCON samples. Figures 6a, b and 7a, b show stress–strain graphics of CNTRL with no additive and fiber, the sample with silica fume of 15% without fiber, steel fiber SIFCON with silica fume of 15% and woolen polypropylene fiber SIFCON with silica fume of 15%, respectively. Concrete is a brittle material. Thus, it fractures suddenly, and its deformation capacity is low. Fiber content of concrete decreases its brittleness, while it increases its ductility. According to the SIFCON samples stress–strain curves, their deformation capacity is very high versus the strain to which they are exposed. Another indicator suggesting that toughness increased as a result of the conducted tests is the fact that the concrete samples were crushed rather than ruptured or fractured when they lost their carrying capacity (Fig. 8).

It is assumed that the mineral additives have positive effect on the SIFCON results because they influence the concrete's internal structure and increase compactness. However, it is seen that toughness decreases a bit when mineral additives are used in the without fiber samples. The reason may be that mineral additives reduce gaps in concrete while they increase brittleness and this ends in sudden fracture.

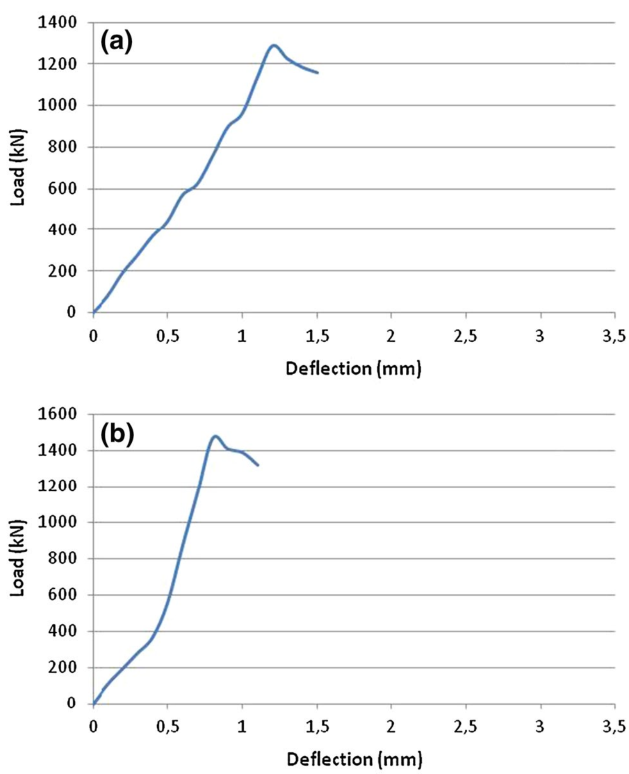

Fig. 6 **a** CNTRL without fiber and additive, **b** without fiber with silica fume of 15%

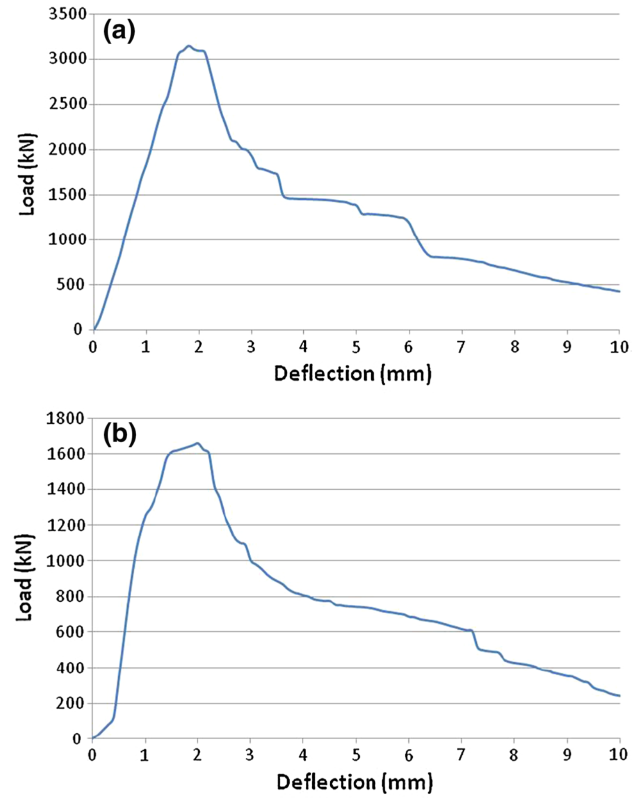

Fig. 7 **a** Steel fiber SIFCON with silica fume of 15%, **b** woolen polypropylene fiber SIFCON with silica fume of 15%

Fig. 8 Crushing cubic and prism samples

4 Conclusions

Compressive strength, flexural strength and toughness tests were conducted to compare mechanical features of 10% steel fiber and 10% woolen polypropylene fiber SIFCON samples with without fiber concretes. Furthermore, effect of the used mineral additives on mechanical behavior of slurry and SIFCON was examined, and the following results were obtained.

According to the compressive strength test results, steel fibers increased strength approximately 2–2.5-fold, while woolen polypropylene fibers increased the same approximately 1.1-fold. Silica fume content of 15% and fly ash content of 20% increased compressive strength 1.1-fold.

According to the flexural strength test results, steel fibers increased flexural strength approximately 11.5-fold (1051%), while woolen polypropylene fibers increased the same approximately fourfold (287%). Silica fume content of 15% and fly ash content of 20% increased flexural 1.3-fold.

According to the toughness test results, steel fibers increased toughness approximately tenfold (890%), while woolen polypropylene fibers increased the same approximately fivefold (400%). In case of silica fume content of 15% and fly ash content of 20%, toughness decreased 0.25-fold in without fiber samples, while it increased 1.25-fold in SIFCON.

The results obtained in the study are similar to the results of studies related to this subject, like Shah and Ribakov (2011), Schneider (1992) and Homrich and Naaman (1987). The common idea is that, mechanical properties such as compressive strength, flexural strength and toughness of steel fiber SIFCON specimens are superior to woolen polypropylene fiber SIFCON specimens. Also, few studies exist about the effect of mineral additives on SIFCON. In this study, it is tried to determine the optimum percentage of fly ash and silica fume.

Considering the results obtained from the present study and the data produced in previous experiments, 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.

Furthermore, it is believed that the samples containing woolen polypropylene fiber that we used in this study lose less strength when they are exposed to extreme temperatures compared to those containing steel fiber. In addition, woolen polypropylene fibers are more advantageous compared to steel fibers with respect to reinforcement corrosion and segregation in concrete. This prediction may be examined in studies to be conducted in the future.

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