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Autoclaved SIFCON with high volume Class C fly ash binder phase

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Abstract

The effect of incorporating high volume of Class C fly ash (FA) on mechanical properties of autoclaved SIFCON (slurry infiltrated fiber concrete) has been investigated in this study. Cement was replaced with up to 60% FA in SIFCON compositions and three different steel fiber volumes (2%, 6% and 10%) were used. Test results were presented in comparison with the control mix (0% FA and 0% fiber). Mechanical properties were positively affected almost at every FA replacement. Moreover, by increasing the fiber volume, flexural strength and toughness were remarkably increased. This behavior was more pronounced at 10% fiber volume. At this fiber volume ratio, flexural strength of 55 MPa could be achieved with 60% FA replacement.
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1. Introduction

In spite of their relatively high cost, high performance fiber reinforced cement-based composites are used more widely all over the world especially in seismic retrofit design and in the structures under explosive and impact effects. High or ultra-high strength concrete with very high compressive strength values remains basically a brittle material. The inclusion of adequate fibers improves tensile strength and provides ductility [1,2]. The fiber volume fraction of conventional fiber reinforced concrete and ultra-high performance fiber reinforced concrete is generally limited to 1–3% [3]. On the other hand, some special composites are produced with fiber volume fraction values between 5% and 30%. These composites can be classified as SIFCON (slurry infiltrated fiber concrete) and SIMCON (slurry infiltrated mat concrete), which have high ductility and tensile strength properties. The dry mixing of the composition is not possible due to interlocking effect of the high volume of steel fibers. In order to overcome this problem, the fibers can be pre-placed in the forms. Also, the homogeneity of the material can be provided by full placement of fibers up to the top level. It is difficult to obtain uniformly distributed fibers due to the manual sprinkling process [4]. However, the alignment of fibers can be controlled by using special sieves. After that, a fine and cement-rich slurry is poured or pumped into the forms. The main difference between SIFCON and SIMCON is the fiber type. The use of short fibers is the general practice in SIFCON, while a mat with long fibers is the main reinforcement in SIMCON. Thus, fiber alignment can be easily controlled in SIMCON and similar performance can be achieved with lower fiber volumes compared to SIFCON applications [5,6].

A cement-rich flowable mortar is the binder in SIFCON production. The usage of very high amounts of cement not only affects the production costs, but also has negative effects on the heat of hydration and may cause shrinkage problems. Replacing cement with mineral admixtures seems to be a feasible solution to these problems. Furthermore, incorporation of mineral admixtures may positively affect the durability of SIFCON or SIMCON products.

SIFCON or SIMCON composites have superior mechanical properties such as compressive, tensile, shear and flexural strengths with extraordinary toughness values. Compressive strains over 10% without severe strength degradation have been reported in SIFCON specimens. Superior toughness property indicates the potential of using SIFCON in seismic resistant structures [6,7].

There are four main factors to consider when evaluating a SIFCON product. These factors are: mortar strength, fiber volume, fiber alignment and fiber type. The modulus of elasticity,

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tensile strength and compressive strength of the hardened slurry affect the behavior of the SIFCON product [8,9].

The fiber volume depends on the fiber type and the vibration effort needed for proper compaction. Smaller or shorter fibers may pack denser than longer fibers and higher fiber volumes can only be achieved with careful and sufficient vibration [9].

Fiber alignment greatly affects the behavior of a SIFCON product. Fibers can be aligned normal, parallel to the loading direction or can be placed randomly. The ultimate strength, residual strength, ductility and energy absorption properties are all affected by the fiber alignment [10,11].

Autoclave curing is extensively used in the manufacture of lightweight cellular concrete to obtain high early strength and high durability properties. This method also reduces creep, drying shrinkage and moisture movement values. The 28-day strength on normal curing can be achieved in about 24 h with autoclave curing [12]. Furthermore, previous studies showed that the incorporation of fine silica is essential in order to achieve high mechanical properties. Without fine silica, the rapid formation of different hydration products under autoclave curing results in a porous and weak microstructure that leads to lower compressive strength values [13,14].

There are some investigations on the properties of SIFCON. The strength and ductility of SIMCON and SIFCON tension members were investigated to construct a mechanical model for simulating tensile force–displacement relationships by Murakami and Zeng [4]. Use of SIFCON in the hinge regions of earthquake resistant structures was studied by Wood [5]. Stress–strain properties of SIFCON in compression and elastic modulus of SIFCON in tension and compression were studied by Homrich and Naaman [6] and by Naaman et al. [7], respectively. Naaman and Homrich [8] also investigated the tensile stress–strain properties of SIFCON. Performance of SIFCON in the joints of seismic resistant frames was studied by Naaman et al. [10]. The surface crack pattern of concrete with high content of steel fiber was investigated by Yan et al. [15]. Doğan [16] has tried to retrofit of non-ductile reinforced concrete frames by using SIFCON. Furthermore, there are considerable amount of studies about compositions, mechanical and durability characteristics of ultra-high performance concrete and reinforced concrete [17–26].

A statistical approach to optimize the self-compacting silica fume or limestone powder incorporating SIFCON slurry in terms of workability, rheology, penetrability, bleeding and compressive strength was studied by Sonebi et al. [27,28]. It was found that limestone powder had a positive effect on the fluidity and penetrability of the cement slurry to flow through the fiber mass. However, silica fume had a negative effect on the same properties of the slurry. On the other hand, compressive strength of hardened slurries has been decreased by the incorporation of these mineral admixtures. However, the effect of matrix phase composition on the mechanical performance of SIFCON has not been investigated widely, especially under autoclave curing.

Furthermore, a large number of projects abroad have been implemented with “high volume fly ash concrete” using ASTM Class F fly ash and fiber reinforced concrete [29–32]. However, significant amount of fly ashes produced in Turkey are classified as Class C. In this study, the effect of Class C fly ash and fiber volume on the mechanical properties of autoclaved SIFCON has been investigated.

2. Experimental

The physical, chemical and strength characteristics of Portland cement (CEM I 42.5 N) used in this study are presented in Table 1. A crushed basalt sand, quartz sand and quartz powder were used as fine aggregates with maximum sizes of 1 mm, 1 mm and 100 μm, respectively. The specific gravities of basalt sand, quartz sand and quartz powder were 2.75, 2.62 and 2.63, respectively. Gradings of aggregates are given in Table 2. A superplasticizer (SP) of polycarboxylate type meeting standard specifications ASTM C 494 Type F and TS EN 934-2 was used. The chemical composition and other properties of mineral admixtures, fly ash (FA) and silica fume (SF) are also presented in Table 1. Class C fly ash has been procured from Soma Power Plant, Turkey. Silica fume is a product of YKS-SKW-MBT Construction Chemicals. Further-

Table 1
Physical, chemical and mechanical properties of cement, fly ash and silica fume

Chemical composition (%)				Physical properties of cement	
	Cement	Fly ash (FA)	Silica fume (SF)	Specific gravity	3.13
SiO_2	18.69	42.1	92.26	Initial setting time (min)	130
Al_2O_3	5.00	19.4	0.89	Final setting time (min)	210
Fe_2O_3	3.49	4.6	1.97	Volume expansion (mm)	1.00
CaO	63.12	27.0	0.49	Specific surface	
MgO	1.09	1.8	0.96	Cement (m^2/kg) Blaine	380
Na_2O	0.29	–	0.42	FA (m^2/kg) Blaine	290
K_2O	0.76	1.1	1.31	SF (m^2/kg) Nitrogen Ab.	20000
SO_3	2.95	2.4	0.33	Compressive strength of cement (MPa)	
Cl^-	0.010	–	0.09	2 days	29.9
Loss on ignition	3.56	1.3	–	7 days	43.2
Insoluble residue	0.38	–	–	28 days	51.9
Free CaO (%)	1.27	4.3	–	Pozzolanic activity index (%), ASTM C 311	
				FA (28 days)	88
				SF (28 days)	115

Table 2
Grading of basalt sand, quartz sand and quartz powder

Sieve size (mm)	% Passing		
	Quartz sand	Basalt sand	Quartz powder
1	100.0	100.0	100.0
0.5	62.0	68.8	100.0
0.25	37.2	46.0	100.0
0.125	15.2	25.2	100.0
0.063	8.8	16.4	53.0

more, Beksa, Dramix-Bekaert hooked steel fibers were used. Fiber sizes were 30 mm long with the diameter of 0.55 mm. The aspect ratio and tensile strength of this fiber are 55 and 1100 MPa, respectively.

Prismatic specimens with 305 mm length, 60 mm width and 25 mm height were used to determine the flexural strength and toughness of concrete. Load vs. mid-span deflection relationship was determined until the peak load decreased the 10% of its original value. To obtain the mid-span deflection values, two different dial gages were used in the three points loading flexural test. One dial gage, which was located mid-span of the specimen, had direct connection to the testing machine, which could send data to the computer. The other one was located on the upper head of the testing machine. The mid-span deflections over 10 mm were measured by dial gage that is connected upper head of the testing machine. Cube specimens (71 mm) were used to determine the compressive strength. The mechanical properties of each mixture were determined from the average of three specimens.

For each composition, ingredients were mixed in a Hobart mixer. Mini-slump flow of the SIFCON binder was kept constant at about 330 mm. SP was used at a constant ratio of 35 L/m^3 for all mixtures. FA0 slurry consists of one part of binder to one part of aggregate (basalt sand, quartz sand and quartz powder) by mass. Mixture proportions are presented in Table 3.

Cement was replaced by FA at three different ratios, 20%, 40% and 60%. To investigate the effect of fiber volume on mechanical properties, three different fiber volumes were used, 2%, 6% and 10%. Fiber volume was calculated according to the volume of the mold for each specimen. At the first stage, fibers were pre-placed into the molds and then slurry was poured. Specimens with 10% fiber content needed vibration in order to achieve proper compaction.

The specimens were kept in the molds for 12 h at room temperature of 20 ± 2 °C. After demolding, the specimens were autoclaved at 210 °C and under 2.0 MPa pressure for 6 h. After completion of their autoclave period, the specimens were kept in laboratory atmosphere at 20 ± 2 °C for 24 h, and then flexural and compressive tests were applied at the age of 2 days, after their preparation.

3. Results and discussion

Load–deflection relationship of FA0 mixtures with different fiber contents are presented in Fig. 1. It can be seen from the figure that increasing fiber volume changes the behavior of the mixtures dramatically. The behavior of specimens, which have 0% fiber and 2% fiber, is much more different than the mixes that contain 6% and 10% fiber. It is clear that, when the fiber volume increases, the flexural strength increases and the slope of the descending branch of the curve decreases after the peak load. Furthermore, the toughness of the specimens increases impressively with the incorporation of fibers. For example, the deflection of SIFCON sample with 10% fiber was 3.32 mm at peak load and this value reached to 4.10 mm without decreasing the load. However, the maximum deflection of control mix, which is also used in all these series as slurry, is only 0.33 mm. It should be mentioned that specimens incorporating fibers developed multiple cracking at low and intermediate levels of stress. Many small cracks progressed up to the maximum load level. After the peak stress, the failure of SIFCON specimens proceeded along with a single crack opening.

Fig. 2 shows the load–deflection relationship of specimens with FA60 slurry. In this case, difference between using 6% and 10% fiber is clear in terms of flexural strength and toughness. FA20, FA40 and FA60 mixtures exhibit similar behavior. FA replacement generally had a positive effect on the mechanical performance of SIFCON especially at 10% fiber volume compared to the control mixture of FA0 matrix. Previous studies indicated that autoclave curing is most effective when finely ground silica is added to cement owing to the chemical reactions between silica and lime released on the hydration of cement. The higher value of fineness of the silica is a necessity. It should be at least equal to that of cement. A higher fineness, 600 kg/m^2, was found to lead to an increase in strength of 7% to 17% compared with silica having a fineness of 200 kg/m^2 [12]. Due to these findings, in this study, to obtain high mechanical properties under autoclave curing, silica fume which is one of the finest form of silica were used as well as fine quartz. Hydration products of $CaO-SiO_2-H_2O$ system with a CaO/SiO_2 ratio of around two form mainly C_2SH, which has three polymorphs A, B and C depending on the temperatures. All forms of C_2SH have very low strength compared with the CSH with a low CaO/SiO_2 ratio such as CSH(B), tobermorite, xonotlite, etc. formed under hydrothermal conditions. However, the addition of a proper amount of

Table 3
Slurry proportions

Component	FA0	FA20	FA40	FA60
Fly ash (%)	0	20	40	60
Cement (kg/m^3)	800	640	480	320
Fly ash (kg/m^3)	0	160	320	480
Silica fume (kg/m^3)	120	120	120	120
Water (kg/m^3)	313	313	314	322
Basalt (kg/m^3)	600	562	524	486
0–1 mm quartz (kg/m^3)	160	150	140	130
0–100 μm quartz (kg/m^3)	160	150	140	130
Superplasticizer (L/m^3)	35	35	35	35
Water/cement	0.39	0.49	0.65	1.01
Water/binder	0.34	0.34	0.34	0.35
Aggregate/binder	1.0	0.94	0.87	0.81
Mini-slump (mm)	330	330	330	330

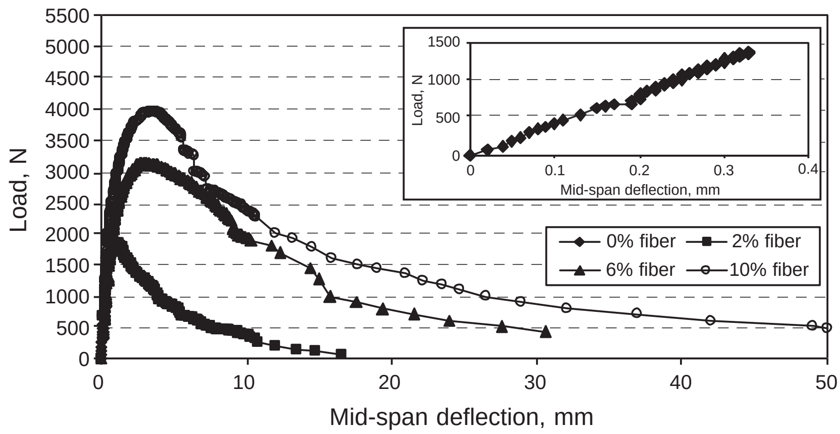

Fig. 1. Load–deflection relationship related to the fiber volume for the FA0 slurry.

silica into system can change the hydration products and increases the strength remarkably. Furthermore, the use of lime obviously increases the amount of available reaction products in the system [14]. Shi and Hu [14] investigated the cementitious properties of ladle slag fines under autoclave curing condition. The results indicated that the small amount of Portland cement or hydrated lime into ladge slag fine-silica flour system can increase strength significantly. However, the use of Class F fly ash instead of silica flour resulted in a very low strength. The authors explained this negative finding with Al content of FA and using amorphous ingredients results in a lower reaction degree and a lower crystallized degree of reaction products compared with the use of crystalline ingredients. Thus, in this study, Class C fly ash that has high lime content used with silica fume and quartz fine and generally mechanical properties was improved by FA replacement under autoclave curing due to the hydration reactions between extra lime released from fly ash and silica. Furthermore, Aldea et al. [13] investigated the effects of curing conditions on the properties of concrete using a slag replacement without incorporation of silica and concluded that normal curing provided higher compressive strength values then autoclave curing. This study also indicates that when the mineral admixtures such as fly ash and/or slag are used under autoclave curing, fine silica must also be added into the system to initiate and progress the above mentioned reactions and to obtain high mechanical performance.

The effect of FA content and fiber volume on flexural strength of all mixtures is presented in Fig. 3. The results show that flexural strength increases sharply with increasing fiber volume at all FA contents. For instance, flexural strength of FA0 slurry is only 14.4 MPa, while this value reaches up to 41.1 MPa at 10% fiber content. Furthermore, generally, FA replacement with cement positively affected the flexural strength. It can be seen from Fig. 3 that increasing FA content in the slurry caused increases in the flexural strength noticeably at 10% fiber volume. Note that the flexural strength of FA60 slurry is about 55 MPa, which is considerably higher than FA0 slurry at 10% fiber volume. This behavior may be attributed to the stronger interface zone between binder and fibers, which improves the bond strength and reduces the progress of microcracks that leads to flexural failure. On the other hand, it is reported that autoclave curing may reduce bond strength between plain reinforcement and matrix [12]. Furthermore, Huang [33] stated that with the addition of SP pores at the interface of PP fiber and the cement–fly ash matrix can be reduced; hence, the fiber-matrix bond was greatly improved. This finding is in accordance with the results of this research.

The relationship between fiber volume and toughness for all mixtures is shown in Fig. 4. It is clear that, with high volume

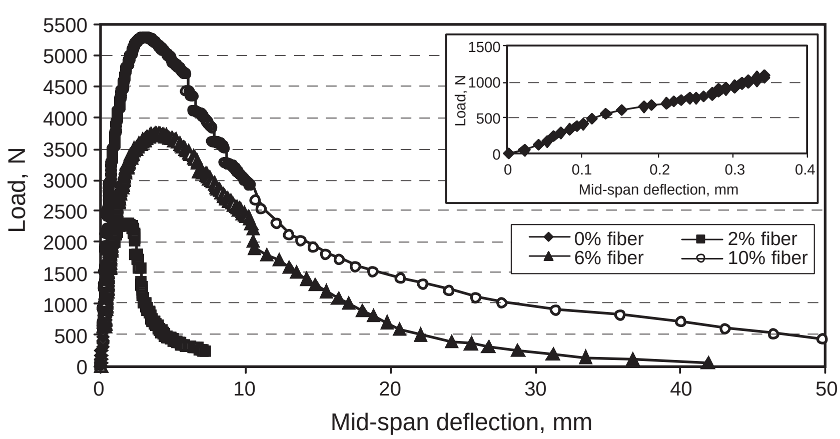

Fig. 2. Load–deflection relationship related to the fiber volume for the FA60 slurry.

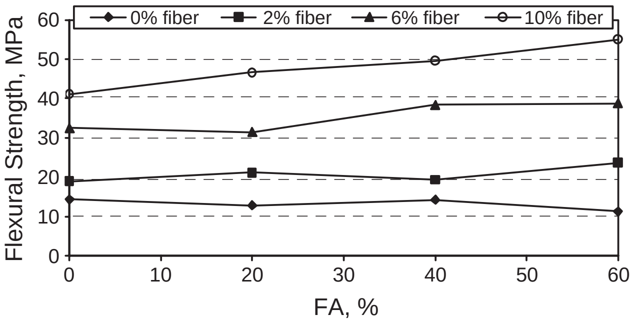

Fig. 3. The effect of FA content and fiber volume on flexural strength.

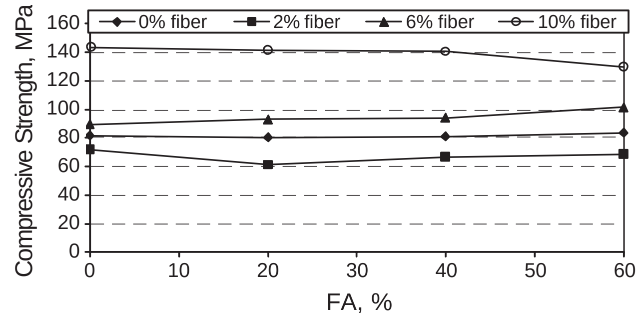

Fig. 5. The effect of FA content and fiber volume on compressive strength.

fiber incorporation, toughness of composites increases impressively. For instance, the toughness of FA60 slurry is about only 189 N mm, while this value has reached to 86 kN mm with 10% fiber incorporation. This calculation is based on the integration of the area under the load–deflection curve, which represents the toughness of the specimen. To obtain the behavior of mixtures containing no fiber more accurately, a closed-loop servo control testing machine is a necessity. However, it must be kept in mind that toughness defined here is related to the area under the load–deflection curve, which was used only to compare the differences between various specimens. The positive effect of FA on toughness can be attributed to improvement in flexural strength and bond strength between fibers and matrix phase. It is clear that fiber volume is the major factor for the improvement in toughness. For instance, toughness of specimens containing 10% fiber is 455 times greater than the toughness of FA60 slurry itself. FA replacement generally increased the toughness values except in some series incorporating small amounts (2%) of steel fiber.

Fig. 5 shows the influence of fly ash content and fiber volume on compressive strength of SIFCON. It is obvious that fiber volume is much more important parameter than FA content in autoclaved SIFCON. With the increasing amount of FA content, compressive strength is not affected significantly even at as high as 60% FA replacement level, which means the mixture has only 320 kg/m^3 cement content. However, fiber content and alignment have also greatly affected the compressive strength of SIFCON, which is quite different from fiber reinforced concrete. It can be seen from the figure that using 6% and 10% fiber can improve the compressive strength as much as flexural strength. This behavior is more pronounced at 10% fiber volume. Compressive strength of hardened slurry is about

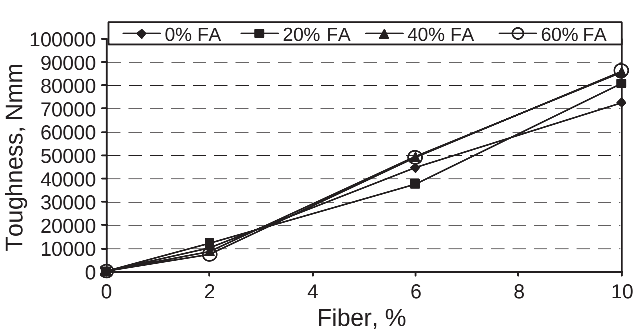

Fig. 4. The effect of FA content and fiber volume on toughness.

between 80 and 84 MPa according to the FA content, while SIFCON containing 10% fiber revealed between 130 and 143 MPa strength values according to the FA replacement. But, compressive strength was negatively affected by 2% fiber incorporation. When the fiber content is not sufficient for completely filling the molds, there may be a lack of fibers at the top layers of the specimens, which affects the compressive strength negatively. Note that, during the compressive strength test, load was applied parallel to the filling direction, which means almost all fibers are perpendicular to the applied load.

In the previous study conducted by the authors [34], mechanical properties of the same mixtures were investigated under normal curing conditions (in water, at 20 °C). Test results indicated that the 28-day flexural strength values of 10% fiber reinforced composites varied between 31 and 34 MPa for various FA contents under normal curing. For this fiber reinforcement ratio, compressive strength values showed a decreasing trend from approximately 76 MPa to 52 MPa when the FA replacement level exceeded 20%. However, under autoclave curing, for 10% fiber content, flexural strength values showed an increasing trend from 40 to 55 MPa, while compressive strengths were between 143 and 130 MPa depending on FA replacement levels. It can be said that autoclave curing improved the mechanical properties (compressive and flexural strengths) remarkably. For instance, at 60% FA replacement level, the flexural strength values can be raised 66%, while compressive strength can be improved almost 150% by autoclave curing. Moreover, the negative effect of high volume FA on the compressive strength of SIFCON diminished by autoclave curing. These findings can be explained by the superior inter-reactions of the ingredients (FA, SF and cement). It is clear that autoclave provides perfect conditions for complete and accelerated hydration media for hydration process especially with combined mineral admixtures. In other words, the mechanical properties of SIFCON depend on the development and quality of matrix as well as fiber content.

4. Conclusions

Test results indicate that Class C fly ash replacement has a positive effect on all mechanical properties of SIFCON in contrast to plain concrete. This behavior is more pronounced at 10% fiber incorporation. In that case, values such as flexural strength of 55 MPa and compressive strength of 130 MPa were achieved even with a 60% of cement replacement, which means this slurry has only 320 kg/m^3 cement content. Furthermore, the ratio between flexural and compressive strength for this mixture is 42.3%, which is considerably higher than conventional concrete. For instance, this ratio is only 12.7% for FA60 slurry without fiber incorporation.

With the increasing amounts of steel fibers, the flexural strength and toughness were improved for all mixtures. For instance, the flexural strength of FA60 slurry is 11.3 MPa. This value reached up to 55 MPa with a 10% fiber incorporation, which means a flexural strength increase of 387%. In fact, the effect of fibers on the toughness is more impressive. Improvement in the toughness of FA60 slurry with 10% fiber incorporation is 455 times compared to the FA60 slurry.

From the point of view of compressive strength, using a low fiber volume (2%) decreased the strength compared to the slurry strength itself. This is probably due to the non-uniform distribution of fibers between upper and lower layers of the specimens. On the other hand, the compressive strength of hardened slurry containing no fibers has improved greatly by 10% fiber content. For instance, compressive strength of FA40 slurry has increased 73% by 10% fiber incorporation. Using 6% fiber content has also positively affected the compressive strength but not at the same extent with 10% fiber incorporation. Class C FA replacement generally has a positive effect on compressive strength even with a 60% of cement replacement. In this case, a compressive strength value of 130 MPa has been achieved.

Compared to the previous study [34], the mechanical performance of SIFCON with 10% fiber content under normal curing at 28 days can be achieved with a 6% steel fiber content under autoclave curing at 2 days for the same mixtures.

It can be concluded that high volume Class C fly ash mixtures are suitable for autoclave production of high strength SIFCON. Fiber volume is the most important parameter that affects the behavior of the SIFCON. Furthermore, the mechanical performance can be improved remarkably by autoclave curing compared to normal curing. The mechanical properties achieved in this research indicate that SIFCON compositions incorporating high volumes of FA and steel fibers may be an ideal material for the construction of seismic resistant structures and under impact and explosion effects.

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