Usak University Journal of Material Sciences

journal homepage: http://uujms.usak.edu.tr

Research article

The effect of metakaolin and end type of steel fiber on fiber-SIFCON matrix bond characteristics

Çağlar Yalçınkaya, Ahsanollah Beglarigale, Halit Yazıcı*

Department of Civil Engineering, Engineering Faculty, Dokuz Eylül University, Turkey

Received 27 December 2013 *Revised 24 February 2014* *Accepted 24 June 2014*

Abstract

SIFCON (Slurry Infiltrated Fiber Concrete) can be described as a special type of cement based composite produced with fiber volume fraction values between 5 to 30%. As a result of superior mechanical properties such as compressive, tensile, shear and flexural strengths with extraordinary toughness values, SIFCON can be used in in industrial floors, repair and reinforcement works and military applications such as anti-missile hangers. Mechanical properties of fiber reinforced cement based composites are dramatically influenced by steel fiber–matrix bond characteristics. Many parameters such as fiber type and geometry, matrix strength, curing conditions and properties of fiber-matrix interface affect the fiber-matrix bond characteristics. The density of this zone can be increased with supplementary cementitious materials such as metakaolin. In this study the effect of metakaolin and end type of steel fiber on bond characteristics has been investigated. The fiber-matrix bond characteristics were determined by applying single-fiber pull-out test. Utilization of metakaolin has improved the compressive strength and fiber-matrix bond characteristics. In addition, hooked-end fiber has a better performance compared to the smooth fiber.

Keywords: *SIFCON, cement based composite, steel fiber-matrix bond characteristics*

1. Introduction

Slurry infiltrated fiber concrete (SIFCON) is a special type of high performance composite materials which includes 5-30% steel fiber volume by placing the steel fibers into a formwork and then infiltrating fine aggregate and cement rich flowable slurry to coat the fibers. SIFCON has superior mechanical properties such as compressive, tensile, shear and especially flexural strengths with extraordinary toughness values. Superior toughness property indicates the potential of using SIFCON in industrial floors, strengthening works, explosion resistant military structures, and seismic resistant structures.

As mentioned above the binder of SIFCON is cement rich flowable slurry. Replacing cement with mineral admixtures decreases the production costs, heat of hydration and

*Corresponding author: Tel: +90 – 232 – 3017042
E-mail: caglar.yalcinkaya@deu.edu.tr
DOI: 10.12748/uujms.201416504

shrinkage problems. There are important factors affect the SIFCON properties. These factors are; mortar properties, fiber volume and type, and fiber alignment [1,2].

Mechanical properties of steel fiber reinforced concrete are dramatically influenced by steel fiber–matrix bond characteristics (Fig. 1). The bond between fiber-matrix provides the stress transferring between the fiber–matrix phases. The fiber-matrix interface characteristic (fiber-matrix transition zone) is the most important factor which affects the bond strength. It is well known that the transition zone in the mature composite is quite porous and also filled with CH in direct contact with the fiber surface [3]. These characteristics are similar to the aggregate-matrix interfacial transition zone [4]. The density of this zone can be increased by supplementary cementitious materials [5-10].

Fig. 1 The interface of steel fiber and cement based matrix

Generally, it can be summarized from many researches that the pull-out behavior depends on both matrix and fiber characteristics. The mechanical properties of matrix, curing conditions, incorporation of mineral additives, and durability problems can affect the fiber-matrix bond characteristics [10-13]. Furthermore, the effect of steel fiber morphology, type and embedment length and fiber type on fiber-matrix bond characteristics has been investigated by many researchers [10-12,14-16].

The fiber-matrix interface density can be increased by incorporating supplementary cementitious materials such as silica fume, ground granulated blast-furnace slag, and metakaolin.

Metakaolin is mineral additive obtained by the calcination of kaolinitic clay at a temperature between 600°C and 900°C and is being used recently in high performance cement based composites. At ambient temperature, the reaction between metakaolin and $Ca(OH)_2$ produces CSH gel [17-19]. Generally, 99.9% of metakaolin particles are smaller than 16 μm with a mean particle size of about 3 μm [17-20]. Utilization of metakaolin in cement based composites have many advantages such as increased compressive and flexural strengths, reduced permeability, and increased resistance to chemical attack [17].

2. Experimental Program

CEM I 42.5 R type cement was used for this research. The properties of Portland cement and metakaolin used in this study are presented in Table 1. A polycarboxylic ether based superplasticizer (SP) was used to reach the target workability. Two different sizes (0-0.125 mm and 0-1 mm) of limestone aggregate were used. The steel fiber used in this study was produced as a hooked-end fiber. For evaluating the effect of end condition of fiber, a series of smooth fibers were used (Table 2).

Table 1
Properties of cement and metakaolin

Chemical composition (%)	Cement	Metakaolin	Physical properties	
CaO	64.25	0.1	**Cement**	
SiO_2	18.52	52-54	Specific surface (cm^2/g)	3860
Al_2O_3	4.70	42-44	Specific gravity	3.15
Fe_2O_3	3.24	<1.0-1.4	**Metakaolin**	
MgO	0.93	<0.1	Specific surface (cm^2/g)	130000
Na_2O	0.35	<0.05	Specific gravity	2.589
K_2O	0.80	<0.4	Pozzolanic activity index	141.4
SO_3	3.03	<0.1		
Loss on Ignition	3.17	-		
Free CaO	1.90	-		

In this study the cement was replaced by 0 wt% (M0), 15 wt% (M15), and 30 wt% (M30) metakaolin. A Hobart mixer was used to prepare fresh mixtures. All dry particles were mixed for 1 min. Then, water-SP solution was added to dry mixture. The mortar was mixed for 5-7 min at high rotation speed. After mixing, mini V-funnel (for flow time) and slump flow tests were immediately applied (Table 3). Utilization of metakaolin increased the need for SP and viscosity of SIFCON mortar. This behavior became stronger with an increase in replacement ratio.

Table 2
Steel fibers' properties

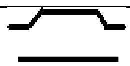
Geometry	Length (mm)	Diameter (mm)	Aspect ratio	Tensile strength (N/mm^2)
 Hooked-end Smooth	50	1.05	48	1000

Table 3
Mix designs and fresh state properties of the mixture

Component	M0	M15	M30
Cement (kg/m^3)	843	717	590
Metakaolin (kg/m^3)	0	127	253
Water (kg/m^3)	285	285	285
0-1 mm Limestone (kg/m^3)	685	661	638
0-125 μm Limestone (kg/m^3)	343	330	319
Superplasticizer (l/m^3)	35	40	50
Water/cement	0.34	0.40	0.48
Water/binder	0.34	0.34	0.34
Flow (mm)	360	360	360
V-box time (s)	6	10	15

After workability tests, fresh SCMs were cast into 50×50×50 mm^3 cubic moulds without any vibration or compaction. A single steel fiber was centrally embedded into the fresh mixture by an apparatus which allowed the fiber becomes perpendicular to the surface of the specimen and adjusts the desired embedment length (half of the steel fiber length) into the matrix (Fig. 2). The casting molds were put in steam curing cabin after 6 hrs, the temperature of the cabin was reached to 100°C and, the specimens were kept in this condition for 12 hrs.

Fig. 2 Preparation of specimens

The schematic diagram of pull-out test setup used in this study is presented in Fig. 3. Capacity of the load-cell was 6 kN. The pull-out test specimen was fixed to the frame on the bottom platen while the free end of the fiber was held by the fiber mounting plate. The matrix remained rigid while the fiber mounting plate moved upward with a rate of 1 mm/min under closed loop control test procedure as shown in Fig. 3. During the slip of fiber from the matrix, corresponding load values were recorded by the load-cell that was connected to a computer. Some important parameters such as peak pull-out load, displacement at the peak load and debonding toughness (slip energy) were find out by analyzing the pull-out load versus end displacement curves plotted using the data from the test. Each data presented here are the average test results of three and six specimens for compressive strength and pull-out test, respectively. On the other hand, pull-out load-displacement curves were drawn using average of the six pull-out test data.

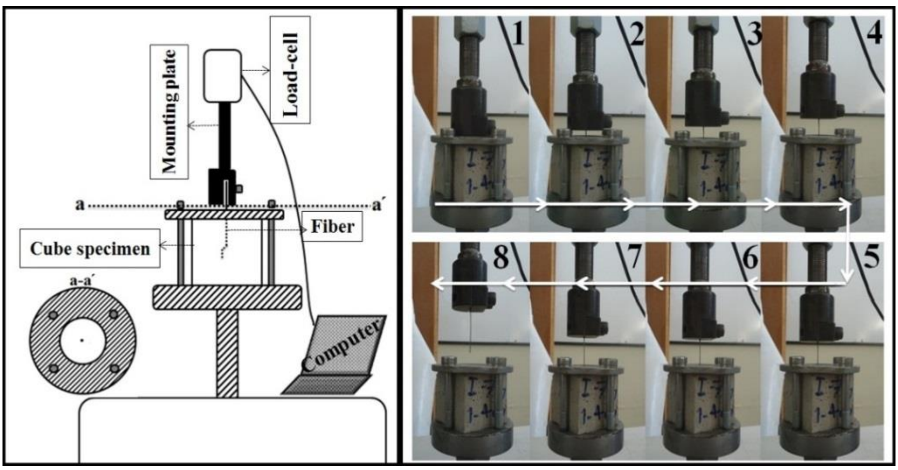


Fig. 3 Pull-out test setup and procedure

3. Results and Discussions

The compressive strength values of SIFCON mortars are presented in Fig. 4. As can be seen from Fig. 4, substitution of metakaolin instead of 15% of cement increased remarkably the compressive strength of the mortar. Increasing of this ratio to 30% did not increase the compressive strength any further. In other words the optimum dosage of metakaolin in terms of compressive strength is 15%. Similar results have been reported in the literature [21,22]. The filling effect of metakaolin particles, pozzolanic reaction with $Ca(OH)_2$, and reduction in cement dosage are three main factors affects the compressive strength [23]. The filling effect and pozzolanic reaction leads to increase in compressive strength, while decreasing in cement dosage has a negative effect [21-24]. The optimum dosage of metakaolin was recommended to be 10-20% by some researchers [21-27].

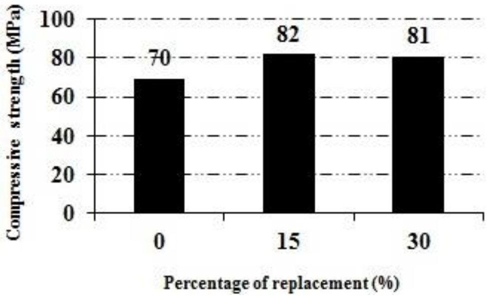


Fig. 4 Compressive strength values of SIFCON mortars

It can be seen from curves that the combination of two different mechanisms constitutes the pull-out behavior of hooked-end fibers (Fig. 5): debonding of the surround interface and frictional slip of the fiber. Firstly, the embedment length of fibers is fully debonded (from outer surface to the interior of specimen), then the fiber pull-out occurs under frictional resistance. High pull-out peak load illustrates the good bond between matrix and steel fiber. It can be stated that fiber elongate until the peak load without the initiation of a considerable debonding. Second peak point in the descending part of hooked-end fiber is related to the mechanical interlock of hooked end [10,13,16]. As can be seen from curves, the pull-out behavior of smooth fiber is different from the hooked-end one. The fiber pull-out of smooth fiber occurs under frictional resistance. Mostly, a sudden load drop was being observed after the peak load in descending part of the graph.

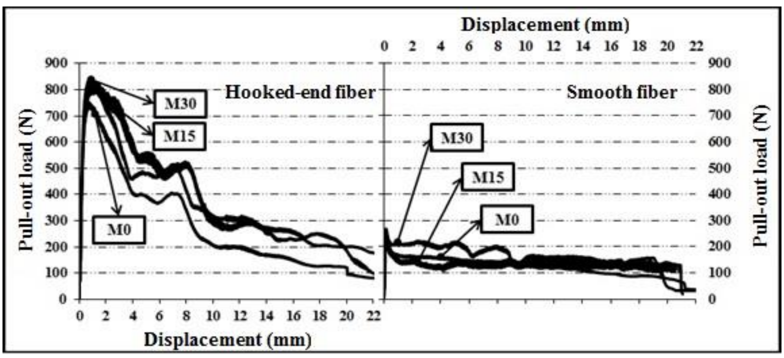


Fig. 5 Pull-out load and displacement relationships

Fig. 6 shows the average of maximum pull-out peak load values of hooked end and smooth steel fiber embedded in the matrix of SIFCON composite. Incorporating of metakaolin increased the maximum pull-out peak load of hooked-end fibers. In accordance with the compressive strength results, 15% is the optimum substitution ratio in terms of pull-out behavior. The pull-out peak load of the hooked-end steel fiber in M15 and M30 are 12% and 10% higher than M0 one (Fig. 7). These increases are not valid in the case of the smooth fibers. It is well known that the fiber-matrix bond strength increases by an improving in mechanical properties of cement based composites matrix [9-16]. On the other hand, pozzolanic reaction between the metakaolin and $Ca(OH)_2$ which exists in the fiber-matrix transition zone (Fig. 8) is another positive impact on the fiber-matrix bond characteristics. This reaction leads to increase the bond strength. Fig. 9 shows the fiber-matrix interface of M15 after pull-out test. As can be seen from Fig. 9 micro scratches were formed in the fiber-matrix interface as the result of fiber friction.

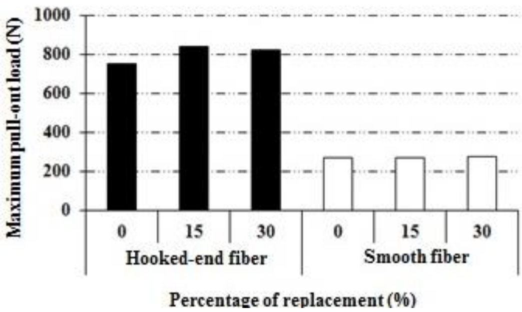


Fig. 6 The average values of maximum pull-out load

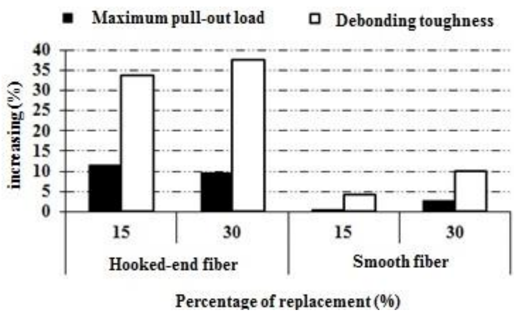


Fig. 7 Increasing in bond parameters provided by incorporating of metakaolin

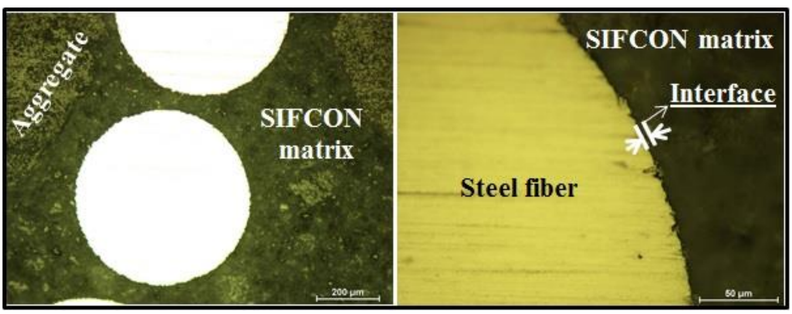


Fig. 8 Optical microscope image of a SIFCON composite phases (polished section)

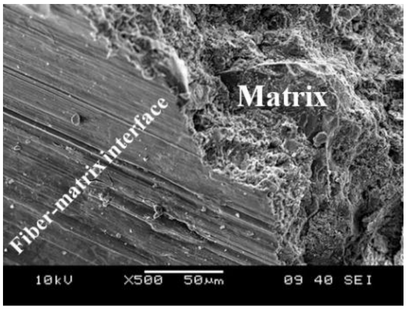


Fig. 9 The fiber-matrix interface after the pull-out test (M15)

The average debonding toughness values of hooked-end and smooth steel fibers are presented in Fig. 10. Debonding toughness values were determined by calculating the area under the pull-out load–displacement curves. Utilization of the metakaolin increased the debonding toughness values similar to the pull-out peak load values. In the case of hooked-end fibers, 15% and 30% metakaolin enhanced the peak load values by 30% and 38%, respectively (Fig. 7). These improvements are very limited in terms of smooth fiber (4-10%).

As can be seen from pull-out load–displacement curves, there are major differences between the pull-out behavior of hooked-end and smooth fibers. The pull-out peak load values of the hooked-end fibers are almost three times higher than the smooth ones. The pull-out peak load of the hooked-end fibers is 180-199% higher than the smooth ones. In the case of debonding toughness, this ratio is 129-187% (Fig. 11).

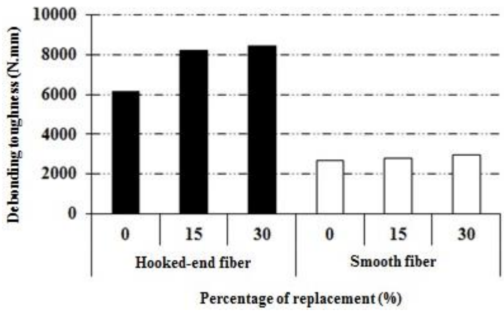


Fig. 10 The average values of debonding toughness

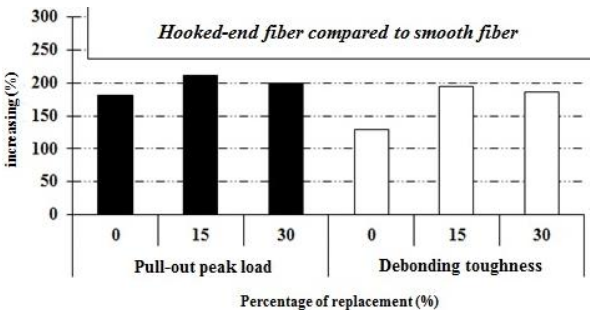


Fig. 11 Pull-out parameters of the hooked-end fiber compared to the smooth fiber

4. Conclusions

In this study the effect of metakaolin and end type of steel fiber on bond characteristics has been investigated by applying single-fiber pull-out test. Major findings of this study can be summarized as following:

- Utilization of metakaolin increased the SP demand and viscosity of SIFCON mortar.
- Substitution of metakaolin instead of 15% of cement increased the compressive strength of the mortar remarkably. Increasing of this ratio to 30% did not increase the compressive strength any further.
- Incorporating of metakaolin increased the maximum pull-out peak load of hooked-end fibers. In accordance with the compressive strength results, 15% is the optimum substitution ratio in terms of pull-out behavior. The bond characteristics of the smooth fiber did not improve significantly.
- The pull-out peak load of the hooked-end fibers is 180-199% higher than the smooth ones. In the case of debonding toughness, this ratio is 129-187%.

Ackowledgement

The author acknowledges to Mr. Mehmet YERLİKAYA from Bekaert (Turkey), Mr. Okan DUYAR from BASF (Turkey), and Modern Beton for their material supports.

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