



FLEXURAL BEHAVIOR OF SLURRY INFILTRATED FIBER CONCRETE (SIFCON) CONTAINING SUPPLEMENTARY CEMENTITIOUS MATERIALS

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Abstract: Slurry Infiltrated fiber Concrete (SIFCON) is a relatively new high performance material and can be considered as a special type of Fiber Reinforced Concrete (FRC) with high fiber content. The matrix consists of flowing mortar or cement slurry which must infiltrate properly through the fiber network placed in molds. SIFCON possessing excellent mechanical properties coupled with large ductility and toughness values. SIFCON has found application in area where high ductility and energy absorption are needed especially in seismic-resistant reinforced concrete frames and in structure under abnormal or explosive loads. Other successful applications include pavement overlays, repair of prestressed beams and repair of structural reinforced concrete element. The main aim of this study is to determine the effect of hooked ended steel fiber content and mineral admixture replacement silica fume (SF) on strength and deformation characteristics of SIFCON specimens under flexural loading. Three volume fraction of steel fiber (6, 8.5, and 11) % were used in this investigation. The percentage of SF replacement was (10%), by weight of cement in SIFCON slurry. Both the flexural strength and toughness characteristic were carried out by testing specimens of 100*100*400 mm at the age of 7 and 28 days. The results obtained from these tests were compared with those carried out on conventional fiber reinforced mortar (FRM) with 2% fiber content, as control specimens. The test results show superior characteristics of SIFCON, as compared with normal FRM, which were affected in positive manner by using cementitious materials (SF) as a partial replacement by weight of cement, and with increasing the volume fraction of steel fiber. The flexural strength and toughness value up to (28.08 MPa) and (159 N.mm), respectively were obtained at age of 28 days.

Keyword, SIFCON, Hooked ended steel fiber, Cementitious materials, Silica fume

سلوك الانتشاء للملاط الخرساني المتخلل للالياف الحديدية (السفكون) الحاوي على مواد اضافية سمنتية

الخلاصة: يعتبر الملاط الخرساني المتخلل للالياف الحديدية (السفكون) مادة جديدة عالية الاداء وايضا هو نوع خاص من الخرسانة المسلحة بالالياف بمحتوى عالي للالياف . و يتكون اما من مونة سائلة او ملاط اسمنتي والذي يجب ان يتخلل بشكل تام خلال شبكة من الالياف موضوعة في القالب . يمتلك السفكون خواص ميكانيكية ممتازة مع قيم مطيلية و صلابة عالية . وقد وجد للسفكون تطبيقات في الاماكن حيث المطيلية العالية وامتصاص الطاقة مطلوبان خصوصا في الهياكل الكونكريتية المسلحة المقاومة للزلازل والاهتزازات وفي المنشآت تحت تاثير احمال غير عادية او متفجرة . التطبيقات الناجحة الاخرى للسفكون تتضمن تغليف التبليط ، تصليح العوارض مسبقة الجهد والاجزاء الخرسانية الانشائية المسلحة . ان الهدف الرئيسي من هذه الدراسة هو ايجاد تأثير محتوى الالياف الفولاذية معكوفة النهاية والاستبدال بالمضافات المعدنية (بخرة السليكا المكثفة) على خواص المقاومة والتشوه لنماذج السفكون تحت تاثير حمل الانتشاء . تم استخدام ثلاث نسب حجمية للالياف هي (6 ، 8.5 و 11) % في هذا البحث . نسبة استبدال السليكا هي 10 % من وزن السمنت في

ملاط السفكون . تم ايجاد كل من مقاومة الانثناء والصلابة باستخدام قوالب فحص بابعاد (400*100*100) ملم بعمر 7 و 28 يوم . ان النتائج التي تم الحصول عليها من هذين الفحصين يتم مقارنتها مع خرسانة تقليدية مسلحة بالالياف بمحتوى حتمي للالياف 2% ، كنماذج مرجعية . اظهرت النتائج الصفات الممتازة للسفكون ،مقارنة بالخرسانة العادية المسلحة بالالياف، والتي تأثرت بشكل ايجابي باستخدام المواد السمنتية المضافة (ابخرة السليكا المكثفة) كاستبدال جزئي من السمنت كما تأثرت بزيادة النسبة الحجمية للالياف الفولاذية . وقد تم الحصول على قيم مقاومة انثناء وصلابة وصلت الى (28,08) ميكاباسكال و (159) نيوتن .ملم ، على التوالي بعمر 28 يوم.

1. Introduction

Slurry infiltrated fiber concrete (SIFCON) is different from normal FRC in two aspects: fiber content and the method of production. The fiber content of FRC generally varies from (1 to 3)% by volume, while the practical fiber content of SIFCON ranges from (4 to 12) % , and when using hooked ended steel fiber with length more than 30 mm the fiber content range between (4 to10)%. SIFCON matrix has no coarse aggregates but a high cementitious content. It may mineral admixture such as silica fume, fly ash and latex emulsions. Therefore, the matrix of SIFCON is either cement slurry or flowing mortar which is different from the concrete used in FRC that includes aggregate. These make the production of SIFCON is far different from FRC, which is fabricated by mixing fibers with fresh concrete, while SIFCON is prepared by infiltrating cement slurry into a bed of fibers preplaced and packed tightly in the molds[1].

SIFCON is unique construction material possessing high strength as well as large ductility and is used more widely all over the world especially in seismic retrofit design and in the structures under impact effects. It also exhibit new behavioral phenomenon that of fiber lock. The fibers are subjected to frictional and mechanical interlock in addition to the bond with the matrix, and the matrix plays the role of transferring the forces between fibers by shear, and also acts as bearing to keep fibers interlock [2]

Cement rich flowable slurry is used as a binder in SIFCON specimens, and the usage of high cement content of the slurry not only causes high production cost but also excessive heat of hydration and may cause shrinkage problems. Replacing the cement with supplementary cementitious materials seems to be a feasible solution to overcome these problems. Furthermore, incorporation of these materials may have positive effects on durability of SIFCON products by modifying the microstructure of concrete and reduce its permeability thereby reducing the penetration of water and water-borne salts into concrete [3]. Therefore, many researchers studied the mechanical properties of SIFCON produced with fly ash replacement and there is very little information about SIFCON properties produced using silica fume as a replacement of cement

Giridhar et al [1] investigated the mechanical properties of SIFCON for various volume fraction of steel fibers (4,6,and 8%). Two types of hooked end steel fibers were used which are of different aspect ratios, 50mm and 35 mm. They found that the increase in volume fraction of steel fiber cause increase in compressive and flexural strength, and 8% Vf showed great strength than the remaining Vf. The compressive strength for 35 mm steel fiber after 28 days of water curing were (90,110,120 MPa)

for (4%,6%, 8%) while The flexure strength were (4.47, 6.84 and 8.90Mpa) for(4%, 6% and 8%) Vf, respectively.

Yazici et al [3] studied the effect of incorporating high volume of class C fly ash (20,40,60)% by weight of cement on mechanical properties of the SIFCON. Hooked end steel fibers of 30 mm long and diameter of 0.55 mm were used. For all SIFCON mixes the fiber volume fraction was 8%. They concluded that by increase in the fiber volume remarkably increases flexural strength and toughness of SIFCON. Also Fly ash replacement has positively affected the flexural behavior of SIFCON.

Sudarsana et al [4] investigated the influence of volume percentage of steel fibers on strength and stiffness characteristics of slurry infiltrated fibrous concrete (SIFCON) slabs which were tested under flexural loading. In order to compare the results, fiber reinforced concrete (FRC) slabs and plain cement concrete (PCC) slabs are taken as control specimens. The test results indicate that the SIFCON slabs exhibit high strength, high energy absorption and more ductility characteristics compared to the control specimens. SIFCON slabs with higher fiber volume fraction (12%) exhibit superior performance among other slab specimens.

There is little information about the flexural behavior of SIFCON containing silica fume (SF) as a replacement of cement. Therefore the main aim of this research is produce SIFCON mixture incorporating (10%) SF by weight of cement and evaluate their effect and the effect of volume fraction of steel fiber ranging from (6 to 11%) on the strength and deformation characteristics of SIFCON under flexural loading.

2. Experimental work

2.1. Materials

2.1.1. Cement

In this study, ordinary Portland cement (Type I) commercially known as (Krasta) was used throughout of the work. Its physical and chemical properties conformed to the criteria of Iraq standard specification No. 5-1984[5].

2.1.2. Fine Aggregate (Sand)

Natural sand was used as a fine aggregate throughout the experimental work. The sand used was passing through sieve (1.18 mm) in order to ensure complete infiltration of the slurry through the dense steel fiber. It is conformed to the requirements of the Iraqi Standard No.45-1984[6] Zone 2. Its sulphate content, specific gravity, and absorption are 0.34%, 2.6, and 2%, respectively.

2.1.3. Mixing Water

Portable water (tap water) was used for all specimens mixing and curing

2.1.4. Silica fume (SF)

In this work densified silica fume from BASF Company ,which is commercially known as MEYCO/MS610, with fineness of (21000 m²/kg) was used as a partial replacement of cement. It conforms to the requirement of ASTM C1240-05[7].

2.1.5. High Range Water Reducing Admixture (HRWR)

A high-range water reducing admixture commercially known as (GLENIUM 54) From BASF Construction Chemicals Company was used throughout the experimental work. The using of HRWR is necessary to improve the workability of SIFCON slurry, which should be liquid enough to flow through the dense fiber bed without leaving honeycombs. This type of admixture conformed to the requirement of ASTM C494 type F[8].

2.1.6. Steel Fiber

Hooked end steel fiber having a diameter of 0.7mm and length of 35 mm with aspect ratio of 50 and tensile strength of 1100 MPa was used in this study. And random orientation of fiber in the matrix was carried out.

2.2. Mix Proportion

In this work, many trial slurry mixes were carried out to produce SIFCON mix with suitable fresh properties that satisfy the criteria of filling ability, fluidity and viscosity without segregation or bleeding through the dense fiber bed. After that, the minimum and maximum steel fiber content were selected to be used with the obtained mortar. Two types of SIFCON mortars (S_1 and S_2) were prepared with the same mix proportion of cement:sand (1:1) by weight, depending on many researchers used the proportion of (cement to sand) equal to 1 in their researches[1,3,9]. Water/binder ratio of 0.3 were used for the two SIFCON mixes (S_1 and S_2). The first type (S_1), which consider as a reference mix, were produced by using cement content of (885 kg/m^3) and HRWR named Glenuim (54), while the second type of SIFCON mortar was produced similar to the reference mix with partial replacement of cement by 10% of silica fume (SF) to improve the mechanical properties of SIFCON, with regulating the dosage of HRWR to obtain flow diameter and viscosity similar to that obtain in mortar S_1 without bleeding or segregation. The details of the mix proportion for the two SIFCON mixes are presented in Table (1)

Table (1): Materials contents and proportions for SIFCON mixes

Mix Symbol	w/b* ratio	Cement kg/m^3	Sand kg/m^3	Silica fume (10% rep.) kg/m^3	Water L/m^3	HRWR** % by wt. of cement
S_1	0.3	885	885	0.0	265.5	1.2
S_2	0.3	796.5	885	88.5	265.5	2.4

* b = binder = (cement + silica fume)

**HRWR dosage was regulate to obtain similar flow diameter and viscosity without bleeding and segregation

The two SIFCON mixes (S_1 and S_2) were prepared with three different volume fraction of steel fiber (6%, 8.5% and 11%). The steel fiber content of 6% was a minimum practical content that could fill the mold without using vibration. The fiber content of 11% was the maximum practical value that fills the mold with using

vibration to obtain complete penetration of the slurry into the fiber network, while the fiber content of 8.5% was used as an intermediate value. And for comparison with SIFCON specimens, mortar (S1) with 2% fiber content (S₁F-2) was also prepared which is taken as a control (reference) specimen.

2.3. Tests on Fresh Properties of SIFCON

SIFCON concrete differs from conventional (FRC) in that its fresh properties are critical to its ability to be placed satisfactorily. The matrix must be liquid and flowable enough to flow through the dense fiber bed. Filling ability, viscosity and passing ability are the key properties of workability which need to be carefully controlled to ensure successful production of SIFCON concrete. According to EFNARC [10], the mini slump flow and V-funnel test were used to determine these properties of the mortar. The mini flow test represents the flowability and segregation resistance of the mortar. Base diameter, top diameter, and height of mini slump flow test apparatus used are 100, 70 and 60 mm, respectively. And a spread diameter between (240-260) mm is required for SIFCON mortar. V-funnel test was the other test to assess the viscosity of the slurry and a flow time between (7-11) seconds is considered appropriate for the mortar [10]. The details of these two tests could be found in EFNARC [10]. The fresh properties results of the two SIFCON mortars are given in Table (2) and shown in Fig.(1)

Table (2) :Fresh properties of SIFCON mortars

Mix symbol	Mini slump flow (mm)	V-funnel (sec)	HRWR % by wt. of cement
S ₁	258	8	1.2
S ₂	257	9.5	2.4



Fig (1): Mini slump flow and V-funnel tests for SIFCON mortar

2.4. Preparing, Casting, and Curing of SIFCON Specimens

At the first stage in preparing SIFCON specimens, fibers were preplaced into the molds and then cement mortar was poured which must be flowable enough to

infiltrate thorough the dense matrix of the fiber -filled mold. The two- layer technique was used for incorporating the steel fiber in to the SIFCON matrix which found to be simpler and easier technique in actual practice than the single technique specially when using high volume fraction of steel fiber.

This technique involved placing and packing of the fibers in the mold only up to the half depth, followed by filling the mold by the mortar up to this level (half depth). Then the mold was vibrated to avoid honey combing. This process was repeated for the second layer where the entire mold was filled with the required volume fraction. No vibration was applied with the minimum volume faction (Vf) of (6%) ,while a vibration for(6-10)sec by table vibrator was required in case of (8.5%) (Vf) and for(15-20)second in case of the maximum(Vf) (11%) to ensure complete penetration of SIFCON mortar into the fiber pack . See Fig.(2)



Fig (2): Casting of SIFCON mixes

The weight of steel fiber to be placed in each mold depends on the dimensions of the mold, the required volume fraction and the density of the steel fiber itself. After casting, the specimens were left for 24 hr in the laboratory then they were demolded, marked and immersed in tap water tank to be cured until the age of 7 and 28 days

2.5. Tests on Hardened Properties of SIFCON Specimens

2.5.1. Flexural Strength Test

This test was done following ASTM- C1609,[11] a prism specimen with dimensions 100×100×400 mm simply supported beam. The specimens were tested with a constant rate of loading about 0.015 MPa/sec. the specimens were tested at age of 7 and 28 days and the average of three beams was adopted for each test. The flexural strength for beam specimens is calculated using the following formula:

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

Where:

fr: Flexural Strength or modulus of rupture, (MPa).

P: maximum applied load, (N).

L: Span length of specimen, (300 mm).

b: the width of specimen, (mm).

d: the depth of specimen aligned with fracture line, (mm)

2.5.2. Flexural toughness and Load –Deflection curves

Flexural toughness can be defined as the measured area under the load-deflection curve, which can be obtained during a flexural test. The stored digital data from the flexural test were used for toughness determination, according to the ASTM-C1609 [11], which recommends that 2 mm (L/150) deflection of middle point of the test beam was employed for toughness calculations. The specimens were tested at age of 7 and 28 days.

3. Results and Discussion

3.1. Properties of Fresh SIFCON

The results of mini slump flow and V-funnel tests on fresh SIFCON mortars (S_1 and S_2) are presented in Table 2, which conformed to EFNARC criteria of sufficient filling ability, adequate flowability and viscosity. The experimental work shows that using of HRWR for the control mortar (S_1) is very important to produce a homogeneous mixture possess the required properties with low w/c ratio. In order to determine the optimum dosage of HRWR needed for S_1 , slump flow test was carried out first with different dosage of HRWR until obtaining the aimed dosage and slump flow diameter which ranges between (240-260) mm. After that the V-funnel test was carried out to check the viscosity of mortar.

The flow time value obtained from V-funnel test is related to rate of flow. Therefore the mortars showing the highest flow time can be regarded as having relatively high viscosity

The using of HRWR in cement mortar causes a reduction in plastic viscosity, thus improving flowability and reducing the yield value. This positive effect of HRWR is due to their long lateral chains of carboxylic ether polymer which when adsorbed on cement particles, they impart a strong negative charge and that minimize the surface tension of the surrounding water molecules and enhances the fluidity of the system [12]

The results of using silica fume (SF), as a partial replacement of cement, to reference mix (S_1) is shown in Table (2) as mix (S_2). It was noticed that this replacement reduces the workability of the mix and making it cohesive and sticky, so to obtain similar viscosity and fluidity, the HRWR dosage of mixture has to be increased. The lower workability and stickiness of the mixtures by SF replacement is a result of its very large surface area.

The superplasticizer (HRWR) when mixed in concrete are absorbed by cement and silica fume particles, make them mutually repulsive as a result of anionic nature of

superplasticizer, which causes the cement and silica fume particles to become negatively charged [13].

It can be seen from the results that SF incorporation reduces the spread diameter of mini slump and increases the V-funnel time. In other words SF replacement causes relatively high viscosity. This can be attributed to increased cohesiveness with SF.

3.2. Hardened Properties of SIFCON

3.2.1. Flexural Strength

The variation in flexural strength of SIFCON specimens at age of 7 and 28 days for the two mortar types (S_1 and S_2) with different steel fiber contents (6, 8.5 and 11)%, and also the flexural strength of control specimens (S_1F-2), are presented in Table (3) and Fig.(3), Fig.(4) and Fig.(5).

When comparing the results of SIFCON specimens with that of control specimens (S_1F-2), it was concluded that the inclusion of steel fiber in SIFCON mixes improve its flexural strength which increased with increasing the volume fraction of steel fiber and for the two Sets (Set 1 and Set 2), where each set includes one type of SIFCON mortar with three different fiber content, as shown in Table (3).

Table (3): Flexural strength results for SIFCON specimens

Set No.	Mix symbol	flexural strength (MPa)	
		7 days	28 days
Reference	S_1F-2	7.32	9.69
	S_1F-6	14.35	17.13
1	$S_1F-8.5$	19.85	23.64
	S_1F-11	21.3	24.12
	S_2F-6	18.9	21.6
2	$S_2F-8.5$	22.5	25.74
	S_2F-11	24.15	28.08

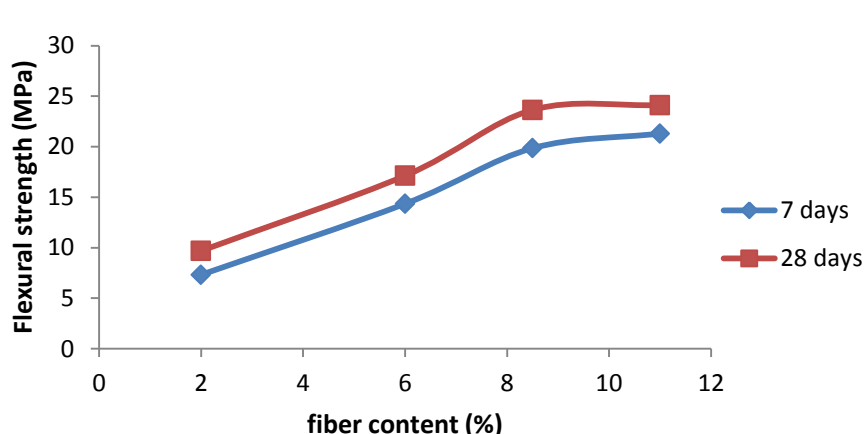


Fig.(3): The flexural strength of mortar (S_1) with different steel fiber content at age of 7 and 28 days

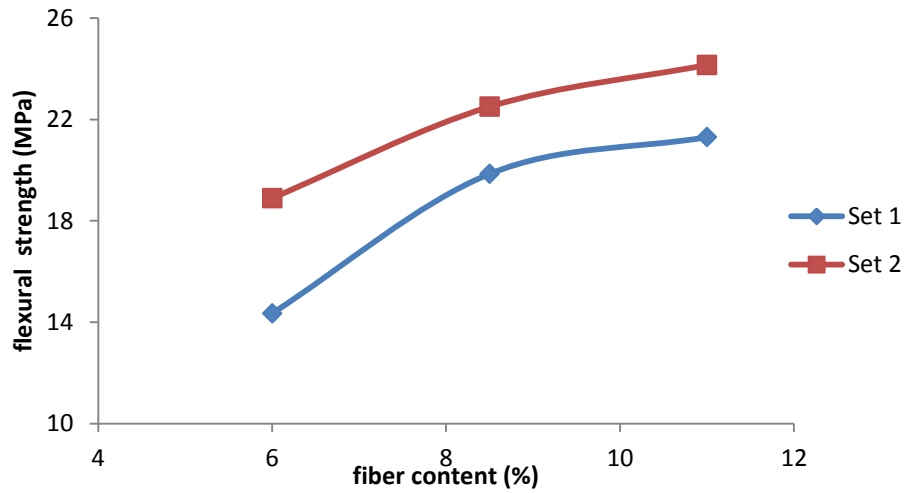


Fig.(4):The effect of steel fiber content on the flexural strength for all SIFCON mixes at age of 7 days

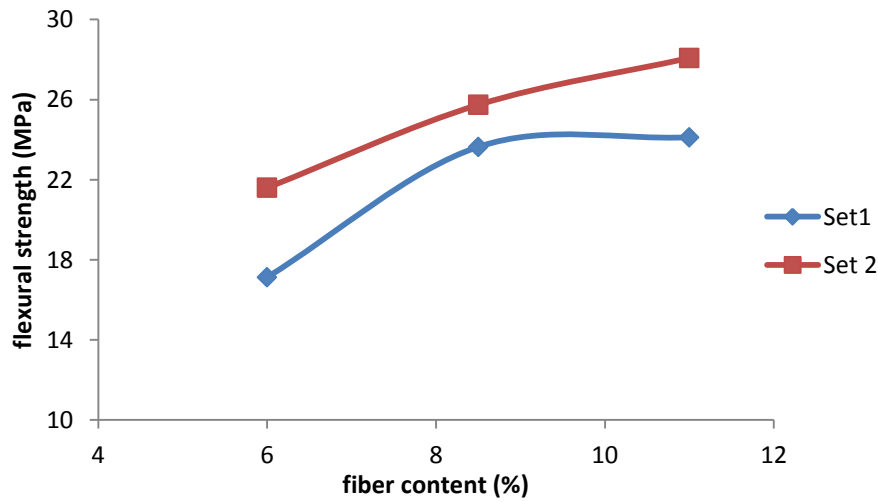


Fig.(5):The effect of steel fiber content on the flexural strength for all SIFCON mixes at age of 28 days

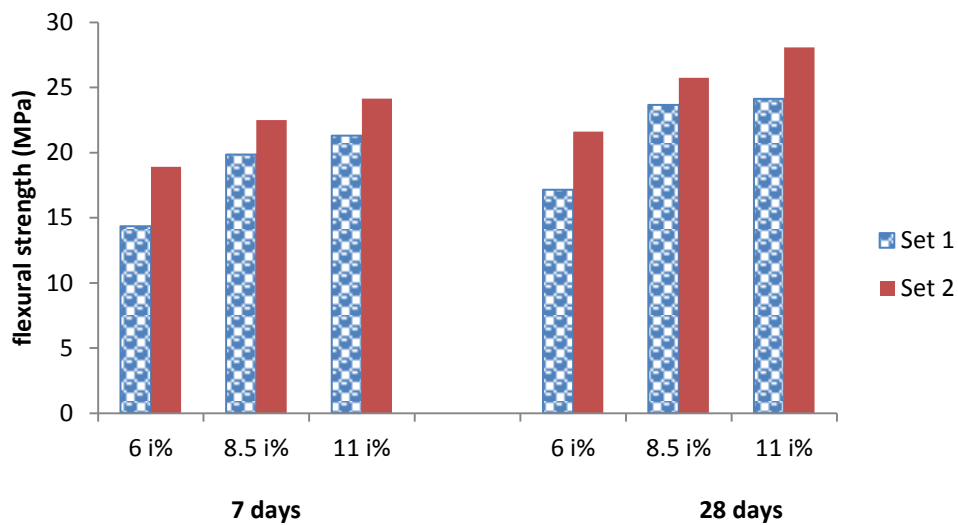


Fig.(6): Flexural strength development with time for SIFCON mixes with different fiber content

For example, in Set (1), the increase in fiber fraction from 2% to (6% ,8.5% and 11%) leads to a significant increase in flexural strength of SIFCON mixes up to (96%,171.2% and 191%) at age of 7 days , and (76.8%,144% and 149%) at age of 28 days, respectively compared with reference mix (S₁F-2). This increase in flexural strength is attributed to the stronger interface zone between binder and fibers which improves the bond strength and reduces the progress of microcracks which leads to flexural failure.

The results also show that SIFCON mixes in Set 2 have an increased flexural strength due to the incorporation of SF, as a partial replacement of cement, which results in an increase by about (31.7% ,13.4% and 13.4%) for 7 days as well as (26.9%, 9%, and 16.4%) at the age of 28 days for (S₂F-6 ,S₂F-8.5 and S₂F-11) mixes in Set 2 compared with their corresponded mixes in Set1, as shown in Fig.(6). This positive affect of SF replacement on the flexural behavior of SIFCON is due to the high surface area of SF which fills in the spaces between cement grains.

Also SF is a very reactive pozzolana material which reacts with calcium hydroxide to form additional binder material called calcium silicate hydrate, as additional binder material, which is similar to that produces from the hydration of Portland cement. And that cause improvement in matrix phase, which also improves the bond strength between the fibers and matrix as well as the flexural strength[14].

3.2.2. Flexural Toughness

Toughness value from the flexural test results (the stored digital data) for control mix (S₁F-2) and all SIFCON mixes with two different types of mortar (S₁ and S₂) and different volume fractions of steel fiber (6,8.5 and 11%), at the ages of 7 and 28 days, are presented in Table (4) .

The results showed an increased flexural toughness values ,throughout the load deflection behavior and consequently the fracture toughness ,with the increase in volume friction of steel fiber for both the Sets (Set 1 and Set 2) ,as shown from Fig. (7) to Fig. (10)

Table 4: Flexural toughness results for SIFCON specimens

Set NO.	Mix symbol	Toughness (N.m)	
		7 days	28 days
Reference	S ₁ F-2	42	47
	S ₁ F-6	77.5	108
	S ₁ F-8.5	97	138.5
	S ₁ F-11	103.4	143
1	S ₂ F-6	98	141
	S ₂ F-8.5	111	148
	S ₂ F-11	131.4	159
2	S ₂ F-6	98	141
	S ₂ F-8.5	111	148
	S ₂ F-11	131.4	159

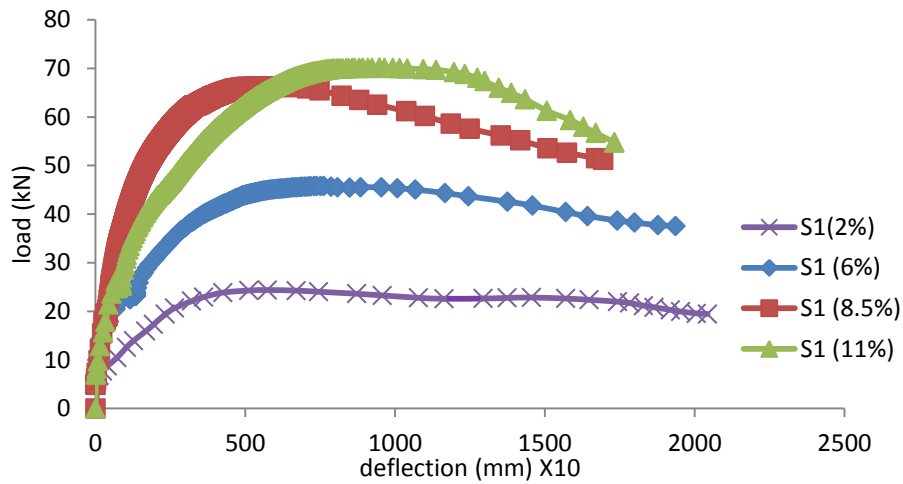


Fig.(7): Comparison between the load- deflection curves for the control mix ($S_1F-2\%$) and SIFCON mixes (Set 1) with different fiber content at age of 7 days

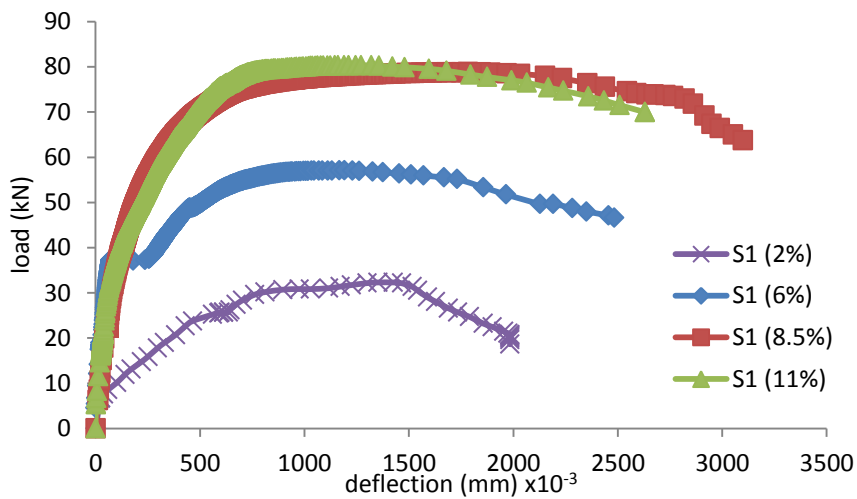


Fig.(8) :Comparison between the load- deflection curves for the control mix(S_1F-2) and SIFCON mixes (Set 1) with different fiber content at age of 28 days

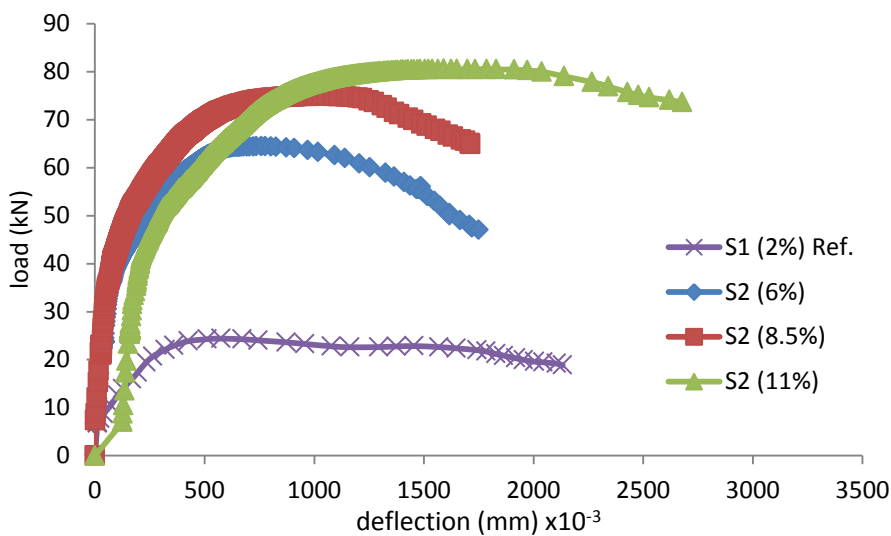


Fig. (9): Comparison between the load- deflection curves for the control mix $S_1(2\%)$ and SIFCON mixes (S_2) with different fiber content at age of 7 days

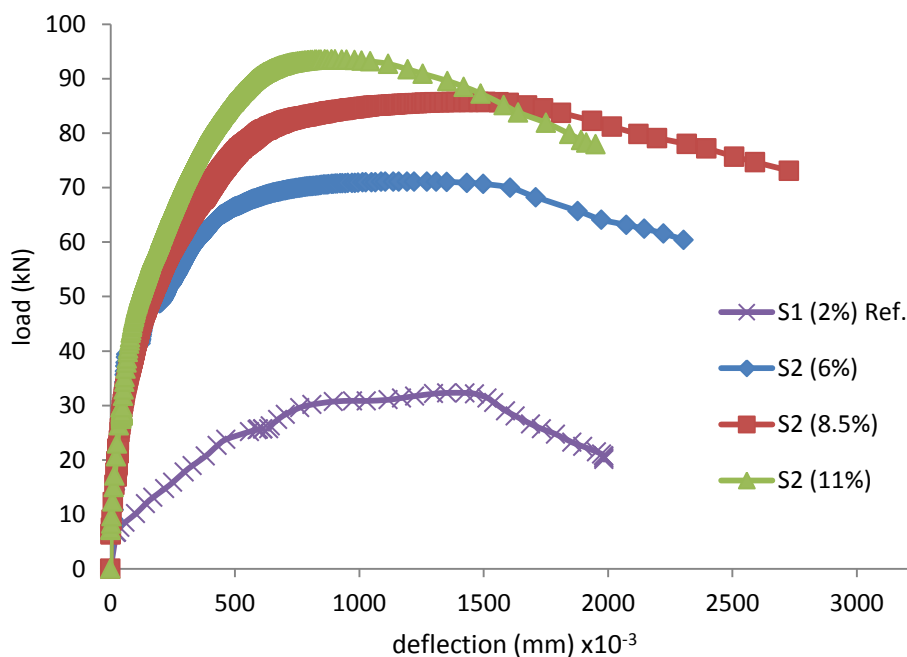


Fig.(10) :Comparison between the load- deflection curves for the control mix S1(2%) and SIFCON mixes (S2) with different fiber content at age of 28 days

As shown in Set. (1), the increase in fiber content from 2% to (6%, 8.5% and 11%) increases the toughness of SIFCON mixes (S_1F-6 , $S_1F-8.5$ and S_1F-11) to (84.5%, 131%, and 146%) at the age of 7 days, and (129%, 195%, and 204%) at the age of 28 days, respectively compared with reference mix (S_1F-2).

The reason behind this behavior is due to the fact that, the fibers bridge the micro and macrocracks by the ability to transfer emerging loads and that increase the maximum applied load and also increase the load deflection curve which does not drop down at once after reaching the maximum load. The property of flexural toughness is proportional to the concrete ability to absorb energy after microcrack initiation and propagation, where the fibers together hold the matrix. [3,12].

The results also show that, Set. 2 SIFCON mixes have an enhanced flexural toughness in comparison with Set.1 mixes as a result of SF incorporation, that results in an increment by about (26.5%, 14.4%, and 27.1%) for 7 days as well as (30.6%, 6.9%, and 11.2%) at the age of 28 days for (S_2F-6 , $S_2F-8.5$ and S_2F-11) respectively, compared with their corresponding in Set1.

This is due to the filler effect, pozzolanic effect and the large surface area of SF particles that enhance the bond between fiber/matrix interface, as shown in Fig. (11).

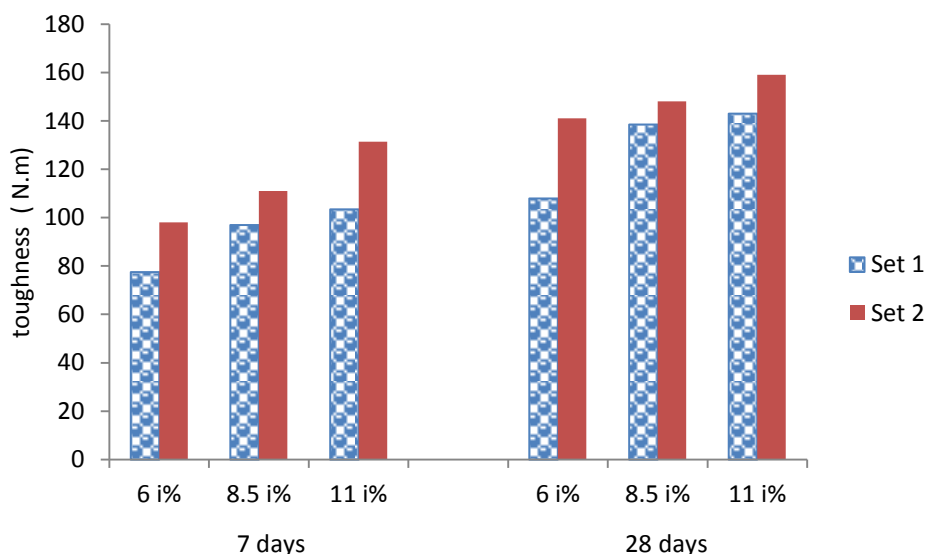


Fig.(11): Flexural toughness development with time for SIFCON mixes with different fiber content

4. Conclusions

1. The test results show that using SF, as a partial replacement of cement, increase the viscosity of SIFCON mortar (decreased the spread diameter of mini slump and increased the V-funnel time) , which can be controlled by using suitable dosage of HRWR. Therefore, SIFCON mortar, that has proper viscosity and filling ability properties, can be produced with SF replacement
2. The flexural strength and toughness value of SIFCON specimens increase with increasing the volume fraction of steel fiber. For Set 1,the increase in volume fraction from (2% to 11%) increases the flexural strength and toughness of SIFCON to 149% and 204%, respectively compared with conventional fiber reinforced mortar (reference mix) (S_1F-2) at age of 28 days.
3. The incorporation of SF, in SIFCON matrix improves the flexural behavior of SIFCON specimens. For Set 2 mixes, with volume fraction of steel fiber (11%), the increase in the flexural strength and toughness value are about 16.4% and 11.2%, respectively compared with their corresponding in Set 1 ,at age of 28 days.

5. Refrencess

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